

“Configurational pathways to ecological footprint: fsQCA analysis of Digital Nations member countries and emerging economies”

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CONFIGURATIONAL PATHWAYS TO ECOLOGICAL FOOTPRINT: FSQCA ANALYSIS OF DIGITAL NATIONS MEMBER COUNTRIES AND EMERGING ECONOMIES

Abstract

This study examines the configurational causality among the shadow economy, corruption perception index, trade levels, population dynamics, urbanization, economic size and renewable energy use, and their impact on overall ecological footprints across the Digital Nations member countries and the seven emerging economies. To analyze the relationship, the study used annual data from 2012 to 2020, and fuzzy set qualitative comparative analysis (fsQCA) was used. While both groups show the absence of a necessary condition for high ecological footprints, there are instances of sufficient pathways across the Digital Nations groups. Based on the intermediate solution, digital grouping reveals a single pathway at a consistency threshold of 80% (consistency = 0.858, coverage = 0.2995), combining low shadow economy, high CPI, high GDP, low trade, high population, high urbanization, and low renewables. However, at the 70% threshold, there are two pathways, and the solution coverage increases to 0.423. Emerging economies yield no valid configurations via the intermediate solution, confirming heterogeneity. The results show how multiple factors, such as governance, demographics, and renewable energy adoption, can shape ecological footprints across economies with different digital, structural, and development statuses. These findings advance beyond traditional variance-based approaches by identifying precise causal recipes rather than net effects. The results offer policymakers targeted interventions prioritizing renewable energy deployment alongside strategic governance reforms to disrupt ecological footprint pathways across developmental contexts.

Keywords

shadow economy, ecological footprint, fsQCA, corruption, economic size

JEL Classification

Q56, O17, D73, O57

INTRODUCTION

Climate change and environmental degradation have become critical global challenges, putting significant pressure on ecological systems and intensifying economic and environmental risks. Global greenhouse gas emissions from fuel combustion reached an approximate level of 35 559 MtCO₂eq in 2023 (International Energy Agency, 2026), showing the persistence of unsustainable patterns of production, consumption, and governance. A significant feature of global emissions is their highly unequal spatial distribution. While Asia accounts for almost half of global emissions, China is responsible for more than a quarter. In contrast, Africa and South America contribute a relatively small share of around 3–4% of global emissions (Ritchie & Roser, 2020). The disparities across economies underscore the importance of identifying context-specific environmental analysis.

While greenhouse gas emissions, particularly CO₂ emissions, are widely used indicators of environmental degradation, they represent

only one dimension of environmental pressure. The ecological footprint provides a more comprehensive measure of environmental impact by capturing not only carbon emissions but also land use demand, resource consumption, and biocapacity stress. It measures human demand on ecological systems by quantifying the biologically productive land and sea area required to support consumption and absorb waste generation across economies (Global Footprint Network). Therefore, this study extends the discussion from emissions-based indicators to the broader ecological footprint framework.

Studies have highlighted the role of economic growth in driving overall economic emissions, with heterogeneous results across economies and over time. One key factor driving these heterogeneous results is variation in structural, economic, and institutional characteristics across countries. While a few factors are repeatedly discussed and documented across studies, others, such as the shadow economy, still need to be assessed. Its role in shaping environmental outcomes is thus an addition to contemporary environmental economics that requires greater scholarly attention. The informal sector of an economy is presumed to have lower environmental compliance and inefficient production practices that may lead to a greater ecological footprint. The rise of the informal sector, along with region-specific heterogeneity, complicates linear interpretations of environmental pressure and requires contemporary tools to identify complex causal relationships.

The main issue addressed in this study is the identification of causal complexity in ecological footprint determination, which is often overlooked in traditional linear analyses. Digital economies, characterized by advanced digital infrastructure, stronger institutions, and higher urbanization, are presumed to have fundamentally different structural conditions than emerging economies, which face demographic pressures and are undergoing institutional transitions. These contrasting contexts amplify configurational effects, wherein similar factors such as the shadow economy, renewable energy, and corruption may produce different environmental outcomes depending on their interaction with other conditions. The continued reliance on average-effect models therefore limits the ability to capture such complexity.

