Research article

Climate change and government policy: Fresh insights from complexity theory

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A B S T R A C T

Governments worldwide are increasingly concerned about ensuring a balance between economic and environmental well being. Global economies, particularly developing ones, emphasize the importance of achieving escofriendly growth to maintain the levels of the ecological footprint while achieving higher economic growth. The ecological footprint is a comprehensive indicator of environmental degradation. It is used to assess the state of the environment because it reflects the impact of all human activities on nature. This study contributes to the literature by offering a novel analytical approach for solving complex interactions of ecological footprint antecedents, advancing the theoretical reasoning behind how government policy combines to explain the ecological footprint from some G7 countries (France, Italy, Japan, United Kingdom, and Germany) from 1996 to 2020. To establish a composite score of environmental footprint, we used complexity theory as well as fuzzy set qualitative comparative analysis (fsQCA) and necessary condition analysis (NCA). Our analysis revealed that low expenditures on environmental protection and waste management, low taxes on transport, and high energy use are sufficient conditions to be included in the causal configurations for a high ecological footprint. Additionally, the sufficient solution, which has the highest coverage score that produces a low ecological footprint relies on high expenditure on environmental protection and high taxes on transportation. In this framework, Japan, Italy, and France have more effective government policies in terms of reducing the ecological footprint.

1. Introduction

Climate change awareness has spread among not only households and firms but also public authorities. In this regard, the ***OECD Green Recovery Database*** identified more than 680 environmental measures adopted by 43 countries and the European Union (EU) and showed that half of these countries have adopted at least 12 measures aimed at addressing issues related to biodiversity, waste and recycling, air pollution, water, plastics, and climate mitigation. These measures were based on grants with or without an interest-free rates, R&D subsidies, regulatory change, tax reduction, or skills training. More surprisingly, government spending on green measures represented only 2% of total spending on COVID-19 stimulus packages (OECD, 2021). Moreover, OECD highlighted that the subnational climate-related spending remained stable from 2000 to 2016 with an average of 1.3% of the national gross domestic product (GDP). Similarly, EUROSTAT found that the EU expenditure on environment protection did not depend on significant changes as it ranged between 0.7% and 0.9% of GDP between 1995 and 2020. This suggests that public environmental initiatives tend to be subject to some financial constraints.

In the context of limited public resources, identifying the optimal subset of government policies that can minimize environmental degradation is important for policymakers and legislators. This study addresses this research question considering the complexity theory. According to Byrne (2002), causal models based on interaction terms and linear equations ignore the degree of complexity that some variables can capture, which leads to the analysis of a context or environment where single causes determine the outcomes. However, the changes in the variance of a variable are determined by multiple causes with a nonadditive interaction, thus affecting the measurement accuracy. In

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our study, the process of reducing the ecological footprint (EF) stems from the effects or a combination of multiple public initiatives. Conventional statistical approaches may be unsuitable for capturing such degree of complexity. Therefore, we rely on fuzzy set comparative qualitative analysis (fsQCA) to identify the optimal configurations of government policies to combat climate change.

In this framework, the fsQCA methodology was applied to several strands of the complexity theory literature dealing with consumer behavior (Olya and Altinay, 2016; Pappas et al., 2016), corporate bankruptcy (Boratyn´ska, 2016; Ben Jabeur et al., 2021a, b), entrepreneurship (Kraus et al., 2018), asset investment (Wu et al., 2016), and corporate performance (Ben Jabeur et al., 2021a, b). The novelty of our research lies in applying fsQCA and NCA methods for the first time to understand how multiple sets of government policies, as captured by public expenditure on climate change issues (environment protection, pollution abatement, waste management) and fiscal strategies (energy, pollution, transport), provide positive or negative ecological footprints in the case of G7 countries from 1996 to 2020. In fact, we shed light on the complexity of climate change phenomena that standard approaches leave unexplored, and we present an overview of the fsQCA method for anyone contemplating using it to expose information on these complexities in a context of global warming. This analytical technique can handle outliers, asymmetric data, asymmetric relationships, and the interdependence of all antecedent conditions, making it a useful supplement to symmetric quantitative approaches (Douglas et al., 2020).

Our findings expand the ecological literature on the consequences of government interventions and institutional quality (Garrone and Grilli, 2010; Lin and Li, 2011; Gani, 2012) by identifying multidimensional policy solutions instead of a common single solution reported by multiple and linear regressions. In this regard, our paper adds to the theory of complexity in economics (Zadeh, 1978; Arthur, 2018) by offering a new way of thinking about ecological economics, emphasizing the importance of interactions and emergence in shaping ecological footprint outcomes. Ecological literature can inform and shape government policy by raising awareness of environmental issues and providing a framework for understanding the complex nexus between human society and the natural environment.

Using observations from some G7 countries over the period 1996–2020, our analysis based on fsQCA points out that a high ecological footprint can be reached in countries subject to low expenditures required for the preservation of the environment and the waste management where the energy use is high and the local legislation imposes low taxes on transport. Additionally, more expenditures on environmental protection and the use of high taxes on transport activities seem to be the most efficient policy mechanisms to combat climate change.

This study is structured as follows. Section 2 presents an overview of the main determinants of public governance of environmental degradation. Section 3 shows the dataset and the fsQCA methodology. Section 4 reports and discusses the main results, while section 5 concludes.

2. Literature review

Recently, studies have focused on ecological footprint rather than on carbon dioxide emissions. Ecological footprint is a comprehensive environmental indicator because it considers the demand created by human activities for natural resources and the ability to assess the environmental issues resulting from the use of natural resources (Chen et al., 2022). The expansion of the ecological footprint may have major consequences for ecosystems and generate environmental issues such as air pollution and climate change. Thus, many academics have selected ecological footprint as a measure of environmental issues (Bandyopadhyay et al., 2022; Wang et al., 2022). Çakmak and Acar (2022) indicated the need to examine global energy consumption, investment in alternative energy sources, and techniques to reduce the effect of economic growth on environmental degradation. Wang et al. (2022) studied the ecological footprint of 166 countries to examine the relationship between renewable energy consumption, population aging, and decoupling economic growth. Their findings showed that economic growth significantly affects the ecological footprint, thus supporting the pollution haven hypothesis, while the use of renewable energy leads to a nonsignificant impact. Baz et al. (2020) discussed the effects of energy consumption and economic development on environmental quality in Pakistan using a nonlinear, autoregressive, distributed lag technique and found an asymmetric relationship between energy use and economic growth on environmental quality.

