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Investigating the Impact of Uncertainty in Influential Factors on the Ecological Footprint in Selected Asian and European Countries

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Abstract

The ecological footprint is an effective tool for evaluating the pressures exerted on ecosystems and the environment. Given its importance, the present study examines the impact of uncertainty in factors influencing the ecological footprint across 10 selected Asian and European countries. To this end, a fuzzy regression model was employed to analyze these effects during the period from 1996 to 2022. Leveraging the capabilities of fuzzy regression, the intensity of each factor's influence on the ecological footprint was calculated in terms of fuzzy centers, left spreads, and right spreads. The findings reveal that Gross Domestic Product (GDP) in Iran (+5.5 and -4.5) had the most significant negative environmental impact, attributable to oil dependence and insufficient attention to environmental concerns. In contrast, China (+0.29 and -0.23) demonstrated improvements due to greener policies. Regarding trade (EX), Azerbaijan and Malaysia exhibited asymmetric effects due to their reliance on natural resource exports, whereas Romania (stable at 0.37) maintained more sustainable performance owing to European regulatory standards. Financial Development (FDI) showed high volatility in China (± 6.13) and Thailand (+2.77 and -2.34), while Belarus (stable at 0.24) had the least impact. Hydropower energy consumption (HP) in Türkiye and Romania faced uncertainties due to large-scale projects, whereas Russia (stable at 0.007) played a minimal role. The key conclusion indicates that resource-dependent countries (e.g., Iran and Azerbaijan) exert greater environmental pressure, whereas economies with diversification (e.g., China) or strict regulatory standards (e.g., Romania) achieve better integration of economic growth and sustainability. These findings underscore the need for revising development policies to prioritize ecological balance.

Keywords: Ecological footprint, Uncertainty, Hydropower Energy, Asian and European Countries.

JEL Classification: Q56, C18, Q42, O52.

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1. Introduction

The ecological footprint is defined as a composite metric for assessing the balance between environmental supply and demand. First introduced by [Rees & Wackernagel \(1997\)](#), this concept is grounded in the principle that human activities impact the environment because they rely on nature's resources and services to meet their needs. By definition, the ecological footprint represents the amount of natural and ecological resources required to sustain an individual's lifestyle. Broadly, the footprint humans leave on the environment includes deforestation, grassland degradation, air pollution, and harm to wildlife. Measured in global hectares (gha)—a unit equivalent to one hectare of land with average global productivity—this metric is essential for environmental decision-making. The present study examines the impact of uncertainty on ecological footprint dynamics in selected Asian and European countries. Here, uncertainty is treated as a key variable, quantified based on indicators of economic instability and fluctuations in environmental policies. These indicators are modeled fuzzily to account for inherent ambiguities in measuring uncertainty. The fuzzy regression approach adopted in this research provides a robust framework for analyzing uncertainty's influence on the ecological footprint. Unlike deterministic models, this method considers a range of possible values for each variable (rather than a fixed value), enabling the evaluation of diverse scenarios. Specifically, the fuzzy method calculates the "impact width" of each factor (including uncertainty) on the ecological footprint, reflecting the degree of ambiguity in these relationships. Thus, our model assesses both the direction and intensity of uncertainty's effects under varying economic and environmental conditions. To contextualize these impacts, we first analyze trends in ecological footprints across the studied countries.

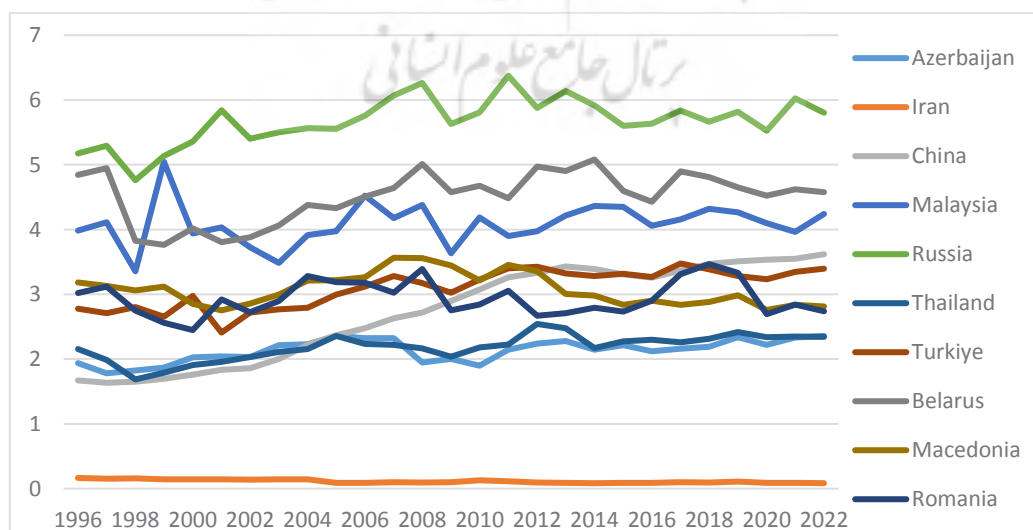


Fig. 1: Trend of Ecological Footprint in Selected Asian and European Countries

According to data from the Global Footprint Network (2023), Figure 1 demonstrates that Russia has the highest ecological footprint at 6.73 global hectares per capita (gha/capita), primarily due to its heavy reliance on oil and gas industries and inefficient natural resource management. Belarus ranks second with 5.92 gha/capita, reflecting the detrimental impact of Soviet-era heavy industries. Malaysia follows in third place with 5.45 gha/capita, resulting from unsustainable palm oil production and tourism development. Notably, China shows improvement at 5.21 gha/capita despite its large population, owing to investments in renewable energy. Turkey (4.89 gha/capita), facing water crises from large infrastructure projects, and North Macedonia (3.76 gha/capita) with outdated heating systems, occupy subsequent positions. Despite EU membership, Romania (3.52 gha/capita) performs poorly due to coal dependence and deforestation. Thailand (3.21 gha/capita) struggles with tourism-related plastic pollution, Azerbaijan (2.95 gha/capita) with oil-dependent mono-economy, and Iran (2.83 gha/capita) with excessive energy consumption and water scarcity, completing the ranking (World Bank, 2022; UNEP, 2023). These trends clearly indicate that energy consumption patterns and natural resource management are the most decisive factors in national ecological footprints.