1. LITERATURE REVIEW

Sustainable development has been at the forefront of micro- and macro-level policy-making, with academia identifying the factors that can assist or delay the attainment of the same. Various studies link multiple factors to high emissions or environmental degradation, but no consistent pattern emerges across regions and time periods. While traditional studies found a direct link between economic growth and emissions, Grossman and Krueger (1991) highlighted an inverted U-shaped relationship between the two. Since then, there have been multiple studies that have tried to empirically assess the relationship between economic growth and environmental deterioration; however, no unanimity has been documented. For instance, Abdi et al. (2025) tested the applicability of EKC in Somalia and found no inverted U-shaped relationship. Another study analyzing EKC applicability across the E7 economies, however, verified the inverted U-shaped relationship (Satrovic et al., 2025). The framework has been further extended to eco-

logical footprints as it depicts humanity's total demand on Earth's regenerative capacity. While the initial growth phase across economies is linked to increased resource extraction, waste generation, and land conversion, technological changes and a transition toward a circular economy and sustainable practices can help drive turning points.

Literature on ecological footprint reveals complex, non-linear interactions between economic, institutional, demographic, and technological factors, as environmental outcomes emerge from factor combinations rather than isolated effects. This has led to the evolution of studies wherein, in addition to economic growth, multiple factors are empirically tested for their impact on ecological footprints, environmental degradation, and emissions, among others. Khan et al. (2026), for instance, supported the EKC hypothesis and documented that renewable energy consumption negatively affects the ecological footprint across India, highlighting the significant role of human capital in reducing it. Wang et al. (2026) docu-

mented a significant but heterogeneous relationship between human development and ecological pressure. The studies thus highlighted the role of human development in mitigating ecological pressure across heterogeneous contexts. However, despite human capital being an important factor in mitigating environmental deterioration (Satrovic et al., 2025), its large share in the informal sector leads to a loss of the true benefits. Rahman et al. (2026) supported these results, showing the role of the shadow economy in increasing ecological footprints across the G7 economies. The adverse effect is, however, mitigated by the presence of higher environmental taxes, highlighting the importance of interactive effects across factors.

In addition to human development, another important factor that contributes significantly to environmental change is trade. This is because, as economies expand, there is integration across borders that leads to increased imports and exports, a rise in demand, and a change in consumption patterns that can put pressure on ecological footprints if it is not backed by appropriate environmental regulations and sustainable trade policies. Bekun and Ozturk (2025) highlighted the positive impact of globalization and enhanced economic activities in increasing the ecological footprint. Sultanova and Naser (2025) examined the impact of export diversification on the ecological footprint in 87 countries and suggested that developing nations should focus on effective export diversification, while developed countries can expand green technology exports and reduce their ecological footprint. Beyond trade, adopting renewable energy, increasing female employment, and increasing urbanization are also documented to mitigate ecological footprints, while rising income disparity increases across the E7 economies (Zheng et al., 2025). Zhu et al. (2024) analyzed the increased use of green finance sources and fintech adoption across the E7 economies and concluded that they help mitigate emissions, thereby reducing ecological footprints. Even factors like the exploitation of natural resources and industrialization may have a positive impact on ecological footprints, with renewable energy consumption and ICT development significantly reducing the same (Riaz et al., 2025). Recent studies have also identified population density and energy consumption as factors that increase ecological pres-

sure, while education is found to have a mitigating environmental impact (Abdi et al., 2025). Kholil et al. (2025) report similar results, highlighting the role of FDI, urbanization, tourism, and total patents in negatively affecting ASEAN environments, while GDP growth contributes positively to ecological footprint mitigation. Recent quantile ARDL evidence from China (1995–2023) analyzed asymmetric effects, where green innovation is documented to mitigate ecological footprints, with economic growth having an adverse effect (Xinyu et al., 2025).

A common limitation across studies is their predominant focus on formal economic indicators and growth factors, with minimal attention to the informal economy's environmental role. A key feature of economies with rising growth is the size of the informal economy, proxied by the shadow economy, which has important implications for environmental outcomes. The relationship between the shadow economy and ecological footprint, however, is not unidimensional and requires integrating various factors that can together lead to the same outcome. Existing studies have highlighted multiple variables that can impact an economy's ecological footprint. While few studies provide for a linear relationship, others support the inverted U-shaped relationship (fsQCA is highly suitable for analyzing U-shaped and inverted U-shaped relationships, as it can effectively model complex, non-linear, and asymmetrical causal relationships). This can thus help understand the applicability of the environmental Kuznets Curve (EKC).