Ashraf et al. (2022) found that financial development has an inverted-U-shaped impact on ecological footprints in consumption, imports, and production. Ahmad and Wu (2022) used a panel quantile regression based on a sample of 20 countries from 1990 to 2017 to emphasize that both linear and nonlinear increases in green productivity can reduce environmental deterioration; however, the impacts of economic globalization were shown to be contradictory. Dasgupta et al. (2021) studied the impact of global GDP and its growth rates on the ecological gap and found that egalitarian economic redistributions can result in larger global ecological footprints. Based on the Markov switching model, Charfeddine (2017) examined how environmental degradation was affected by urbanization, energy use, trade openness, and financial development and found that electricity consumption and financial development are favorably associated with ecological footprint.

To preserve environmental quality and ensure the longevity of natural resources, environmental governance must be stringent. Several studies have recently begun to highlight the role(s) played by public government in addressing climate change challenges (Stef and Ben Jabeur, 2020; Stef and Ben Jabeur, 2023). Gani (2012) highlighted the importance of having high-quality macro-level governance because it may lead to implementing environmental degradation reduction policies. In this regard, Liu et al. (2022) empirically analyzed the dynamic effect of fiscal decentralization and institutional governance on ecological sustainability and found these measures improved environmental sustainability. In constrast, AL-Barakani et al. (2022) investigated the direct and indirect regional effects of financial development, renewable energy use, and institutional quality on the ecological footprint and found that institutional quality is crucial for enhancing environmental quality. Yao et al. (2021) also stressed that corruption adversely affects the ecological footprint. Consequently, environmental regulations should be effectively enforced to preserve environmental quality (Stef and Ben Jabeur, 2020). More recently, Fang et al. (2023) examined the consequences of environmental policies from the perspective of various ecological footprints. The authors found that environmental protection taxes have a larger inhibitory effect on ecological footprints than pollution costs. Additionally, Hussain et al. (2023) investigated the role of transport infrastructure expenditure on ecological footprint in India. Their findings revealed that transport expenditure and economic development can diminish the ecological footprint. In the case of BRICS countries, Sun et al. (2023) explored the nonlinear effects of energy consumption and globalization on ecological footprint showing that those effects are heterogeneous among different quantiles.

3. Data and methodology

In environmental literature, carbon emission, as a substantial contributor to greenhouse gas emissions, is used to measure environmental pollution. However, scholars have often criticized it for being superficial (Bello et al., 2022). In contrast, the EF is a more complex measure of ecological quality and increasingly used in various studies on environmental management (Long et al., 2020; Caglar et al., 2021). Therefore, we used ecological footprint (Number of Earths) developed by Wackernagel and Rees (1998) to measure environmental pollution. The dataset was provided by the Global Footprint Network (2019). The panel dataset of government variables includes environmental taxes (ET), taxes on energy (TE), taxes on pollution (TP), taxes on transport (TT), expenditure on environment protection (EEP), expenditure on pollution abatement (EPA), and expenditure on waste management (EWM). Our initial sample consisted of a group of seven countries (G7); owing to the availability of government policy determinants for some countries, the following countries were selected: France, Italy, Japan, United Kingdom, and Germany. To complete our sample, we used the World Bank (2021) database by including economic development (*GDP Capita*), energy per capita (*Energy Use*), and renewable energy consumption (REC). Table 1 provides the sources and detailed definitions of these variables. Fig. 1 shows the intensity of the relationships between the ecological footprint and the explanatory variables. Statistics for all variables are shown in Table 2.

In this study, we follow the set-theoretic method to discover the simplest combinations of conditions that produce a certain outcome (Vis, 2012). For example, we used the fuzzy set qualitative comparative analysis (fsQCA) methodology developed by Ragin (1987, 2000, 2008). This technique searches for causal relationships by recognizing the conditions or a combination of conditions (independent variables) sufficient for a particular outcome (dependent variable) to exist. The fsQCA methodology is now attracting considerable interest from professionals and researchers who use it as a robust analytical tool to evaluate theories in the social sciences (Bell et al., 2014)

Hsu et al. (2013) claimed that this method is more suitable when the result comes from complex iterations because fsQCA helps the researcher to find and understand patterns or configurations in the condition variables for the cases under study. Fiss (2011) stressed that the set-theoretic approach differs from conventional variable-based approaches because it does not decompose cases into independent characteristics of observations but rather combines observations or cases into causal combinations or configurations.

Table 1
Variables definitions.

Variables	Code	Description	Source
Ecological footprint	EF	The Ecological Footprint is a measure of the biologically productive land and water area an individual, population or activity requires to produce all the resources it consumes, to accommodate its occupied urban infrastructure, and to absorb the waste it generates, using prevailing technology and resource management practices.	Global Footprint Network
GDP per capita	GDP	GDP per capita (constant 2015 USD)	World Bank
Renewable Energy Consumption	REC	Renewable energy consumption (% of total final energy consumption)	World Bank
Energy Use	EU	Energy use (kg of oil equivalent per capita)	World Bank
Taxes on Energy	TE	Taxes on Energy including fuel for Transport (% GDP)	International Monetary Fund
Taxes on Pollution	TP	Taxes on pollution (% GDP)	International Monetary Fund
Taxes on Transport	TT	Taxes on Transport excluding fuel for Transport (% GDP)	International Monetary Fund
Expenditure on environment protection	EEP	Expenditure on environment protection (% GDP)	International Monetary Fund
Expenditure on pollution abatement	EPA	Expenditure on pollution abatement (% GDP)	International Monetary Fund
Expenditure on waste management	EWM	Expenditure on waste management (% GDP)	International Monetary Fund

