Shadow Economy and Ecological Footprint: The Moderating Role of Environmental Taxes

Purpose

This study investigates the relationship between the shadow economy and environmental degradation, measured through the ecological footprint, in G7 countries over the period of 1995–2020. It further examines how environmental taxes and the dynamics of financial institutions moderate this relationship.

Methodology

Using macro-level panel data, the analysis applies advanced econometric techniques, including FMOLS, DOLS, AMG, GMM and PSCE, followed by the Dumitrescu and Hurlin (2012) panel causality test. These methods allow for robust estimation of long-run relationships and causal linkages while accounting for cross-sectional dependence and heterogeneity.

Findings

The results reveal that the shadow economy significantly increases the ecological footprint, as shown in Fig. 1. However, this adverse effect is mitigated by higher environmental taxes, while positively moderated by greater access to financial institutions and improved financial efficiency. While environmental taxes and financial depth/efficiency demonstrate a negative association with ecological footprint, financial depth exhibits a positive relationship.

Originality/value

This study contributes to the literature by integrating the shadow economy, environmental taxation, and financial development dimensions within a single empirical framework for the G7 economies. The findings provide actionable insights for policymakers seeking to design tax reforms and financial sector interventions that jointly curb both the shadow economy and environmental pressures.

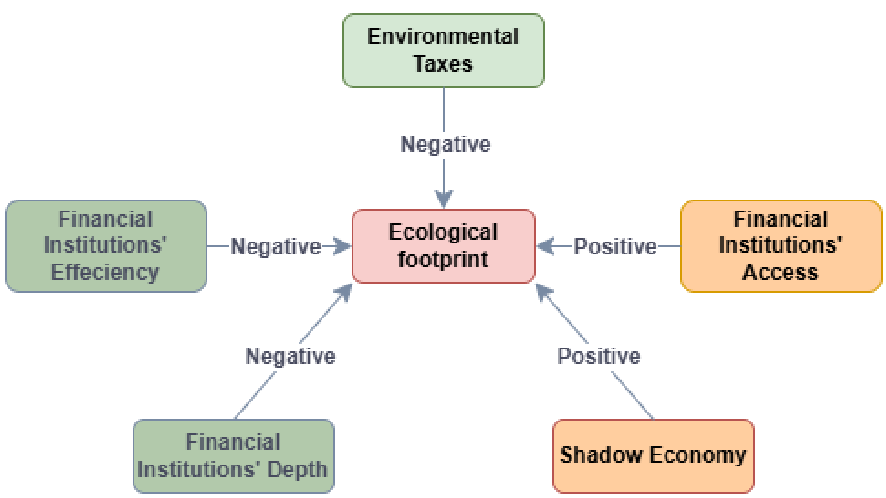

Figure 1: Graphical abstract

Keywords: *Shadow Economy, Environmental Taxes, Financial Institution Development, Ecological Footprint*

JEL: E26, Q56, G2, H2

1. Introduction

The increasing carbon emissions resulting from immense resource consumption have raised worldwide concerns (Chaudhuri & Mukhopadhyay, 2006). The excessive use of fossil fuels during the industrial revolution and, more recently, trade liberalisation for economic growth have negatively impacted bio-capacity and carbon footprint (Zhang et al., 2021). In this context, the Paris Climate Change Agreement in 2015 is a significant initiative to reduce greenhouse gases (GHG), and restrict global warming to 1.5°C by 2030 through adopting net-zero strategies (Udeagha & Ngepah, 2023). This encompasses the introduction of carbon taxation and the provision of green finance to promote sustainable practices. Countries across the globe are making efforts to curtail environmental degradation by introducing measures such as carbon taxes, green innovation, and green credit (Chang et al., 2023). However, the shadow economy (SE) is not impacted by carbon taxation, nor do they access the green or any finance (Biswas et al., 2012; Schneider, 2012). Consequently, the nexus between SE and green finance is an omission from the literature that this paper addresses.