While literature extensively examines formal economy-environment relationships, the informal economy's role in ecological footprints remains underexplored. The shadow economy, in fact, can interact with growth factors to produce complex ecological outcomes. Literature confirms GDP per capita and its growth to be the most significant factors in limiting the size of the shadow economy in the EU countries (Przekota et al., 2025). Similar results hold for the emerging BRICST economies, where GDP, along with other factors, reduces the informal economy (Faisal et al., 2025), yet its environmental implications remain underexplored. This gap is critical because the relationship between the shadow economy and the environment

is inherently configurational, as unregulated activity amplifies ecological footprints through unmonitored resource extraction, waste generation, and evasion of environmental regulations, interacting with formal factors (trade, urbanization, and renewables) to produce equifinal high-footprint pathways.

Hardi et al. (2024) documented that the shadow economy increases ecological footprints in Indonesia, while Bitassa et al. (2025) showed that the shadow economy negatively affects green growth across developing economies. The study further highlights the role that political stability plays in the relationship by mitigating the overall impact. To add to the depth of the shadow economy and emissions relationship, Li et al. (2025) found that an increase in the shadow economy leads to an increase in emissions. Lyeonov et al. (2025) conducted a bibliometric analysis of the impact of the shadow economy on renewable energy usage and found the growing but fragmented nature of the study domain. The relationship between the shadow economy and the environment is shaped by multiple interacting factors beyond informality alone. Studies have focused on how the two indices, namely government efficiency and corruption control, can influence tax competitiveness and the shadowing of the economy (Mazurenko et al., 2023). The literature thus highlights how different factors, when used in conjunction with the shadow economy, can influence ecological footprints.

In addition to the factors discussed above, corruption levels also affect sustainable development across economies. Al-Raggad (2024) found that economic crimes and criminal offenses have a significant impact on sustainable development in Jordan, while Popescu et al. (2018) supported the findings by highlighting a high level of corruption being associated with increasing incidences of shadow economic activity in Romania. The study thus justifies the corruption perception index as an important condition in the present study. Renewable energy adoption, on the other hand, is essential to promote carbon neutrality. Stancu et al. (2025) presented the key trends in technological breakthroughs across different energy sources, highlighting the rising interest of academia in clean energy. The transition to clean energy sources is also documented as a way to reduce the shadow

economy's impact on emissions (Li et al., 2025), thereby justifying the selection of the condition for the present study.

Based on the existing literature and the research gap identified, the present study focuses on the seven economies in the emerging and Digital Nations member groups. The literature shows that factors such as renewable energy adoption, economic size, industrialization, the shadow economy, and others affect ecological footprints across economies. However, there is no consensus on the relationship, and no study examines configurational causality across these two distinct sets of economies, DN and E7. Naz et al. (2025) also study these two groups of economies, though in a different context in which they assessed the role of financial inclusion in economic growth across the two sets of economies. While there are a few studies that highlight the relationships between the shadow economy and environmental degradation, as far as we know, there is a gap in existing literature that identifies the configurational causality across the DN that are presumed to possess low informality and strong regulation with the E7 (emerging economies) that are supposed to have high informality and weak enforcement. This institutional contrast represents a critical research gap best addressed through fsQCA configurational analysis.

Overall, the existing literature highlights the role of multiple economic, institutional, and technological factors in shaping ecological footprints. However, the findings remain fragmented and inconclusive, particularly due to the reliance on linear methodologies that fail to capture causal complexity. Furthermore, the role of the shadow economy and its interaction with other determinants remain insufficiently explored, especially across heterogeneous economic contexts.