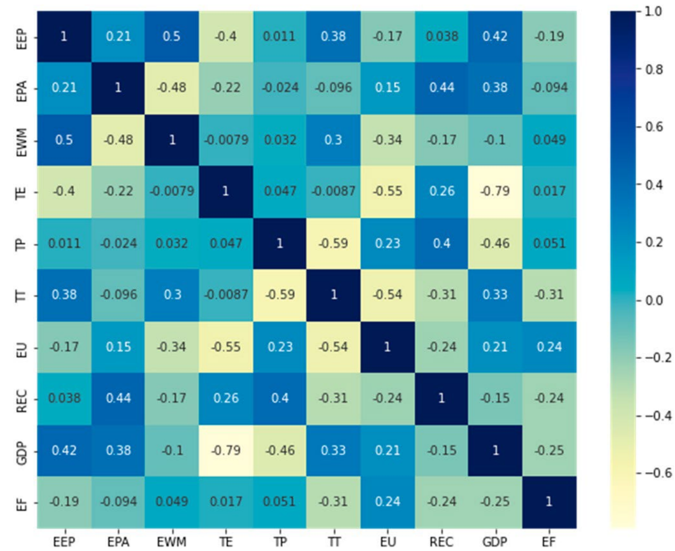

Fig. 1. Correlation matrix.

Table 2
Descriptive statistics.

	Mean	Median	Standard Deviation	Minimum	Maximum
EEP	0.842	0.837	0.227	0.437	1.374
EPA	0.065	0.056	0.043	0.002	0.214
EWM	0.415	0.414	0.157	0.162	1.159
TE	1.756	1.764	0.542	0.76	2.94
TP	0.105	0.05	0.138	0.005	0.422
TT	0.457	0.475	0.128	0.193	0.665
EU	3635.563	3804.025	500.006	2414.484	4301.737
REC	7.988	7.126	4.67	0.852	17.131
GDP	2.89E+12	2.63E+12	7.80E+11	1.80E+12	4.59E+12
EF	2.971	2.927	0.206	2.578	3.545

Ordinary least squares (OLS) regression is used to determine whether a given variable in a sample has a significant positive or negative effect on a dependent variable. This effect is considered a net effect of the other variables. A regression analysis provides the magnitude and direction of the effect of a particular variable, but in isolation, without considering the other model variables. Conversely, fsQCA does not consider the independent effect of a variable but the combined effect of the various variables. Its goal is to identify the conditions (variables) responsible for a particular outcome or response by seeking combinations or causal configurations (Elliott, 2013). The fsQCA method is used to comprehensively examine how a causal condition or set of conditions can determine a particular outcome and explain the complex causal relationships (Ragin, 2000, 2008). Cases or observations are combinations of causal conditions and an outcome or response value.

In summary, fsQCA is a method for analyzing complex causality, and it is used when the research question is focused on identifying sufficient conditions for a particular outcome. This technical approach allows researchers to analyze causal complexity by examining combinations of variables that lead to an outcome of interest. Unlike OLS, fsQCA doesn't assume that there is a linear relationship between variables, being well-suited for analyzing non-linear relationships, interactions, and asymmetries. Thus, this method offers significant advantages over traditional statistical procedures such as regression-based analysis.

Moreover, fsQCA is based on set theory and Boolean algebra, and it allows researchers to identify the sufficient conditions for a particular outcome, which can help to address endogeneity issues. FsQCA allows researchers to analyze the sufficient conditions for an outcome, which can help to address endogeneity by ruling out alternative explanations for the outcome. By analyzing the combinations of conditions that lead to the outcome, researchers can identify the specific causal pathways that are relevant for the outcome of interest, and compare them to alternative pathways to rule out alternative explanations. Moreover, fsQCA does not rely on the same assumptions about linearity, additivity, and normality as traditional statistical methods, which can be problematic when endogeneity is a concern. Instead, fsQCA uses set-theoretic methods that allow for non-linear and non-additive relationships between variables, which can help to better capture complex causal relationships.

Additionally, fsQCA is a method that may be used to handle the problem of collinearity or correlation between variables; it can identify causal configurations of variables that are associated with a particular outcome, even in the presence of collinearity or correlation between variables. Ragin (2008) discusses how fsQCA can identify causal configurations of variables that lead to a particular outcome, even in the presence of collinearity or correlation between variables. Specifically, he notes that fsQCA can handle the problem of collinearity by using fuzzy set theory, calibration, and Boolean algebra to identify causal configurations.

Alternative mechanism thinking shows that different causal recipes may be associated with a given outcome (or dependent variable); therefore, this is a better approach than developing a theory based on the effects caused by independent variables (Woodside, 2013). According to Schneider and Wagemann (2010), the fsQCA method identifies patterns that reveal the relationship between observations to determine the possible causal relationships. It is important to clarify that the identified causal relationships must be interpreted through the mathematical laws of Boolean algebra.

To apply the fsQCA methodology, the considered variables must be transformed into values that indicate their degree of a group or set membership. Thus, a researcher can investigate what combinations of sets can lead to a given outcome. According to Longest and Vaisey (2008), this approach can be used to identify the combination or combinations of conditions (the equivalent of the independent variables in an ordinary regression) that might lead to an outcome (the equivalent of the dependent variable in an ordinary regression). This leads to various combinations, called configurations or causal recipes, which allow the existence of the outcome under study.

This study identifies the combinations of government policies that constitute the subsets that produce a high score of ecological footprints. In other words, the present research determines the conditions or causal configurations that can lead to a negative ecological footprint. Therefore, using the complexity theory, we apply fsQCA, which constitutes one of the set-theoretic methods proposed by Ragin (1987, 2000, 2008), to avoid issues related to conventional statistical techniques. To achieve this research goal, we implement two propositions (complexity and equifinality) using fsQCA to identify the various combinations of government policies that propose sufficient conditions for the adoption of a negative ecological footprint.

4. Results

4.1. FsQCA results of conditions leading to a negative ecological footprint

Nine variables were used for the analysis, as indicated earlier, with the following expression:

Ecological footprint = f(Expenditure on environment protection + Expenditure on pollution abatement + Expenditure on waste management + Taxes on Energy + Taxes on Pollution + Taxes on Transport + Energy Use + Renewable Energy Consumption + GDP per capita)

$$EF = f(EEP + EPA + EWM + TE + TP + TT + EU + REC + GDP)$$

Consequently, nine conditions or variables help in finding the causal recipes or configurations leading to the outcome of a high score for ecological footprints.