Considering the critical role of energy consumption patterns in ecological footprint calculations, renewable energy sources - particularly hydropower - emerge as a key factor warranting in-depth examination. The examination of factors affecting ecological footprint has consistently been a compelling subject in environmental economics. Hydropower consumption, as one such factor, has increased significantly with economic activity. While hydropower serves as a renewable resource that effectively reduces air pollution, its expanded generation and consumption may substantially decrease pollution levels. However, extensive use of both renewable and non-renewable energy sources can increase ecological footprints. Nevertheless, renewables generally have fewer environmental impacts than non-renewables, making them preferable for achieving environmental sustainability (Nathaniel and Khan, 2020). Although hydropower offers significant advantages, its environmental consequences should not be overlooked. Despite its benefits of renewability and low-carbon production, hydropower carries notable environmental consequences. Large reservoir construction can destroy natural ecosystems, eliminate forests and wetlands, and displace communities. These reservoirs render natural habitats unusable for flora and fauna while disrupting river flows, particularly harming migratory fish species. Changes in sediment and oxygen levels degrade aquatic habitats and threaten species survival. Additionally, submerged forests in reservoirs generate methane from anaerobic decomposition of organic matter, increasing greenhouse gas emissions - an effect

more pronounced in tropical regions. Organic and sediment accumulation also reduces water quality and compromises dam functionality, requiring increased maintenance. In addition to hydropower, other macroeconomic variables affecting the ecological footprint have been considered in this study. Other significant variables affecting ecological footprint include per capita GDP, financial development, trade openness, among others, which have been explored in various studies and are examined in this research.

Today, rapid economic growth and industrial development in many countries have placed unprecedented pressure on natural resources and the environment. The ecological footprint, as a comprehensive indicator for measuring these pressures, reveals that current development patterns in many countries—particularly those dependent on natural resources—are unsustainable and pose a serious threat to natural ecosystems. Despite numerous studies on factors affecting the ecological footprint, the impact of economic uncertainties on this indicator and its cross-country variations have received less attention. Yet, economic fluctuations, policy changes, and macroeconomic instabilities can significantly alter the relationship between economic growth and environmental pressures. Accurately identifying the factors influencing the ecological footprint under uncertain conditions is crucial for formulating effective sustainable development policies. This study combines ecological footprint analysis with economic uncertainty to provide a more comprehensive framework for understanding these relationships. By employing fuzzy regression methods and examining selected countries at different development levels, the research offers deeper insights into the complex interplay between economic and environmental variables. The findings can assist policymakers in developing countries in designing strategies to mitigate environmental pressures while accounting for uncertainty effects. Additionally, comparing the performance of different countries may help identify successful models for reconciling economic growth with environmental sustainability. Therefore, this study aims to measure the impact of uncertainty in ecological footprint determinants across selected Asian and European countries (Iran, Azerbaijan, China, Russia, Malaysia, Thailand, Turkey, Belarus, North Macedonia, and Romania) through fuzzy analysis of right and left spreads. This methodology enables precise determination of each factor's influence on ecological footprint. This study employs fuzzy regression analysis as a novel and robust methodological approach for ecological footprint assessment, offering distinct advantages over conventional techniques. The selected methodology demonstrates particular efficacy in modeling complex nonlinear relationships among variables, accommodating varying degrees of membership, and processing incomplete or uncertain datasets, making it exceptionally well-suited for analyzing the

multidimensional nature of ecological footprint dynamics. The principal innovation of this research lies in its application of fuzzy regression to concurrently examine economic and environmental determinants, thereby enabling the investigation of uncertainty both as an independent variable and as an intrinsic system property. A critical methodological advantage is the generation of interval-based outputs, which facilitates scenario analysis by policymakers - a particularly crucial capability for environmental assessments characterized by inherent uncertainties. Methodologically, this approach represents a significant advancement by enabling: (1) integrated analysis of qualitative and quantitative variables, (2) explicit incorporation of uncertainty as a system component, and (3) comprehensive modeling of nonlinear relationships, collectively providing a more nuanced and realistic representation of the complex interplay between economic and environmental variables than previous research frameworks. The paper comprises five sections: following the introduction, Section 2 reviews existing literature; Section 3 details the model and methodology; Section 4 presents empirical data analysis and results; and Section 5 provides conclusions and policy recommendations.

2. Theoretical Foundations of the Research

2-1. Impact of GDP on Environmental Quality

Numerous studies have demonstrated that the relationship between per capita GDP and environmental quality follows the Environmental Kuznets Curve (EKC) pattern. In the early stages of economic growth, countries typically focus on industrial development and increased production, leading to greater exploitation of natural resources and higher consumption of fossil fuels. This process is associated with rising pollution levels and environmental degradation ([Selden & Song, 1994](#)). However, after reaching a certain per capita income threshold (typically in developed countries), public demand for a cleaner environment increases, and stricter regulatory policies are implemented. At this stage, investments in clean technologies and energy efficiency improvements lead to reduced pollution and enhanced environmental quality ([Grossman & Krueger, 1991](#)). Studies such as [Cole et al., \(1997\)](#) further emphasize that strong institutions and effective environmental policies can shift the EKC's turning point to lower per capita income levels.