Given the gap in the literature, this study aims to examine the configurational pathways through which socio-economic, institutional, and structural factors jointly influence ecological footprints across Digital Nations member countries and emerging (E7) economies using a fuzzy-set qualitative comparative analysis (fsQCA) approach. As fsQCA does not require the formulation of hypotheses, the study develops the following propositions:

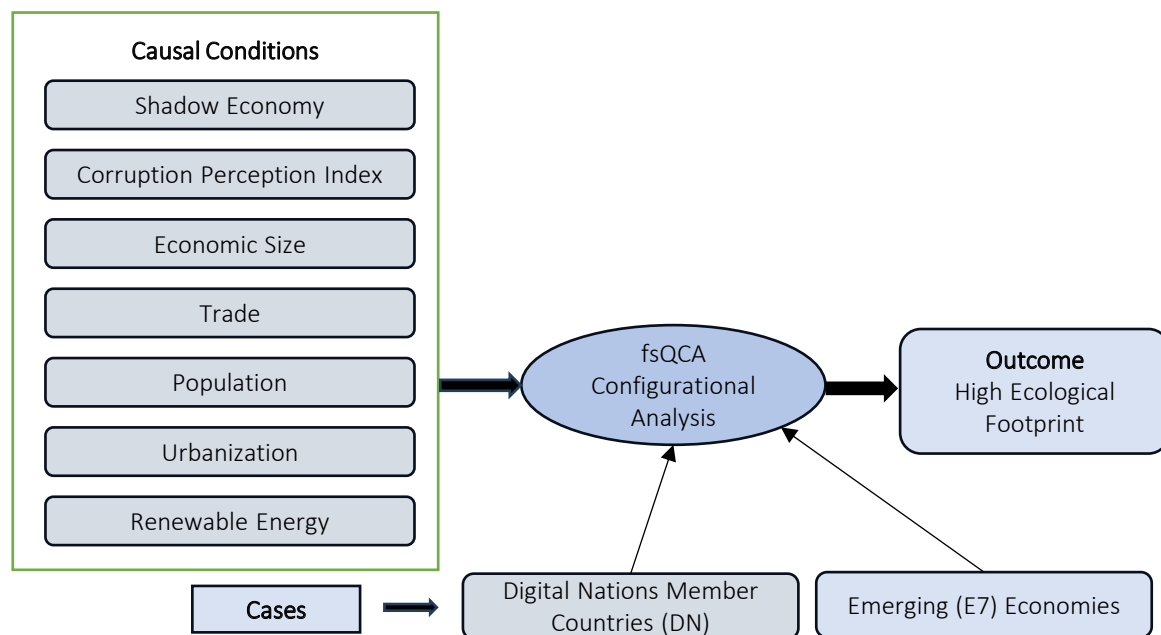


Figure 1. Conceptual model

Proposition 1: To identify different configurations of the shadow economy, corruption (CPI), GDP, trade, population, urbanization, and renewable energy that lead to high ecological footprints in seven digital nations member countries (DN) and emerging (E7) economies.

Proposition 2: To assess whether seven Digital Nations member countries (DN) and emerging (E7) economies exhibit distinct configurational pathways leading to ecological footprints.

Figure 1 provides a conceptual model for the assessment of the above-mentioned aims.

2. METHOD

2.1. Fuzzy set qualitative comparative analysis (fsQCA)

The study uses fsQCA, which helps identify different configurations that achieve the same outcome and the necessary and/or sufficient conditions. The fsQCA approach uses set theory, a configurational method that enables the analysis of complex causalities by identifying combinations of conditions that are sufficient or necessary for a given outcome (Ragin, 2008a). Unlike regression analysis, which

provides a variance-based solution, it offers an outcome driven by a range of combinations of causal conditions (Pappas & Woodside, 2021). fsQCA helps in providing a better understanding of the conditions under which the outcome occurs (Vis, 2012). It accounts for equifinality, conjunctural causation, and asymmetry (including causal and conditional asymmetry) (Ragin, 2008b). It uses both qualitative and quantitative assessments, hence bridging the gap between these two methods. For the analysis, fsQCA software version 4.1 (Ragin & Davey, 2022) was used for data calibration, necessary conditions testing, truth table construction, and identifying configurations of conditions leading to ecological footprints as the outcome among different economies.