However, there is a lack of uniform policy and practices to regulate environmental standards, especially for SE[1] (Chaudhuri & Mukhopadhyay, 2006; Schneider, 2012). The presence of SE is worldwide, but its size varies from developed to developing countries (Schneider, 2012). The SE size varies for the group of seven (G7) countries (Canada, France, Germany, Italy, Japan, the United Kingdom and the United States) from 8.5% to 29% for the period 1995 to 2020, as depicted in Figure 2 (Elgin et al., 2021). Therefore, the invisible nature of SE is a significant challenge when examining its impact on environmental degradation (Baloch et al., 2022; Schneider, 2012). The SE is a sizable part of the manufacturing and services sector, especially in the extraction of raw materials, which tends to be unregulated and has a higher tendency to pollute the environment (Chaudhuri & Mukhopadhyay, 2006). The presence of SE prevents governments from achieving environmental targets, as they use outdated energy-intensive technologies due to limited access to finance (Chu & Hoang, 2022; Udeagha & Ngepah, 2023). The entities operating within SE tend to avoid taxes and environmental regulations; therefore, depriving the government of tax revenue and negatively impacting the environment (Biswas et al., 2012; Dondeyne et al., 2009). For

[1]It includes all the economic activities and income that evade or otherwise escape the government's taxation, regulations, or oversight (Schneider, 2012).

instance, the OECD (2023) reports 0.1% reduction in tax revenue, including environmental taxes[2]. Therefore, it is vital to explore the impact of SE on the ecological footprint—an indicator of environmental degradation, which not only considers emissions, but also the impact of human activities on the environment on air, soil, forests and water (Balsalobre-Lorente et al., 2024).

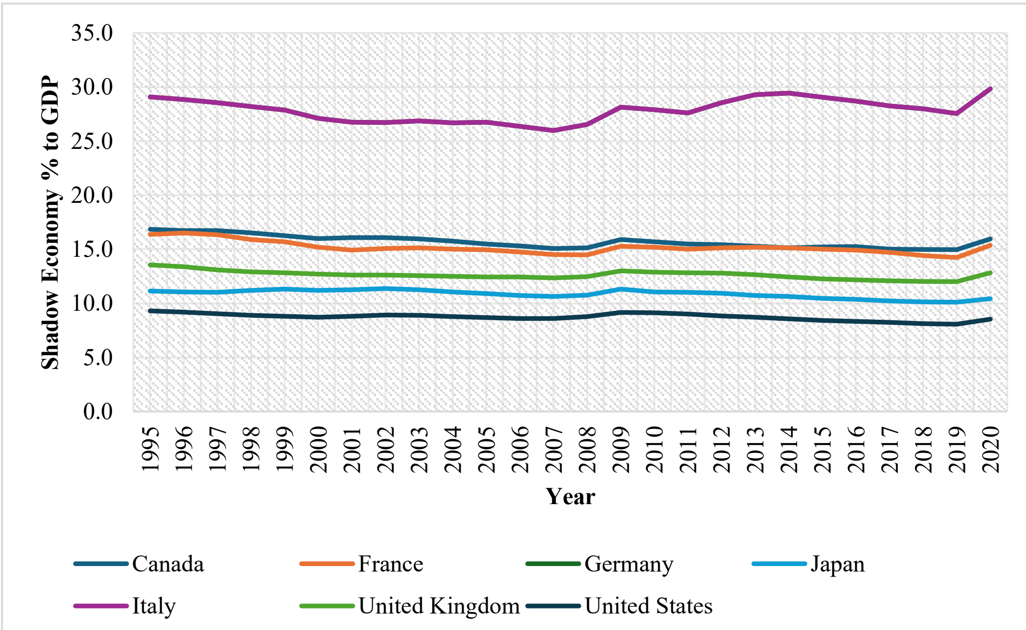

Figure 2: Size of Shadow Economy in G7 countries

It has been suggested (Canh et al., 2019; Schneider, 2012) that SE, although labour-intensive, is a major employer of unskilled workers and contributes to the GDP (Remeikiene et al., 2014). However, SE is labour-intensive and uses low-scale machines, which produce low carbon emissions (Chu & Hoang, 2022; Elgin & Oztunali, 2014). There is an argument that SE is environmentally friendly.