2-2. Impact of Financial Development on Environmental Quality

Financial development—defined as the improvement in the quantity, quality, and efficiency of financial intermediation services—has dual effects on the environment. On one hand, by facilitating access to capital, financial development enables the expansion of

industrial and manufacturing activities, which may increase energy consumption and pollutant emissions (Sadorsky, 2010). On the other hand, it reduces financing costs, promoting investments in environmental projects and clean technologies (Tamazian & Bhaskara, 2010). Additionally, developed financial markets can introduce innovative instruments such as green bonds and low-interest credits for sustainable projects, thereby reducing ecological footprints. Thus, the environmental impact of financial development depends on a country's economic structure, policy orientation, and regulatory institutions.

2-3. Impact of Trade on Environmental Quality

International trade affects environmental quality through three primary mechanisms: the scale effect, composition effect, and technique effect. The scale effect refers to increased economic activity due to trade expansion, which may raise resource consumption and pollution. The composition effect relates to shifts in production structures based on comparative advantages—e.g., specialization in energy-intensive goods may increase pollution, while knowledge-based production reduces environmental harm. The technique effect captures technology transfers and efficiency gains from trade (Grossman & Krueger, 1991). If the technique effect dominates, trade can improve environmental quality. Furthermore, international trade agreements incorporating environmental clauses may amplify these positive effects.

2-4. Impact of Energy on Environmental Quality

Energy consumption, particularly fossil fuels, is a key driver of ecological footprint growth (Charfeddine & Mrabet, 2017). Rising energy use increases greenhouse gas emissions and other pollutants, degrading air, water, and soil quality. However, transitioning to renewables (e.g., hydropower, solar, wind) can mitigate these impacts. Studies show that expanding clean energy shares not only reduces emissions but also fosters low-consumption, sustainable production processes. Energy policies such as environmental taxes and clean energy subsidies further incentivize efficiency and decarbonization.

3. Empirical Studies

3-1. Domestic Empirical Studies

Shad Stanjin & Safarzadeh (2022) analyzed the short-term and long-term relationship between hydropower consumption and environmental degradation indicators (ecological footprint, carbon footprint, and CO₂ emissions) in Iran's economy from 1980 to 2018.

Results revealed significant negative relationships between hydropower consumption and both CO₂ emissions and carbon footprint across both time horizons. Hydropower also demonstrated short-term positive effects on reducing ecological footprint. [Esfahani et al., \(2022\)](#) examined the nexus between economic growth, energy consumption, and ecological footprint across 72 developed and developing countries (1990-2018) using Generalized Method of Moments (GMM). Findings indicate bidirectional relationships between economic growth and both energy consumption/ecological footprint in both country groups. Non-renewable energy consumption, urbanization, fertility, and mortality rates positively increase ecological footprint, while renewable energy, technological progress, and human capital reduce it. Economic growth decreases ecological footprint in developed nations but increases it in developing countries, reflecting greater renewable energy adoption in developed economies. Interestingly, ecological footprint negatively impacts economic growth in developed nations while showing positive effects in developing contexts. [Mohammadi-Nia et al., \(2024\)](#) employed a Nonlinear ARDL (NARDL) model to investigate asymmetric relationships between globalization, economic growth, financial development, and ecological footprint in Iran (1981-2021). Results demonstrate symmetric long-term effects of globalization and financial development shocks on ecological footprint, but asymmetric effects for economic growth, confirming nonlinear dynamics. Financial development showed significant positive impacts on ecological footprint.

3-2. International Empirical Studies

[Liu and Kim's \(2018\)](#) Panel VAR analysis of 44 Belt and Road countries (1990-2016) revealed unidirectional causality from ecological footprint to FDI, supporting the Pollution Haven Hypothesis (PHH) for both FDI and GDP, with notable heterogeneity among variables. [Nathaniel's \(2020\)](#) study on Indonesia identified urbanization, economic growth, and energy consumption as drivers of environmental degradation, while trade showed long-term negative environmental impacts. Results confirmed unidirectional causality from economic growth to ecological footprint and from urbanization to energy consumption. In their 2022 study, Radmehr et al., employed the Generalized Method of Moments (GMM) to analyze the tripartite relationships among ecological footprint, renewable energy consumption, and income across G7 nations from 1990 to 2018, revealing significant bidirectional linkages: their findings not only demonstrate mutual causality between GDP and renewable energy but also confirm reciprocal relationships between ecological footprint and both GDP and renewable energy consumption, highlighting the complex interdependencies among economic growth, clean energy adoption, and environmental

impacts in advanced economies. [Irina Georgescu and Jani Kinunnen's \(2023\)](#) ARDL analysis of Finland (1990-2021) found GDP and FDI significantly reduced ecological footprint, while energy consumption increased it, validating an Environmental Kuznets Curve (EKC) relationship. [Khan et al., \(2023\)](#) investigated the dynamic relationships between urbanization, energy consumption, and environmental pollution in India during the 1971-2018 period. Their study employed the nonlinear autoregressive distributed lag (NARDL) cointegration test developed by [Shin et al., \(2014\)](#) to analyze these dynamic interactions. The findings reveal that while urbanization has proven environmentally beneficial in India's long-term development, energy consumption has consistently exerted harmful environmental effects. Notably, both positive and negative shocks from energy use and urbanization demonstrate asymmetric impacts on ecological footprint. [Aldegheishem \(2024\)](#) extended this research focus by examining how urbanization, energy consumption, natural resources, economic growth, and technological innovation affect ecological footprint in Saudi Arabia (1990-2022). Utilizing multinational data sources, the empirical results demonstrate consistent patterns across both short- and long-term analyses: urbanization, natural resource abundance, and technological innovation significantly reduce ecological footprint, whereas energy consumption and economic growth contribute to its expansion. These contrasting effects highlight the complex environmental trade-offs accompanying development processes.

4. Methodology

Fuzzy regression models were first introduced by [Tanaka et al., \(1982\)](#). These models obtain the optimal regression equation by minimizing the degree of fuzziness, achieved through minimizing the sum of the membership function widths of the fuzzy coefficients in the equation. Fuzzy regression models possess distinct characteristics compared to classical regression models. Classical regression requires a set of strong statistical assumptions for valid results, including: Normality of errors, Absence of autocorrelation & Homoscedasticity (constant error variance).