The application of the fsQCA method first requires the calibration of the variables to convert them into conditions of the outcome variable. This calibration process is performed to assign a degree of membership in the set to the variables. This is similar to normalizing a variable's source data (Woodside, 2013). It consists of expressing the degree of membership in a set and requires the use of three threshold values: full membership in the set (1.0), full nonmembership in the set (0.0), and a value of maximum ambiguity where the observation or case is neither inside nor outside the set (0.5). We have followed a cluster-based approach to obtain these three thresholds using clusters "Euclidian Distance." This procedure helps in finding the calibration thresholds to convert the raw variables into sets. According to Duşa (2018), cluster analysis is instrumental in determining the threshold that best divides the scores into a certain number of groups, dividing the raw data into the most important groups.

All models were fitted using version 4.1.3 of the R statistical package (R Core Team, 2022), and the fsQCA analysis was conducted using version 3.2 of the QCA package (Duşa, 2018).

The qualitative comparative analysis aims to identify the conditions that are sufficient to yield a particular outcome. Thus, it is essential to extract the combinations of attributes that are sufficient to produce the outcome from the causal conditions (Fiss, 2011). A condition is sufficient if it always yields a result or an outcome, and observations or cases that prove to be sufficient also agree with the outcome. A condition is sufficient if it is a subset of the outcome set. To establish this relationship of sufficiency, we should create a truth table. Therefore, we must identify all possible combinations of the various causal conditions (one row for each combination) that can generate the desired result or outcome. In other words, according to Fiss (2011), the truth table consists all possible logical combinations that can be formed from all conditions. Thus, the observations or cases are assigned to the logical combination with a degree of membership above 0.5. Subsequently, the results are analyzed using Boolean algebra, which usually means the logical reduction or simplification using the Quine–McCluskey algorithm (Fiss, 2007). For a number n of conditions, the truth table would have 2^n rows. As we have nine conditions in our study, 512 possible causal configurations could be an antecedent of the desired outcome. Two indicators are commonly used to assess the strength of causal relationships identified by the fsQCA method: consistency and coverage (Hsu et al., 2013). As Duşa (2018) stated, in the sufficiency relationship, consistency represents the proportion of observations or cases that consists of both a causal condition or configuration and the desired outcome, relative to the total number of cases in which the causal condition or configuration occurs. In other words, consistency quantifies how closely do observations or cases with a similar causal configuration match the desired outcome. In terms of sufficiency, however, the coverage provides a measure of how much of the desired outcome is explained by a causal configuration or condition, that is, this indicates the empirical relevance of the causal solution. It is the degree to which the cases or observations belong to a particular configuration and the desired outcome relative to all cases leading to the outcome. The higher the degree of coverage, the more important the condition. If a causal configuration covers 100% of the desired outcome, it is both sufficient and necessary. According to Hsu et al. (2013), comparing these measures to traditional statistics, consistency can be viewed as equivalent to Pearson's correlation coefficient r, and coverage would be analogous to the coefficient of determination R2.

Table 3 summarizes the analysis results of the sufficiency of conditions that can lead to a negative ecological footprint, with reasonable and acceptable values for global consistency (0.890) and coverage (0.491). Three possible solutions or causal configurations produce the outcome (high values of ecological footprint).

a) First solution: low EEP, low EPA, low EWM, low TE, low TT, and high energy use.

Table 3
Analysis of the sufficiency of the conditions for a negative ecological footprint.

Solution: ~EEP*~EPA*~EWM*~TE*~TT*EU + ~EEP*~EWM*~TE*~TP*~TT*EU*GDP + ~EEP*~EPA*~EWM*~TP*~TT*EU*~REC*GDP → EF

	Consistency	Coverage
~EEP*~EPA*~EWM*~TE*~TT*EU	0.915	0.417
~EEP*~EWM*~TE*~TP*~TT*EU*GDP	0.898	0.256
~EEP*~EPA*~EWM*~TP*~TT*EU*~REC*GDP	0.944	0.188
Minimum total	0.890	0.491

Notes: Sample size = 125. The ~ symbol indicates the absence of the condition, and their omission indicates its presence. The variables are defined in Table 1.

This solution includes France from 2001 to 2008.

b) Second solution: low EEP, low EWM, low TE, low TP, low TT, high energy use, and high GDP per capita.
This solution includes Germany from 2012 to 2017 and 2020.

c) Third solution: low EEP, low EPA, low EWM, low TP, low TT, high energy use, low REC, and high GDP per capita.

This solution includes Germany from 2000 to 2005.

In the notation, the ~ symbol was used to indicate a particular condition and their omission indicate the negation or absence of the condition.

4.2. FsQCA results of conditions leading to a positive ecological footprint

To complete the analysis, we applied the fsQCA method to the opposite outcome, namely, a positive ecological footprint. Hence, the values of the expected outcome variables must first be inverted as 1 indicates the state of a much negative ecological footprint, and 0 indicates the opposite situation. The Boolean algebra operation 1–***negative ecological footprint*** was used to obtain the negation of the raw data, termed as a positive ecological footprint situation (*LOW_EF*).

Table 4 shows the results of the fsQCA based on the conditions considered for a negative ecological footprint in our study but are now considered determinants for the opposite outcome, i.e., a positive ecological footprint. Accordingly, there are two solutions for a sufficiency relationship.

a) First solution: high expenditures on environmental protection and high TT.

This solution includes Japan and for 1996, 2000, 2002–2015, and 2017–2019, as well as Italy from 2011 to 2019.

b) Second solution: high EEP, high EWM, high TP, high REC, and low GDP per capita.

This solution includes France from 2011 to 2016.

Importantly, the analysis using the fsQCA method produces three solutions: complex, intermediate, and parsimonious. As Ragin (2008) highlighted that although tthe causal configurations in these solutions may differ from each other, they are consistent with Boolean logic and never contain contradicting information. The complex solution does not include assumptions to simplify the results; therefore, the causal configurations obtained are complex and difficult to interpret, especially when there are many causal antecedents or conditions. The parsimonious solution reduces the causal configurations to their minimal expression, including only the so-called prime implicants, which must not be omitted in any solution derived from the truth table. The fsQCA algorithms automatically make decisions about logical remainders without considering the theoretical arguments that support such automatic decisions. Ragin (2008) did not recommend using such rigorous simplification criteria, and hence, against the computation and specification of the parsimonious solution in fsQCA.