2.2. Conditions, outcome, and cases for fsQCA

fsQCA requires the determination of an outcome and its specification in terms of high or low. The outcome in the present study is the ecological footprint, and the study identifies different combinations that lead to a high level of it across the selected cases. fsQCA further requires classification of the cases across which the configurations would be tested. The study uses two diverse sets: the Digital Nations member countries (DN) group and the Emerging (E7) economies. The Digital Nations is an international collaborative network

of the world's leading digital governments, founded in 2014. It represents the world's most digitally advanced governments that are focused on digital transformation, originally formed as a combination of five economies and called D5 (2014), which was later expanded to include Canada and Uruguay in the early 2018, with two new entrants in the latter half of 2018, namely Portugal and Mexico, making the new classification D9. Selection of the seven Digital Nations member countries follows the Digital Nations charter, with the earliest entrants to the group based on the availability of data. Both sets, that is, DN and E7, consist of seven different economies. The selection of seven economies that are part of Digital Nations member countries (DN) is done to ensure a comparative analysis with the seven economies that are part of the E7 and includes Canada, Estonia, Israel, New Zealand, South Korea, the UK, and Portugal.

E7 includes China, India, Indonesia, Brazil, Mexico, Russia, and Turkey. Further, fsQCA requires the identification of different conditions to stipulate the pathways that lead to high ecological footprints. The methodology needs conditions that are not only theoretically linked to the outcome but are also backed by literature. The present study thus employs the shadow economy, corruption perception index, economic size (GDP), trade, population, urbanization, and renewable energy as suitable conditions, all of which are backed by theory and literature. Though there are various other factors that can impact ecological footprints, such as financial development, tourism, economic policy uncertainty, and others, due to parsimony, only a few important conditions are being analyzed. Table 1 describes the outcome and the conditions used in the study.

2.3. Data and sources

All data are sourced from open sources. For instance, data on the shadow economy is sourced from Elgin et al. (2021), which is the most up-to-date and cited database for shadow economy data and is used in many studies, such as Ciucci (2026). The Elgin database is the most recent comprehensive database, providing data for around 196 countries across different parameters using a unified methodology. The dataset is critical for the DN and E7 comparative analysis, ensuring methodological consistency across heterogeneous economies (from the United Kingdom to Brazil). More recent estimates (2022–2024) are limited to regional subsets (EU/Balkans) or forecasts, precluding cross-country comparability. The data related to the corruption perception index is extracted from the Transparency International database. It is based on the standardized 0–100 methodology post-2012 rescaling, where the results of the CPI are given on a scale of 0 (highly corrupt) to 100 (very clean). Data for the ecological footprint are taken from the Global Footprint Network, while other data are collected from the World Development Indicators. All data are annual from 2012 to 2020 and are then averaged to identify different configurations. Averaging is done as we want to focus on long-run structural conditions rather than short-term dynamics. Using data up to 2020 covers the pre-COVID period, so it does not require identifying a structural break or using other methods to account for pandemic-related disruption. fsQCA is conducted using the fsQCA 4.1 software (Ragin & Davey, 2022).

Table 1. Description of outcome and conditions

Variables of Interest	Description	Source
Outcome		
Ecological Footprint	Ecological Footprint (Global Hectares - gha per person)	Global Footprint Network
Conditions		
Shadow Economy	Multiple indicators, multiple causes model-based (MIMIC) estimates of informal output (% of official GDP)	Elgin et al. (2021), Informal Economy Database
Corruption Perception Index	Score on a scale of 0 (highly corrupt) to 100 (very clean)	Transparency International
Economic Size (GDP)	GDP (constant 2015 US\$)	World Development Indicators
Trade	Trade (% of GDP)	World Development Indicators
Population	Population, total	World Development Indicators
Urbanization	Urban population (% of total population)	World Development Indicators
Renewable Energy	Renewable energy consumption (% of total final energy consumption)	World Development Indicators

3. RESULTS

The first step in the fsQCA analysis is to calculate the descriptives. Tables 2 and 3 provide the basic descriptives for the E7 and digital economies, respectively. The analysis highlights a lower per capita ecological footprint across the E7 (mean: 2.84 gha, SD 1.33) as compared to DN (mean: 5.09 gha, SD 2.69). The values are indicative of the emerging economies' pre-consumption peak status. In addition, the values related to the shadow economy indicate the presence of a larger share of the informal economy in the E7, with a mean value of 27.47 as compared to 19.70 across the DN. The difference in governance status, as measured by the CPI, is also evident across the two sets of economies (mean 36.55 in E7 and 71.25 in the digital group). The emerging economies exhibit substantially higher GDP (mean: \$2.94 trillion, SD: \$4.07 trillion) compared to the seven DN (mean: \$0.98 trillion, SD: \$1.10 trillion), reflecting the dominant scale of China and India within the emerging group. There is also a difference in the average values and variability across trade, population, urbanization, and renewable energy use in the two groups, justifying the grouping of the two economic groups for fsQCA analysis. These differences provide empirical support for using fsQCA to identify pathways that capture heterogeneity across emerging and digital nations.