Violation of any of these assumptions can significantly undermine the validity of classical regression analyses. In many cases, justifying these assumptions is difficult or the necessary conditions for their application may not be properly met. For instance, observations or system definitions may be influenced by insufficient information or imprecise human judgments. Although classical regression has wide applications, it may produce misleading results under the following conditions: Insufficient observational data,

Non-normal error distributions, Ambiguity in relationships between independent and dependent variables, Uncertainty regarding events & Invalid linearization assumptions.

When classical regression methodology and its assumptions are difficult to justify, fuzzy regression can serve as a more effective tool. This approach utilizes membership functions and possibility distributions to model imprecise or ambiguous conditions, enabling better system understanding and more accurate results. In classical regression, a specific output value is computed for each set of input variables, whereas fuzzy regression estimates a range of possible outputs whose distribution is defined by membership functions.

Three main categories of fuzzy regression models exist: Possibilistic fuzzy regression models, Least squares fuzzy regression models & Interval analysis-based regression models.

This study employs possibilistic fuzzy regression. To achieve optimal fitting, an optimal model must be estimated. Since the membership functions used to represent fuzzy numbers are triangular, fuzzy regression can be formulated as a linear programming problem. One type of possibilistic fuzzy regression model uses fuzzy coefficients with non-fuzzy input and observed output. The general form of the fuzzy regression model with fuzzy coefficients is shown in Equation (1):

$$\tilde{Y} = f(x, A) = \tilde{A}_0 + \tilde{A}_1 x_1 + \tilde{A}_2 x_2 + \dots + \tilde{A}_n x_n \quad (1)$$

Where:

$\tilde{Y}$ is the fuzzy dependent variable (output)

$x = (x_1, x_2, \dots, x_n)$ is the vector of independent variables (input)

$A = \{\tilde{A}_0, \tilde{A}_1, \dots, \tilde{A}_n\}$ is a set of fuzzy numbers

The fuzzy linear regression model with fuzzy parameters, non-fuzzy inputs, and fuzzy output is formulated as a linear programming problem aimed at minimizing the ambiguity of the fuzzy linear regression model, ensuring that the estimated value range covers the observed value range at a specified level. In this study, regression coefficients are defined as triangular fuzzy numbers:

$$\tilde{A}(x) = \begin{cases} 1 - \frac{a-x}{s^L} & a - s^L \leq x \leq a \\ 1 - \frac{x-a}{s^R} & a < x \leq a + s^R \end{cases} \quad (2)$$

Where: a is the central value

s^L and s^R are the left and right widths of $\tilde{A}$, respectively

When $s^L \neq s^R$, the triangular fuzzy number $\tilde{A}$ is called asymmetric. In this case, the membership function $\tilde{A}$ can alternatively be expressed in terms of three parameters ($a, s^L,$

s^R) by expressing the right width in terms of the left width. Letting $s^R = ks^L$, where k is a positive real number called the stretch coefficient, the asymmetric triangular fuzzy number $\tilde{A}$ can be described by the triple $[\tilde{A} = (a, s^L, k)]_T$, and its membership function becomes:

$$\tilde{A}(x) = \begin{cases} 1 - \frac{a-x}{s^L} & a - s^L \leq x \leq a \\ 1 - \frac{x-a}{ks^R} & a < x \leq a + ks^R \end{cases} \quad (3)$$

Accordingly, the fuzzy output $\tilde{Y}$ is also an asymmetric triangular fuzzy number:

$$\begin{aligned} f^c(\underline{x}) &= a_0 + a_1 x_1 + \dots + a_n x_n \\ f_{s^L}(\underline{x}) &= s_0^L + s_1^L x_1 + \dots + s_n^L x_n \\ f_{s^R}(\underline{x}) &= s_0^R + s_1^R x_1 + \dots + s_n^R x_n \end{aligned} \quad (4)$$

Where:

$$\begin{aligned} f^c(\underline{x}) &= a_0 + a_1 x_1 + \dots + a_n x_n \\ f_s^L(\underline{x}) &= s_0^L + s_1^L x_1 + \dots + s_n^L x_n \\ f_s^R(\underline{x}) &= s_0^R + s_1^R x_1 + \dots + s_n^R x_n \end{aligned} \quad (4)$$

The membership function of $\tilde{Y}$ can thus be expressed as:

$$\tilde{Y}(y) = \begin{cases} 1 - \frac{f^c(\underline{x}) - y}{f_s^L(\underline{x})}, f^c(\underline{x}) - f_s^L(\underline{x}) \leq y \leq f^c(\underline{x}) \\ 1 - \frac{y - f^c(\underline{x})}{f_s^R(\underline{x})}, f^c(\underline{x}) < y \leq f^c(\underline{x}) + f_s^R(\underline{x}) \end{cases} \quad (5)$$

In fuzzy regression, the objectives are:

Ensure all fuzzy output values $\tilde{Y}_j$ ($j = 0, 1, 2, \dots, m$) have membership degrees of at least h :

$$\tilde{Y}_j(\tilde{y}_j) \geq h, \quad i = 1, 2, \dots, m \quad (6)$$

Determine fuzzy coefficients $\tilde{A}_i$ ($i = 0, 1, 2, \dots, n$) that minimize the output's fuzziness.