An intermediate solution is achieved by selectively considering assumptions that help reduce the complexity of causal phenomena. These assumptions refer only to scenarios consistent with theoretical knowledge or empirical evidence. The application of this solution relies heavily on the researcher having a clear understanding of the relationships between the conditions and the expected outcome based on their theoretical knowledge or demonstrated empirical evidence.

In our study, we included the intermediate solution, as displayed in Tables 3 and 4 We consider this solution the most appropriate as it does not clude the simplified solution's weaknesses or the complications in interpreting the more complex solution. Table 5 shows the expected relationships between the causal conditions and a situation of a negative ecological footprint.

Table 4
Analysis of the sufficiency of the conditions for a positive ecological footprint.

Solution: EEP*TT + EEP*EWM*TP*REC*~GDP → LOW_EF

	Consistency	Coverage
EEP*TT	0.800	0.371
EEP*EWM*TP*REC*~GDP	0.885	0.113
Minimum total	0.807	0.452

Notes: Sample size = 125. The ~ symbol indicates the absence of the condition, and their omission indicates its presence. LOW_EF refers to a positive or low ecological footprint. The remaining variables are defined in Table 1.

4.3. Necessary condition analysis

Necessary Condition Analysis (NCA) is complements fsQCA as it can test the necessary statements in degrees and relationships of necessity, whereas fsQCA only test relationships of necessity in kind (Vis and Dul, 2018). NCA is an emerging method that uses the logic of necessity to pinpoint individual requirements that must be satisfied to obtain the desired result (Dul, 2016, 2022). According to To´th et al. (2019), a necessary condition must exist for the outcome to be realized; however, the presence of a condition alone does not guarantee the outcome. Specifically, in the absence of the essential condition, the desired result cannot be achieved. Thus, the NCA provides accurate estimates with simple theoretical models (Dul, 2019). Moreover, traditional models require control variables to eliminate bias, but not the NCA. Thus, the NCA uses basic theoretical models to provide accurate estimations (Dul, 2019). Furthermore, conventional models require control variables to reduce bias, while the NCA does not. NCA may be employed as a stand-alone approach or in conjunction with other methods such as multiple linear regression and structural equation modeling, as well as fuzzy set qualitative comparison analysis (Dul, 2023). NCA has the ability to provide novel theoretical and practical discoveries (Aguinis

Table 5
Expected relationships between causal conditions and ecological footprint.

Condition	Expected sign
EEP	Negative
EPA	Negative
EWM	Negative
TE	Negative
TP	Negative
TT	Negative
EU	Positive
REC	Negative
GDP	Positive

Notes: The "Negative" sign indicates that the condition is expected to contribute to a low score of the outcome, and the "Positive" sign indicates that the condition is expected to contribute to a high score of the outcome. The variables are defined in Table 1.

et al., 2020; Dul et al., 2023).

Using effect size and a scatterplot, the NCA is used to determine whether a variable is necessary and to determine the number of explanatory variables required to achieve a given level of result (ecological footprint). The first step is to study the sample data scatterplot, which indicates the potential necessary conditions for the independent variable on the *x*-axis (horizontal) against the outcome ecological footprint. This scatterplot has an empty space in the top left corner above the data area, indicating the potential existence of a necessary condition. Fig. 2 displays the scatter plots with ceiling lines. The OLS regression line runs through the center of the data. In addition to the data, two "ceiling lines" are displayed: the widely used step function for discrete data, ceiling envelopment with a free disposal hull (CE-FDH) and ceiling regression with a free disposal hull (CR-FDH) for continuous data. Consistent with Dul (2016), the CR-FDH ceiling line was used in this study. For example, Fig. 2 shows the plot between EWM and EF. The empty zone in the upper left corner suggests that the EWM is a necessary condition for the ecological footprint. Similarly, there are empty spaces in the upper left corners of energy use and TE, including fuel for transport (Fig. 2d), which indicates that these conditions are important for the ecological footprint.

According to Dul (2016), the necessary conditions are measured through effect size ($0 < d < 0.1$ "small effect," $0.1 = d < 0.3$ "medium effect," $0.3 = d < 0.5$ "large effect," and $d \geq 0.5$ "very large effect"). The NCA results demonstrate in Table 6 that energy use, TE including fuel for transport and the EWM are necessary for ecological footprint, with small and medium effect sizes. These results align with the findings of Ben Jabeur (2020) and Stef and Ben Jabeur (2020), who confirmed that energy use enhances environmental degradation. In the case of CO_2, Alola and Nwulu (2022) found identical results: only energy tax significantly mitigates emissions and energy intensity. In contrast, pollution and resource taxes increase emissions and energy intensity.

The bottleneck table provides the ceiling line for determining how specific levels of the resulting condition may be achieved. Table 7 is a "bottleneck table" developed by Dul (2016) that lists the threshold values for each of the nine necessary conditions that must be met to achieve a certain degree of ecological footprint. Using the bottleneck table, we make the necessary statements in degrees. "NN" indicates that