After determining the basic characteristics for the two groups of economies, the next step in fsQCA is to calibrate the raw values into fuzzy-set membership scores (0 = full non-membership, 1 = full membership, 0.5 = crossover/neither in nor out). For calibration, the study used the 95th, 50th, and 5th percentiles as the anchors, as used by various studies like Diao and Liu (2021). After calibration, the next step is to identify the conditions necessary for producing the outcome. The condition that has a consistency greater than 90% is considered necessary (Ragin, 2008a). The necessity table includes both the presence and absence of the condition that is imperative for producing the outcome (Table 4).

Table 4. Necessary condition

Condition	Consistency	Coverage	Consistency	Coverage
	DN		E7 Economies	
~RE	0.44	0.46	0.75	0.85
RE	0.66	0.68	0.52	0.47
~U	0.64	0.66	0.50	0.50
U	0.57	0.61	0.72	0.72
~P	0.69	0.76	0.77	0.71
P	0.55	0.54	0.45	0.49
~T	0.62	0.61	0.54	0.55
T	0.60	0.67	0.63	0.63
~GDP	0.67	0.71	0.66	0.57
GDP	0.59	0.60	0.59	0.70
~CPI	0.47	0.48	0.69	0.61
CPI	0.69	0.73	0.59	0.67
~SE	0.71	0.69	0.55	0.51
SE	0.54	0.61	0.75	0.82

Note: ~shows low/absence of a condition.

Table 2. Descriptives of emerging economies (E7)

Descriptives	EF	SE	CPI	GDP	T	P	U	RE
Mean	2.84	27.47	36.55	2935146714285.71	47.00	506034143.70	66.87	20.56
Std. Dev	1.33	11.04	5.10	4070227896655.78	14.15	589477413.15	19.40	14.94
Skewness	0.37	-0.04	-0.65	2.57	0.63	1.19	-0.88	0.71
Kurtosis	0.55	-1.24	-0.57	6.69	1.24	-0.86	-0.04	-0.67
95th Percentile	4.58	41.18	41.93	9140322999999.99	67.23	1373082926.40	85.65	41.77
50th Percentile	2.79	30.10	38.89	1395970000000.00	44.73	203028910.00	74.35	12.87
5th Percentile	1.18	13.79	29.27	8997273000000.00	30.63	92135745.49	39.14	5.31

Table 3. Descriptives of Digital Nations group

Descriptives	EF	SE	CPI	GDP	T	P	U	RE
Mean	5.09	19.70	71.25	980572648780.43	78.51	25393496.48	78.76	17.60
Std. Dev	2.69	6.82	12.13	1100000205364.66	33.29	25492728.35	10.31	12.09
Skewness	-0.77	0.27	0.25	1.07	2.16	0.73	-0.86	-0.34
Kurtosis	1.20	-1.41	-1.34	0.21	5.00	-1.34	0.21	-2.45
95th Percentile	8.16	28.63	86.80	2551721000000.00	129.60	61133706.17	89.59	28.78
50th Percentile	5.21	20.10	70.44	317701000000.00	64.42	10358243.89	81.55	22.44
5th Percentile	1.36	12.19	57.50	72263779024.10	55.45	2339075.69	63.43	3.09

Table 5. Sufficiency condition for DN (Intermediate solution)

Conditions	DN		
	At 80% Consistency Threshold	At 70% Consistency Threshold	
	C1	C1	C2
SE	○	○	○
CPI	●	●	●
GDP	●	○	●
T	○	○	○
P	●	○	●
U	●	●	●
RE	○	●	○
Raw Coverage	0.299451	0.21978	0.299451
Unique Coverage	0.299451	0.123626	0.203297
Consistency	0.858268	0.740741	0.858268
Solution Coverage	0.299451	0.423077	
Solution Consistency	0.858268	0.773869	

Note: ○ stands for the absence of a condition, ● shows the presence of a condition.