For symmetric $\tilde{A}_i$ ($i = 0, 1, \dots, n$), the objective function (sum of output fuzzy widths for all data) is:

$$Z = 2ms_0 + 2 \sum_{i=1}^n (s_i \sum_{j=1}^m x_{ji}) \quad (7)$$

Where x_{ji} represents the j -th observation of the i -th variable. For asymmetric $\tilde{A}_i$, Z becomes:

$$\mathbf{Z} = \mathbf{m}(\mathbf{s}_0^L + \mathbf{s}_0^R) + \sum_{i=1}^n [(\mathbf{s}_0^L + \mathbf{s}_0^R) \sum_{j=1}^m \mathbf{x}_{ji}] \quad (8)$$

For symmetric $\tilde{A}_i$ ($i = 0, 1, 2, \dots, n$), substituting Equation (4) into (10) and (5) yields the constraints:

$$(1 - h)\mathbf{s}_0 + (1 - h) \sum_{i=1}^n (\mathbf{s}_0 \mathbf{x}_{ji}) - \mathbf{a}_0 - \sum_{i=1}^n (\mathbf{s}_0 \mathbf{x}_{ji}) \geq -\mathbf{y}_i, j = 1, 2, \dots, m \quad (9)$$

$$(1 - h)\mathbf{s}_0 + (1 - h) \sum_{i=1}^n (\mathbf{s}_0 \mathbf{x}_{ji}) + \mathbf{a}_0 + \sum_{i=1}^n (\mathbf{s}_0 \mathbf{x}_{ji}) \geq +\mathbf{y}_i, j = 1, 2, \dots, m \quad (10)$$

Where $\mathbf{x}_{ji}$ represents the j -th observation of the i -th variable. Based on the above explanations, the right and left widths are calculated for a membership degree of 0.9 (Cheshmaghil *et al.*, 2024).

The fuzzy regression method was selected for this study due to its capability to model inherent data uncertainties and complex inter-variable relationships. While classical regression relies on restrictive assumptions such as error normality and homoscedasticity, fuzzy regression employs asymmetric triangular membership functions to represent interval-valued possibilities, offering greater flexibility when handling imprecise or incomplete data. By minimizing model ambiguity (through linear programming) while guaranteeing a minimum membership degree ($h=0.9$), this approach yields more reliable results under real-world conditions—making it better suited for our research problem than conventional methods.

5. Data and Results

This study examines the impact of uncertainty factors on ecological footprint in selected Asian and European countries (Iran, Azerbaijan, China, Malaysia, Russia, Thailand, Turkey, Belarus, North Macedonia, and Romania) using annual data from 1996 to 2022. The study population comprises 10 selected Asian and European countries classified as upper-middle-income economies according to World Bank statistics. Within this category, Europe includes 13 countries and Asia 7 countries. Nations such as Iraq, Jordan, Lebanon, Albania, Bosnia, Bulgaria, Georgia, Kazakhstan, Montenegro, and Serbia were excluded

due to insufficient data on ecological footprint and GDP. Consequently, the final sample consists of Iran, Azerbaijan, China, Malaysia, Russia, Thailand, Turkey, Belarus, North Macedonia, and Romania. Per capita ecological footprint data were obtained from the Global Footprint Network, while macroeconomic variables including per capita GDP, energy consumption, financial development, and trade openness were collected from the World Bank's World Development Indicators (WDI) for the period 1996-2022. As noted, the selected countries fall under the upper-middle-income category based on the World Bank's 2017 classification using gross national income (GNI) per capita, reflecting comparable levels of economic development, production capacity, and macroeconomic challenges. Although geographical and social differences exist, their similar income levels lead to shared challenges such as transitioning to advanced technology-based economies, attracting foreign direct investment, and improving labor productivity. The study period covers years when these countries experienced significant global developments (e.g., financial crises and commodity price fluctuations), making their policy responses comparable. Thus, despite apparent diversity, focusing on this group is methodologically justified due to their homogeneity in key economic indicators. The fuzzy regression model was estimated using MATLAB software. Following the studies of [Elnour et al., \(2022\)](#), [Rahman et al., \(2021\)](#), and [Nathaniel et al., \(2020\)](#), the model is specified as:

$$ECFP = F(GDP, GDP^2, EX, FDI, HP) \quad (11)$$

In this section, a fuzzy regression with symmetric coefficients will be estimated to examine the impact of the uncertainty of per capita GDP (GDP), squared per capita GDP (GDP^2), trade openness (EX), financial development (FDI), and hydropower energy consumption (HP) on the ecological footprint (ECFP) in selected Asian and European countries. The 26-year study period (1996-2022) includes 52 constraints for minimizing the objective function to assess ecological footprint uncertainty. All computations were performed in MATLAB. After establishing the constraints, the optimization problem was solved using symmetric fuzzy coefficients with a 0.9 membership level, calculating: Fuzzy center values, Right fuzzy spreads & Left fuzzy spreads

Table 1: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Iran

Variable Name	Left Width	Average Width	Right Width
GDP	-4.500	0.500	5.500
GDP^2	-8.570E-14	1.288E-15	8.288E-14
EX	-1.406E-14	1.552E-15	1.716E-14

FDI	-1.567E-13	2.084E-15	1.609E-13
HP	-5.838E-13	3.281E-14	6.495E-13

The results from Table (1) indicate that per capita GDP (GDP) in Iran shows the highest level of uncertainty in its impact on ecological footprint, with a right spread of 5.5 and left spread of -4.5, reflecting the asymmetric effect of economic growth on the environment, which is likely due to Iran's heavy reliance on oil industries and insufficient consideration of environmental factors in development planning. The squared GDP (GDP²) demonstrates negligible impact on ecological footprint with values close to zero, suggesting that the relationship between economic growth and environmental degradation has not yet reached saturation point. Trade openness (EX) shows minimal influence on Iran's ecological footprint index with very small coefficients, potentially indicating the unique nature of Iran's foreign trade that primarily relies on crude oil exports. Financial development (FDI), despite high uncertainty, exhibits moderate impact, likely due to structural limitations in attracting foreign investment. Hydropower consumption (HP) displays wide spreads but moderate effects, revealing the insignificant share of renewable energy in the country's energy portfolio. These findings collectively demonstrate that Iran's economic growth pattern exerts substantial pressure on the environment, necessitating a fundamental revision of development policies with greater emphasis on environmental considerations.