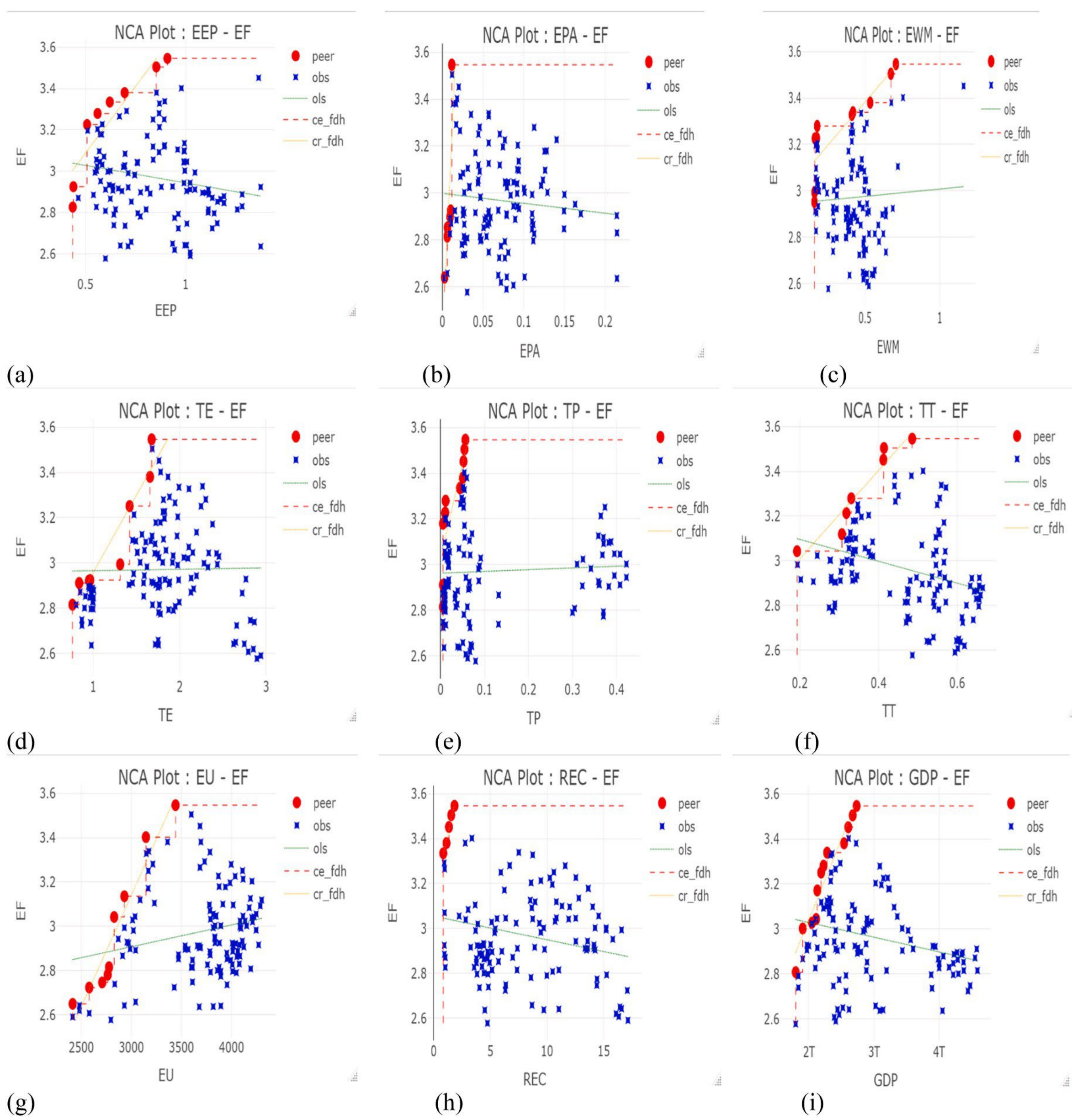

Fig. 2. Scatterplots of the nine single necessary conditions of outcome ecological footprint.

Table 6
Results of necessary condition analysis.

Conditions	Accuracy	Effect size	P-value
EEP	94.4%	0.125	0.196
EPA	95.2%	0.031	0.714
EWM	92%	0.120***	0.006
TE	95.2%	0.196**	0.014
TP	93.6%	0.033	0.220
TT	96.8%	0.168	0.136
EU	92%	0.269***	0.004
REC	97.6%	0.006	0.936
GDP	94.4%	0.109	0.166

Notes: 0 < d < 0.1 "small effect", 0.1 = d < 0.3 "medium effect", 0.3 = d < 0.5 "large effect", and d ≥ 0.5 "very large effect". * implies significance at 10% level, ** at 5% level and *** at 1% level.

X is not necessary for Y at the indicated value. For example, Table 6 shows that to reach a low ecological footprint (40% or less), EEP, EWM, TP, TT and REC are not necessary. To reach medium-level ecological footprint (50%), the required minimum levels of the conditions are 4.7% (EEP), 3.1% (EPA), 18% (TE), 7.2% (TT), 26.9% (EU), and 8.3% (GDP), respectively. Hence, for high levels of the ecological footprint (100%), all conditions are necessary but not the highest levels of the condition.

4.4. Robustness analysis

Robustness analysis is performed for the identified conditions that lead to a negative ecological footprint. According to Dusa and Alrik (2012), there could be a scenario in which a causal condition or configuration is sufficient to produce both the expected outcome and its negation, which would constitute a contradiction or a paradoxical relationship. Therefore, it is crucial to confirm that this contradiction is avoided. Thus, a new fsQCA algorithm is applied using the solutions or causal configurations identified for a negative ecological footprint, but this time to negate the expected outcome, the absence of a negative ecological footprint. Table 8 shows low consistency and very low coverage values for the negation of the outcome, implying that the aforementioned contradictory or paradoxical relationship does not hold true.

When a causal condition or configuration and its negation are both sufficient to achieve the same desired result, another possible problem can arise (Dusa and Alrik, 2012). Table 9 shows that the negation of the causal configuration identified for a negative ecological footprint would not, similarly, lead to a negative ecological footprint; in fact, it can be seen that the consistency and coverage values are relatively low. Therefore, it is verified that this possible contradiction does not exist in the obtained solution.

However, continuing the robustness analysis, Fig. 3 shows the results of the solution with three sets of conditions identified, using their membership scores and the outcome of a negative ecological footprint. Most cases are located above or around the diagonal line, supporting the existence of the sufficiency relationships among the three sets of conditions and the outcome.

5. Discussion and implications

This is the first empirical study to examine the distinct characteristics of an ecological footprint using a mix technique. An innovative mixed-method approach was applied, revealing the conditions required to improve environmental quality. In this study, we assessed the output of the configurational model considering the nine tenets of complexity theory (Woodside, 2013). The fsQCA results indicated that the two formulas explain a positive ecological footprint. The empirical analysis from fsQCA suggests that government policy can moderate environmental degradation. Among our public governance variables, the level of high EEP, high TT, high EWM, and high TP have a significant moderation effect. According to Fan et al. (2022) expenditure on environmental protection is the most common governmental policy related to environmental governance. In countries with a high degree of environmental protection (e.g., Japan), economic resources tend to be allocated more to preventing, reducing, and eliminating pollution and

Table 8
Analysis of the sufficiency solution for the absence of a negative ecological footprint (~EF).