As expected, there is no single condition that exceeds 0.90 consistency (neither presence nor absence), so the next step is to proceed to sufficiency analysis via the truth table. The truth table uses the Boolean minimization principles wherein the minimum case frequency per configuration is set to 1, and the consistency threshold is kept at 0.80 for causal inference, which is later reduced to 0.70 for identifying multiple configurations. Table 5 provides the different configurations for the DN.

The truth table for DN highlights a single pathway at 80% consistency, showing how the low levels of the shadow economy, along with high CPI, high GDP, low trade, high population, high urbanization, and low levels of renewable energy are sufficient for high ecological footprints. The raw coverage and unique coverage both stand at 29.9% as there is a single pathway with consistency of 0.858, depicting how different conditions, when integrated, are sufficient for high ecological footprints. However, to test the robustness when the consistency is changed to 0.70, there are two pathways leading to the same outcome with an enhanced solution coverage of 42.30%. Across all paths, the relationship between the shadow economy and CPI remains the same, showing their association with larger ecological footprints across the seven digital nations.

Regarding the different configurations for the E7 economies, the results are provided in Table 6. At the threshold of 80% consistency, there are no intermediate solutions for the given set of econ-

omies, and hence the same is reduced to a lower threshold where one configuration is attained, but that also fails consistency standards (<0.80). This may be due to greater heterogeneity across the E7 countries.

Table 6. Intermediate solution for E7 economies

Conditions	Intermediate Solution
SE	○
CPI	○
GDP	○
T	○
P	●
U	○
RE	●
Raw Coverage	0.0742857
Unique Coverage	0.0742857
Consistency	0.238532
Solution Coverage	0.0742857
Solution Consistency	0.238532

Note: ● stands for the presence of a condition, ○ shows the absence of a condition.

E7 intermediate analysis produced one configuration but critically low solution consistency overall (0.238), indicating that no clear sufficient configuration emerges for E-7 economies under this threshold. Given E7's heterogeneity, the results of the parsimonious solution (Table 7) are also provided.

The parsimonious solution includes only individual conditions rather than a configuration, with a solution consistency of 0.592 and full coverage (1.000). Both intermediate (consistency = 0.238)

Table 7. E7 parsimonious solution

Condition	Raw Coverage	Unique Coverage	Consistency
~RE	0.751	0.003	0.854
~P	0.766	0.000	0.713
SE	0.749	0.000	0.819
GDP	0.586	0.026	0.695
T	0.634	0.000	0.631
U	0.717	0.000	0.719
CPI	0.586	0.000	0.674
Solution Summary			
Solution Coverage	1.000		
Solution Consistency	0.592		

and parsimonious (consistency = 0.592) fail standard consistency thresholds (>0.80), confirming that no valid sufficient configurations exist for E7 economies. This suggests that, in E-7 economies, the outcome is not consistently explained by any clear causal configuration under the specified conditions and thresholds. The absence of any configuration obtained through the intermediate and/or parsimonious solution indicates wide disparities across emerging economies in conditions and outcomes. No sufficient configurations across E7 economies may be indicative of their causal complexity versus digital economies' clear pathways. High heterogeneity across E7 economies precludes reliable causal configurations for high ecological footprint. In E-7 economies, both the intermediate solution and the parsimonious solution yield non-configurational results. This indicates that the specified conditions do not form a robust sufficient configuration for the outcome in E-7 economies, underscoring the need for further refinement of the causal model or inclusion of additional contextual factors.

4. DISCUSSION

The growth of an economy has an impact on the environmental status and, hence, its ecological footprint. Although the formal economy and its impact on the latter are officially accounted for, the relationship between the shadow economy and its role in promoting high ecological footprints remains nascent. The results across the DN provide different configurations of the shadow economy with other related conditions, while E7 shows no valid pathways, thereby providing the ground for context-specific policymaking that can promote sustainable development across different sets of economies. Results of the sufficiency condition