Table 2: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Azerbaijan

Variable Name	Left Width	Average Width	Right Width
GDP	-1.231	3.020E-16	1.231
GDP ²	-2.921E-15	1.728E-16	3.267E-15
EX	-1.385	0.461	2.307
FDI	-1.748	0.089	1.927
HP	0.332	0.332	0.332

In Azerbaijan, per capita GDP (GDP) demonstrates a more balanced impact on ecological footprint with a symmetric spread of ± 1.231 , likely attributable to the relative diversity in the country's economic structure. In contrast, squared GDP (GDP²) shows negligible influence on ecological footprint, indicating a linear relationship between economic growth and environmental pressure. Trade openness (EX) exhibits significant asymmetric effects on the ecological footprint index with a right spread of 2.307 and left spread of -1.385, which may stem from Azerbaijan's heavy reliance on oil and gas exports.

Financial development (FDI) displays high uncertainty (right spread: 1.926; left spread: -1.748), probably linked to oil price volatility and its impact on investment attraction. Hydropower consumption (HP) has a relatively small but definitive effect (constant value: 0.332) on the dependent variable, reflecting development constraints in this sector. These results collectively indicate that while Azerbaijan maintains a more balanced situation compared to Iran, its continued dependence on extractive industries still exerts considerable pressure on the country's environment.

Table 3: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in China

Variable Name	Left Width	Average Width	Right Width
GDP	-0.234	0.028	0.291
GDP ²	-0.358	1.441E-10	0.358
EX	0.183	0.183	0.183
FDI	-6.138	1.246E-09	6.138
HP	-0.287	2.464E-10	0.287

The results from Table (3) for China indicate that per capita GDP (GDP) has a relatively balanced impact on the ecological footprint index with a right spread of 0.29132 and left spread of -0.234, likely reflecting China's recent policies integrating economic growth with environmental considerations. Squared GDP (GDP²) shows greater uncertainty with a symmetric spread of ± 0.358 , which may stem from regional differences in implementing environmental policies. Trade openness (EX) has a stable but minor effect on ecological footprint with a constant value of 0.183. Financial development (FDI) displays the highest level of uncertainty (± 6.138), clearly related to the massive scale and diversity of foreign investments in China. Hydropower consumption (HP) has a moderate impact with symmetric spread of ± 0.287 , probably indicating the complex effects of large-scale hydropower projects. These findings collectively suggest that while China has taken significant steps toward aligning economic growth with environmental protection, notable challenges remain, particularly in managing foreign investments and large infrastructure projects.

Table 4: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Malaysia

Variable Name	Left Width	Average Width	Right Width
GDP	-3.565E-09	2.674E-10	4.100E+09

GDP ²	-5.409E-09	3.039E-10	6.017E-09
EX	-0.725	0.587	1.899
FDI	-4.817	0.458	5.733
HP	-1.655	1.847E-10	1.655

The results of Table (4) for Malaysia show that per capita GDP (GDP) exhibits significant uncertainty with a very large right spread (4.100E+09) and left spread (-3.565E-09), likely due to Malaysia's unique economic mix of industry, services and agriculture. Squared GDP (GDP²) also shows high uncertainty with a right spread of 6.017E-09 and left spread of -5.409E-09. Trade openness (EX) demonstrates notable asymmetric impact on ecological footprint with right spread of 1.899 and left spread of -0.725, probably related to environmental effects from tourism and agricultural exports. Financial development (FDI) shows extremely high uncertainty (right spread: 5.733; left spread: -4.817), likely stemming from intense regional competition for investments. Hydropower consumption (HP) has moderate symmetric impact (± 1.655), probably due to geographical constraints in developing this sector. These results collectively indicate that Malaysia's economy faces complex challenges in balancing economic growth with environmental protection, particularly in agriculture and tourism sectors.

Table 5: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Russia

Variable Name	Left Width	Average Width	Right Width
GDP	-1.157	2.151E-12	1.157
GDP ²	-3.320E-11	2.606E-12	3.841E-11
EX	0.574	0.574	0.574
FDI	-2.499	0.053	2.605
HP	0.007	0.007	0.007

The analysis reveals distinct patterns in Russia's ecological footprint drivers. Per capita GDP (GDP) demonstrates balanced environmental impact with a symmetric spread of ± 1.157 , likely attributable to Russia's vast territory and low population density. Squared GDP (GDP²) shows negligible influence on ecological footprint with minimal coefficients, suggesting limited non-linear effects. Trade openness (EX) exhibits stable but moderate impact (constant: 0.574), reflecting Russia's resource-based export structure dominated by energy commodities. Financial development (FDI) displays significant yet highly uncertain effects (right spread: 2.605; left spread: -2.499), primarily tied to oil and gas price volatility.

in this energy-exporting economy. Hydropower consumption (HP) has minimal impact (constant: 0.007), indicating Russia's predominant reliance on other energy sources like fossil fuels and nuclear power.

Table 6: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Thailand

Table 6 - Fuzzy Estimation of The Impact Width of Factors Affecting the Ecological Footprint in Thailand

Variable Name	Left Width	Average Width	Right Width
GDP	-0.817	3.320E-10	0.817
GDP ²	-7.278E-09	6.773E-10	8.633E-09
EX	0.593	0.593	0.593
FDI	-2.344	0.215	2.774
HP	-2.782	0.203	3.189

The analysis reveals that per capita GDP (GDP) in Thailand demonstrates a balanced impact on ecological footprint with a symmetric spread of ± 0.817 , while squared GDP (GDP²) shows negligible influence with minimal coefficients. Trade openness (EX) exhibits stable but moderate effects (constant: 0.593), likely reflecting Thailand's unique export composition combining agricultural and industrial products. Financial development (FDI) displays both high uncertainty (right spread: 2.774; left spread: -2.344) and significant impact, probably stemming from volatility in Thailand's tourism industry. Hydropower energy consumption (HP) shows the highest uncertainty among all variables (right spread: 3.1887; left spread: -2.782), potentially due to hydropower development in ecologically sensitive areas. These findings collectively indicate that Thailand faces significant challenges in balancing tourism and agricultural development with environmental conservation, particularly given the ecological sensitivity of its key economic sectors and the environmental pressures associated with its energy infrastructure projects. The results underscore the complex trade-offs between economic growth and environmental sustainability in Thailand's development pathway, highlighting the need for sector-specific policies that address the unique environmental impacts of tourism, agriculture, and energy production while maintaining economic competitiveness.