Solution: ~EEP*~EPA*~EWM*~TE*~TT*EU **+** ~EEP*~EWM*~TE*~TP*~TT*EU*GDP **+** ~EEP*~EPA*~EWM*~TP*~TT*EU*~REC*GDP → ~EF

	Consistency	Coverage
~EEP*~EPA*~EWM*~TE*~TT*EU	0.629	0.044
~EEP*~EWM*~TE*~TP*~TT*EU*GDP	0.755	0.034
~EEP*~EPA*~EWM*~TP*~TT*EU*~REC*GDP	0.731	0.021
Minimum total	0.663	0.056

Notes:Sample size = 125. The ~ symbol indicates the absence of the condition, and their omission indicates its presence. Variables are defined in Table 1.

Table 9
Analysis of the sufficiency solution for the negation of the causal configuration for a negative ecological footprint.

Solution: negation(~EEP*~EPA*~EWM*~TE*~TT*EU **+** ~EEP*~EWM*~TE*~TP*~TT*EU*GDP **+** ~EEP*~EPA*~EWM*~TP*~TT*EU*~REC*GDP) → EF

	Consistency	Coverage
negation(~EEP*~EPA*~EWM*~TE*~TT*EU)	0.729	0.285
negation(~EEP*~EWM*~TE*~TP*~TT*EU*GDP)	0.680	0.167
negation (~EEP*~EPA*~EWM*~TP*~TT*EU*~REC*GDP)	0.696	0.136
Minimum total	0.673	0.320

Notes: Sample size = 125. The ~ symbol indicates the absence of the condition, and their omission indicates its presence. Variables are defined in Table 1.

Table 7
Bottleneck Levels (in %) using.

EF	EEP	EPA	EWM	TE	TP	TT	EU	REC	GDP
0	NN	NN	NN	NN	NN	NN	NN	NN	NN
10	NN	0.6	NN	NN	NN	NN	6.6	NN	NN
20	NN	1.2	NN	NN	NN	NN	11.7	NN	NN
30	NN	1.9	NN	5.0	NN	NN	16.7	NN	NN
40	NN	2.5	NN	11.5	NN	NN	21.8	NN	3.5
50	4.7	3.1	NN	18.0	NN	7.2	26.9	NN	8.3
60	12.7	3.7	3.9	24.5	2.5	17.6	32.0	NN	13.2
70	20.7	4.3	16.9	31.0	5.3	28.0	37.7	NN	18.0
80	28.6	4.9	29.8	37.5	8.1	38.3	42.2	0.6	22.8
90	36.6	5.5	42.7	44.0	10.9	48.7	47.2	3.2	27.7
100	44.6	6.1	55.6	50.5	13.7	59.1	52.3	5.8	32.5

Notes: NN: not necessary. The percentages of the condition's range between the dataset's lowest and highest observed values are used to represent the threshold levels.

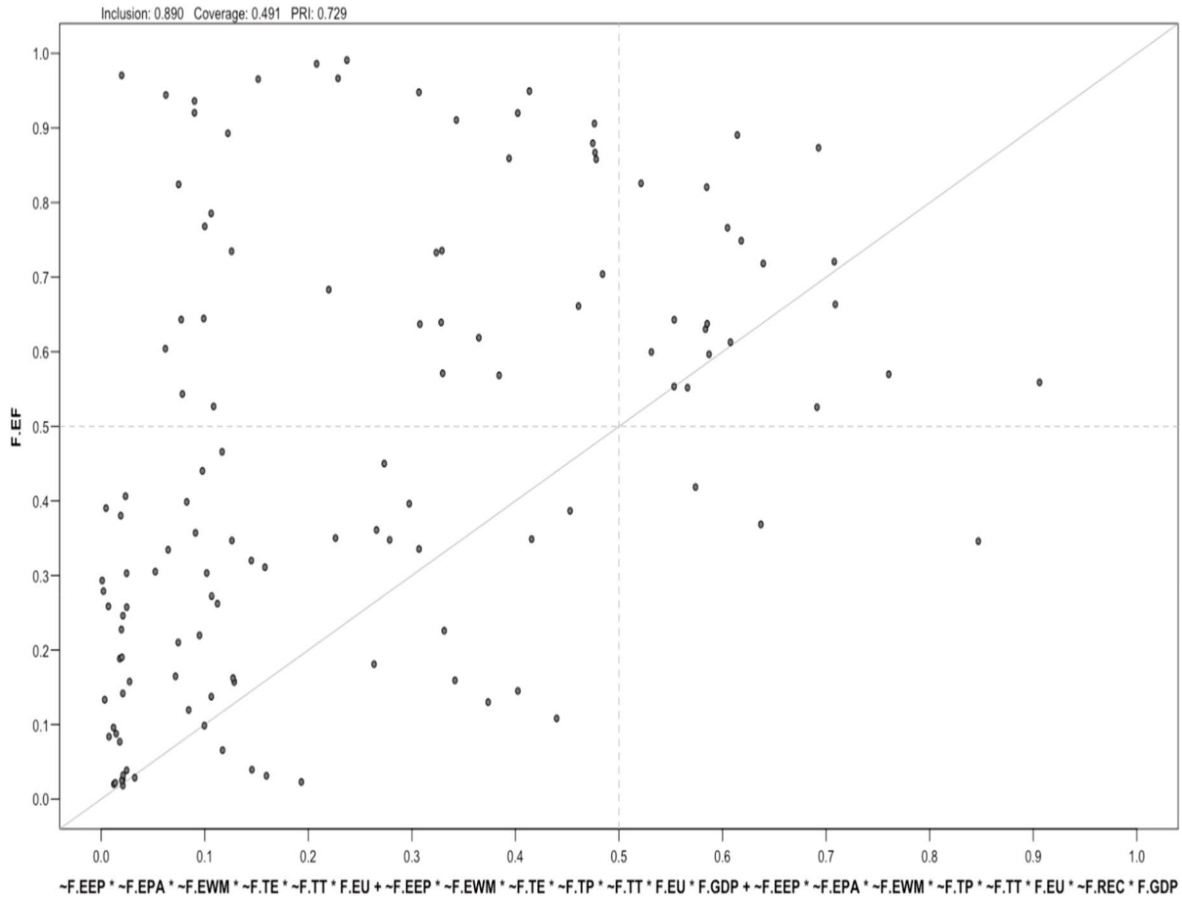

Fig. 3. Plot of sufficiency conditions for the outcome of a negative ecological footprint. Note: The "F." preceding the variable names indicates that they have been fuzzied.

any other degradation of the environment. In contrast, Ren and Albrecht (2023) and Li et al. (2021) documented that environmental taxes have increasingly become the primary means of environmental governance in various countries. A stringent ecological protection tax may motivate firms to achieve emission reductions. Public environmental expenditures and emissions taxes are tools for reducing pollution and other harmful environmental effects (Pang, 2019).