across the DN provide evidence that the absence of the shadow economy with high CPI, increased urbanization, low levels of trade, and different combinations of economic size, population, and renewable energy use are sufficient conditions for high levels of ecological footprints. fsQCA analysis thus highlights that even economies with strong governance and minimal shadow activity, when combined with different conditions, can still exhibit elevated ecological footprints. The results are similar to those observed across ASEAN economies by Kongbuamai et al. (2025), where energy consumption, shadow economy size, and FDI positively affect the ecological footprint. Similarly, Shahbaz et al. (2023) found institutional quality to have differing results across the group of emerging economies from Europe and Asia. Abid et al. (2022) used ARDL analysis and found that the informal economy positively affected the ecological footprint in Saudi Arabia in the long term, with bidirectional Granger causality between the two. While informality is found to have a positive and significant effect on the ecological footprint across emerging European countries, the effect is negative for emerging Asian countries. The results thus document heterogeneity across economies based on their level of development and differences in the institutional quality and other parameters. Dada et al. (2023) tested the impact of the shadow economy on African nations based on the method of moments quantile regression and found that the shadow economy has a negative impact on environmental degradation across the quantiles, which helps in improving environmental quality. The studies thus show how traditional econometrics that capture the net effect are unable to identify the conjunctural causality documented in this study, along with providing a comparison across the two different sets of economies, namely the DN and the E7.

The findings align with institutional theories suggesting that advanced economies can face greater environmental challenges if growth is not channeled through the formal economy. The results across the two diverse sets of economies, however, are in contrast, wherein the results of E7 provide for greater causal heterogeneity, and there is no identified configuration providing for structural diversity across the rapidly transforming economies. The digital and emerging nations contrast demonstrates how institutional convergence enables predictable environmental pathways while structural diversity precludes them.

While most studies provided for a linear relationship, others document an inverted U-shaped relationship between the shadow economy and ecological footprints (Chu & Hoang, 2022). Policymakers thus need to prioritize governance improvements that can assist in reducing the informal sector, thereby leading to enhanced environmental quality. The heterogeneous relationship identified across the studies thereby provided for the possibility of having an interactive effect across the variables, which is not captured by traditional econometric modeling. The present study fills this gap by using fsQCA, which does not isolate net individual effects and identifies diverse

pathways that can produce the same outcome. These configurational insights offer policymakers precise leverage points for sustainable transitions tailored to the developmental context, providing various policy implications.

For instance, one main implication is better governance, as just reducing the share of the informal economy across different economies may not produce desired results. Renewable energy adoption should also be the focal point of policymaking for disrupting high ecological footprint trajectories. Policymakers should prioritize comprehensive clean-energy infrastructure deployment to ensure a smooth transition toward sustainable development. Another important implication is fostering international cooperation through technology transfer from advanced to emerging economies; a high-return investment bridges developmental gaps. Meanwhile, market-based instruments like carbon pricing can effectively internalize environmental externalities across all contexts, creating incentives for sustainable choices everywhere. These targeted interventions, grounded in configurational insights, offer policymakers precise leverage points for achieving sustainable development goals while respecting developmental path diversity.

CONCLUSION

The primary objective of the study is to identify how multiple factors can impact the level of ecological footprint across two different sets of economies, namely the digital and emerging. The study, instead of using the traditional variance-based measures that identify the net individual effect, documents different combinations of the shadow economy along with the level of corruption, economic size, demographic pressure, urbanization, and clean energy transition that can be indicative of a high ecological footprint. The results show how different conditions behave differently across digital and emerging economies when integrated with other variables. While there is no necessary condition that is found to be present in both sets of economies, the presence of one sufficient condition at the 80% threshold of consistency based on intermediate solutions across the digital economies highlights the role of economic size, formal economy, clean governance, increased population, urbanization, and others that can together produce enhanced ecological footprints. In contrast, no equivalent configuration is found for E7 economies, indicating that the relationship between governance, informal economy, demographic pressure, and energy transition is context-specific rather than universal. The fsQCA results show that no single condition operates as a standalone determinant of ecological footprint; instead, the outcome emerges from specific combinations of governance, economic, demographic, and energy conditions.

Future studies can take the analysis forward by increasing the number of countries and testing the relationship across different sets of economies, like the natural resource-rich economies vs. the lagged economies, or between the top emitters and their counterparts. The studies can thus illuminate how

developmental context shapes ecological pressures, thereby providing a new paradigm for global transition, balancing institutional realities with universal clean energy imperatives. In addition, while the present study has focused on long-run configurational combinations, future studies may also extend this work by integrating panel-based fsQCA approaches to capture temporal dynamics and allow for comparison of configurational changes across sub-periods.

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