Table 7: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Turkiye

Variable Name	Left Width	Average Width	Right Width
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GDP	-2.162	0.258	2.679
GDP ²	2.084E-10	3.593E-10	5.103E-10
EX	0.382	0.382	0.382
FDI	-4.599E-08	1.170E-10	4.622E-08
HP	-3.255	0.164	3.584

Table (7) Results for Turkey demonstrate that per capita GDP exerts a significant asymmetric impact on ecological footprint with a right spread of 2.679 and left spread of -2.162, while squared GDP shows negligible influence. Trade openness exhibits stable but moderate effects (constant coefficient: 0.382), likely reflecting Turkey's diversified export composition. Financial development (FDI) displays minimal impact, suggesting relative stability in foreign investment absorption. Hydropower energy consumption reveals substantial uncertainty (right spread: 3.584; left spread: -3.255) and notable environmental effects, primarily attributable to recent large-scale hydropower developments. Collectively, these findings indicate that while Turkey maintains relative stability in attracting foreign capital, its ambitious infrastructure expansion projects - particularly in energy sector - impose significant environmental pressures, highlighting the critical trade-off between economic development and ecological sustainability in Turkey's growth model. The asymmetric impacts across different economic variables underscore the complex challenges Turkey faces in balancing modernization with environmental conservation.

Table 8: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Belarus

Variable Name	Left Width	Average Width	Right Width
GDP	-4.035	0.435	4.906
GDP ²	-4.162E-16	9.759E-17	6.114E-16
EX	0.118	0.118	0.118
FDI	0.242	1.520E-16	0.242
HP	-1.980E-15	4.925E-17	2.079E-15

The analysis reveals that per capita GDP (GDP) exhibits the highest uncertainty among all variables, with a right spread of 4.906 and left spread of -4.035, likely stemming from Belarus's heavy dependence on Russia's economy and its associated volatility. Squared GDP (GDP²) shows negligible impact on ecological footprint, with minimal coefficients. Trade openness (EX) demonstrates very limited influence (constant: 0.118), likely due to the country's trade restrictions. Financial development (FDI) has a stable but minor effect

(constant: 0.242), reflecting Belarus's limited appeal to foreign investors. Hydropower energy consumption (HP) shows insignificant impact, as the country primarily relies on other energy sources.

Table 9: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Macedonia

Variable Name	Left Width	Average Width	Right Width
GDP	-2.583	0.247	3.077
GDP ²	-0.050	6.167E-16	0.050
EX	-2.175	0.309	2.792
FDI	-5.697E-14	1.753E-16	5.732E-14
HP	-1.177	0.196	1.569

The analysis reveals that per capita GDP (GDP) has a significant yet highly uncertain impact on ecological footprint, with a right spread of 3.077 and left spread of -2.583, while squared GDP (GDP²) shows negligible influence (constant: 0.050). Trade openness (EX) exhibits substantial asymmetric uncertainty (right spread: 2.792; left spread: -2.175), likely tied to the country's EU accession process and evolving trade standards. Financial development (FDI) demonstrates minimal effects, reflecting the constraints of North Macedonia's small economy. Hydropower energy consumption (HP) has a moderate impact (right spread: 1.569; left spread: -1.177), constrained by the sector's limited development.

Table 10: Fuzzy Estimation of the Impact Width of Factors Affecting the Ecological Footprint in Romania

Variable Name	Left Width	Average Width	Right Width
GDP	-1.319	0.190	1.698
GDP ²	-6.897E-10	1.158E-10	9.215E-10
EX	0.370	0.370	0.370
FDI	-1.724E-08	1.254E-10	1.749E-08
HP	-3.147	0.117	3.380

The analysis reveals that per capita GDP (GDP) has a balanced impact on ecological footprint with a right spread of 1.698 and left spread of -1.319, while squared GDP (GDP²) shows negligible influence. Trade openness (EX) demonstrates stable but moderate effects (constant: 0.370), likely due to Romania's EU membership and compliance with its

environmental standards. Financial development (FDI) has minimal impact, reflecting relative stability in foreign investment attraction. Hydropower energy consumption (HP) displays the highest uncertainty among variables (right spread: 3.380; left spread: -3.147), probably resulting from recent renewable energy project developments.

6. Conclusions

The findings of this comprehensive study demonstrate that the relationship between economic growth and environmental pressures in upper-middle-income countries follows a complex pattern influenced by the interplay of economic, institutional, technological, and geographical factors. The analysis of data from 10 selected Asian and European countries over a 26-year period (1996-2022) using fuzzy regression revealed that in resource-dependent economies such as Iran, Russia, and Azerbaijan, economic growth has been accompanied by a significant increase in ecological footprint. In contrast, more economically diversified countries like China and Malaysia have been able to moderate this relationship through smart policy interventions. Of particular importance is the asymmetric and varied impact of macroeconomic variables on environmental indicators across different countries, which underscores the need for designing localized policies tailored to each nation's specific conditions.