This study contributes to our understanding of how to address climate change by describing and explaining the complex relationship between various government policies and their environmental quality in the context of an ecological footprint problem. First, in this study, we addressed a gap in the extant literature on climate change, which lacks theoretically grounded and empirically tested models to solve ecological deterioration problems. Our study extend our understanding that an overall improvement in environmental quality can be achieved through a combination of government policies. This confirms Stef and Ben Jabeur (2020) argument that governance quality is a necessary condition to achieve environmental quality.

The fsQCA approach supports the nine tenets of complexity theory (Hajiheydari et al., 2021). The fsQCA, based on complexity theory, is recognized as a set-theoretic technique that adds to the literature by producing knowledge through causal recipes for both high and low ecological footprint scores. This study also offers theoretical contributions to the literature on climate change by analyzing the necessary conditions. The NCA technique used to examine the degree of necessity, or how much of a given set of factors must exist to achieve a certain ecological footprint. This study also supports the idea that fsQCA should be used along with NCA to better understand the necessary conditions. According to Dul (2022), NCA may be effectively used in either single- or multi-method research when combined with fsQCA.

The study results have management implications for governments and institutions that evaluate environmental quality and have various consequences for environmental policy. Policymakers can use the high EEP, high TT, high EWM, and high TP as instruments of environmental regulation to improve environmental quality in selected G7 countries. Morover, identifying the necessary conditions is valuable to policymakers. This study identifies the bottlenecks at each level of production of the ecological footprint and at each level of output. The values acquired for the bottlenecks may influence the plans that governments implement to improve environmental quality (Torres and Godinho, 2022). The values of the bottlenecks may help in making informed decisions about the policy resource allocation. Focusing on the factor most likely to have the least effect is one strategy that governments may use. However, to develop more effective policies, these same governments should consider the degree to which each condition is necessary.

6. Conclusion

This study examines how government policy impacts the ecological footprint. Based on a sample composed of France, Italy, Japan, the United Kingdom, and Germany from 1996 to 2020, our empirical analysis supports the complexity and equifinality principles. The findings contend that policymakers should control the ecological footprint while achieving higher economic growth, which depends on a complex combination of certain elements. According to these results, the obtained relationships revealed that low EEP, low EWM, low TT, and high energy use are sufficient conditions to be included in the causal configurations leading to a high ecological footprint. Particularly, France from 2001 to 2008 and Germany from 2000 to 2005 and from 2012 to 2017 belong to causal configurations that produced high ecological footprint.

However, the sufficient solution with the highest coverage score that leads to a low ecological footprint contains high expenditure on environmental protection and high TT. These attributes play an essential role as recipe ingredients and, in a suitable combination, ensure a balance between economic and environmental well-being. Specifically, France from 2011 to 2016, Japan for most years from 2000 to 2019, and Italy from 2011 to 2019 are included in this causal solution. Consequently, Japan, Italy, and France appear to have more effective government policies to reduce the ecological footprint, France during recent years, which indicates a government change to improve the ecological footprint.

Our results provide fresh perspectives on the moderating impact of policies developed by governments in addressing problems related to environmental deterioration. In this regard, Stef and Ben Jabeur (2020) confirmed that a large reduction in CO2 emissions may be achieved by adopting new climate change rules (such as amendments, decrees, and orders) in conjunction with a strong rule of law. Similarly, Ali et al. (2022) found that economic governance institutions can reduce the ecological pressure in African countries. Therefore, in terms of government expenditure structure, the most prevalent expenditure related to environmental governance is on environmental protection. The overall goal of national environmental policy should be to continually upgrade governement policy through amendments, decrees, and directives while focusing on two distinct ways to enhance institutional quality. The findings herein are essential for policymakers and regulators in terms of amending the legal rules to emphasize the importance of achieving ecofriendly growth that can control ecological footprints while achieving higher economic growth.

The findings of this study have important economic and policy implications. The results suggest that policymakers should focus on a complex combination of policy elements to achieve economic growth while controlling the ecological footprint. Specifically, the study highlights the importance of high expenditure on environmental protection and high levels of taxes on transport in reducing the ecological footprint. These policy elements play an essential role in achieving a balance between economic growth and environmental well-being. Local authorities and legislators may need to consider new regulations based on those policy tools to improve the quality of institutions in adressing the consequences of global warming.

Our research has both theoretical and practical implications, but there are still a number of open questions that need to be explored in further research. First, one limitation of this study is that the government fiscal policy data are only accessible for a limited number of G7 countries. In addition, our analysis should be expanded by considering the pandemic period and the post-pandemic period that had major consequences on government spending policy. Second, studies might be conducted to investigate the effects that carbon prices, subsidies for renewable energy, and pollution restrictions have on the emissions produced by the industry sector. Third, other government policy determinants, such as regulations and laws, may be used as control variables in the conceptual framework. Moreover, future studies may use additional econometric techniques that consider nonlinearities. Finally, this topic may be explored across countries or using a panel that includes developing countries.

Credit author statement

Pedro Carmona: Conceptualization, Methodology, Formal analysis, Writing – original draft, Reviewing and Software, **Nicolae Stef**: Conceptualization, Formal analysis, Writing and Reviewing, **Sami Ben Jabeur**: Conceptualization, Data curation, Formal analysis, Writing and Editing, **Younes Ben Zaied**: Conceptualization, Formal analysis, Writing and Reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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