At the micro level, the findings indicate that financial development has had dual effects in most of the studied countries. On one hand, it has facilitated investments in clean technologies and energy optimization projects, yielding positive impacts. On the other hand, it has increased environmental pressure through the expansion of industrial and manufacturing activities. This finding highlights the importance of smart financial regulation and directing credit flows toward sustainable activities. Regarding trade, the research results show that in countries transitioning toward high-tech, value-added exports (such as China and Malaysia), trade has had positive environmental effects, whereas in raw material exporting countries (like Russia and Iran), the negative effects have predominated. This reveals the necessity of restructuring trade policies toward knowledge-based exports. In the energy sector, results demonstrate that renewable energy development in countries with coherent long-term plans (such as Romania and China) has helped reduce ecological footprints. However, in some countries like Iran and Azerbaijan, the negligible share of clean energy in the energy mix and heavy reliance on fossil fuels have had significant negative environmental impacts. These findings clearly show that transitioning toward low-carbon energy sources is not merely an option but an unavoidable necessity for developing countries.

Based on these findings, we propose a set of practical policy recommendations at various levels:

- At the macro level:

Countries should move toward developing sustainable development models based on their comparative advantages

National progress indicators should be redefined to incorporate environmental sustainability criteria

Implementation of green tax policies including pollution taxes and subsidies for eco-friendly activities

Establishment of national environmental funds financed by natural resource revenues

- At the sectoral level:

Development of green capital markets focusing on environmental sukuk bonds

Provision of low-interest loans to companies in clean technology and renewable energy sectors

Revision of trade policies to prioritize high-tech, low-pollution exports

Development of recycling industries through tax incentives and banking facilities

- In the energy sector:

Formulation of national energy transition plans with quantitative targets and timelines

Investment in research projects for carbon capture and storage technologies

Implementation of smart pollution monitoring systems using digital technologies

- At the international level:

Establishment of joint environmental commissions among countries with similar socioeconomic conditions

Attraction of green foreign investment with appropriate legal and financial guarantees

Active participation in international agreements to reduce pollutants and greenhouse gases

- For future research directions:

Investigation of nonlinear effects of climate change on the economic growth-environmental footprint relationship

Analysis of how good governance and democratic institutions moderate the negative environmental impacts of economic growth

Comparative studies of environmental policy effectiveness across countries with different technology levels

Development of ecological footprint prediction models combining satellite data and economic indicators

In conclusion, while economic growth may increase environmental pressure in the short term, international experience shows that through smart policies, innovative technologies, and sustainable production/consumption patterns, sustainable development models can be achieved. Success in this path requires national commitment, active private sector participation, strengthened civil society institutions, and international cooperation. This study demonstrates that transitioning to a low-carbon economy represents not only an environmental necessity but also an economic opportunity for job creation, technological advancement, and enhanced international competitiveness.

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Observation Contribution

This article is derived from the first author's Ph.D thesis, which was developed under the guidance and supervision of the second and third authors.

Conflict of Interest

The authors declare that there is no conflict of interest while observing publication ethics in referencing.

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بررسی تأثیر عدم قطعیت در عوامل مؤثر بر ردپای بوم‌شناختی در کشورهای منتخب آسیایی و اروپایی

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چکیده

ردپای بوم‌شناختی، ابزاری مؤثر برای ارزیابی فشارهای وارد شده بر اکوسیستم‌ها و محیط زیست است. با توجه به اهمیت آن، مطالعه حاضر به بررسی تأثیر عدم قطعیت در عوامل مؤثر بر ردپای بوم‌شناختی در ۱۰ کشور منتخب آسیایی و اروپایی می‌پردازد. برای دستیابی به این هدف، از یک مدل رگرسیون فازی برای تحلیل این تأثیرات در دوره زمانی ۲۰۲۲-۱۹۹۶ م. استفاده شد. با بهره‌گیری از قابلیت‌های رگرسیون فازی، شدت تأثیر هر عامل بر ردپای بوم‌شناختی در قالب مراکز فازی، گستره چپ و گستره راست محاسبه شد. یافته‌ها نشان می‌دهد که تولید ناخالص داخلی (GDP) در ایران (+۵/۵ و +۴/۵) بیشترین تأثیر منفی زیست محیطی را داشته است که وابستگی به نفت و توجه ناکافی به ملاحظات زیست محیطی علت آن است. در مقابل، چین (+۲/۲۹ و -۰/۲۳) به دلیل سیاست‌های سبزتر، بهبود نشان داد. درمورد تجارت (EX)، آذربایجان و مالزی به دلیل وابستگی به صادرات منابع طبیعی، اثرات نامتقارن نشان دادند، درحالی‌که رومانی (پایدار در ۰/۳۷) به دلیل استانداردهای نظارتی اروپایی، عملکرد پایداری داشت. توسعه مالی (FDI) در چین (+۶/۱۳) و تایلند (+۲/۷۷ و -۲/۳۴) نوسان بالایی نشان داد؛ درحالی‌که بلاروس (پایدار در ۰/۲۴) کمترین تأثیر را داشت. مصرف انرژی برق‌آبی (HP) در ترکیه و رومانی به دلیل پروژه‌های بزرگ مقیاس با عدم قطعیت مواجه بود؛ درحالی‌که روسیه (پایدار در ۰/۰۰۷) کمترین نقش را داشت. نتیجه کلیدی نشان می‌دهد که کشورهای متکی بر منابع (مانند: ایران و آذربایجان) فشار زیست محیطی بیشتری وارد می‌کنند؛ درحالی‌که اقتصادهای دارای تنوع بخشی (مانند: چین) یا استانداردهای نظارتی سخت‌گیرانه (مانند رومانی)، ادغام بهتری بین رشد اقتصادی و پایداری دست می‌یابند. این یافته‌ها بر نیاز به بازنگری در سیاست‌های توسعه برای اولویت‌دهی به تعادل بوم‌شناختی تأکید می‌کنند.

کلیدواژگان: ردپای بوم‌شناختی، عدم قطعیت، انرژی برق‌آبی، کشورهای آسیایی و اروپایی.

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