While several strategies, such as command & control, economic freedom, financial incentives, and environmental taxes, be used to regulate SE to minimise environmental degradation (Andersson, 2018; Chu & Hoang, 2022). There is ample empirical evidence in support of economic policies that are effective in mitigating environmental, social and economic challenges (Canh et al., 2019; Sever & Yücel, 2023). A few such policies are: pollution fees, provision of green finance, and

[2] https://www.oecd.org/en/publications/tax-policy-reforms-2023_d8bc45d9-en.html

market permits are effective in reducing environmental degradation and encourage the firms to exit SE (Dada et al., 2023; Chen et al., 2021).

Financial institutions could be effective vehicles to enhance access to green finance for the acquisition of green technology and foster environmentally friendly behaviour amongst SE (Jalil & Feridun, 2011). However, on the contrary, it has been suggested that technology could be energy-intensive and adversely increase the use of fossil fuels. Therefore, there is a cost involved in facilitating the transition of SE into a formal economy.

Further, it is suggested (Andersson, 2018; Chu et al., 2023) that environmental levies (carbon or pollution taxes) and the rule of law foster a green economy and discourage the usage of fossil fuels (Zhang et al., 2021). However, the transformation to green activities has financial implications for the firms and drives the formal sector to outsource polluted parts of production to informal sector enterprises (Baksi & Bose, 2016). Since the informal enterprises work outside the government tax net, the law does not apply, resulting in a low cost of production (Assidi et al., 2024; Butt et al., 2024; Dada et al., 2023). The low cost of doing business encourages formal enterprises to transfer whole or part of their business function to the informal sector (Baksi & Bose, 2016). This raises an argument that excessive regulations and taxes (carbon taxes) encourage SE, who avoid the full cost of environmental laws (Markandya et al., 2013; Williams & Schneider, 2013). This raises a question of whether environmental taxes and laws contribute to polluting the environment due to the transfer of industry-polluting activities from the formal to the informal sector. These countries represent around 40% of the global economy and have made remarkable economic progress (Balsalobre-Lorente et al., 2023)[3]. But they are also the largest polluters, as these countries consume around 30% of global energy and contribute up to 25% to the global carbon emissions (Murshed et al., 2022). The ecological footprint in the G7 countries is around 4.5 global hectares, as compared to the global 2.8 on average. Still, there is a desire on their part to become net-zero carbon by 2030, under the framework of the United Nations' SDG goals. It is proposed that the SE in G7 countries and the high environmental compliance cost may hinder the transition to a green economy (Ullah et al., 2023). Therefore, reducing the potential impact of the SE on the ecological footprint is critical in the G7 countries (Rahman et al., 2025). Whereas, an optimal level of

[3] https://www.worldeconomics.com/Regions/G7/

environmental taxes and financial development (access, depth and efficiency) could play a substantial role in determining the impact of SE on ecological impact. As a result, the study examined the nexus of environmental taxes, SE, ecological footprint (EF) and financial institutions dynamics in the most developed economies of the G7.

This study introduces several novel contributions to the literature. Firstly, while previous studies examined the role of SE on environmental degradation (Dada et al., 2023; 2021), assuming a linear and homogeneous relationship among countries. The study uses the Hansen (1999) panel threshold model to investigate the threshold investigate nonlinear impact of the SE on EF—a comprehensive measure encompassing biodiversity components such as fishing grounds, grazing land, forests, water resources, and carbon emissions. The study is the first to our knowledge to examine the moderating role of environmental taxes and financial development, assessed through proxies for access, depth, and efficiency, on the SE–EF relationship, employing both linear and non-linear models (panel threshold). Secondly, SE represent a substantial share of GDP of both developed and developing countries; however, the environmental consequences of SE are rarely investigated in the literature, while the subject is timely and policy-relevant. This study explores the level of environmental taxes which may affect (negative or positive) the direct impact of SE on EF. Thirdly, this study uses several advanced econometric techniques, including CIPS and CADF unit root tests, Westerlund (2007) cointegration tests, FMOLS, DOLS, AMG, PSCE, panel threshold tests, and Dumitrescu and Hurlin (2012) causality tests. The study findings reveal that environmental taxes, financial institutions' depth and efficiency decrease, whilst SE increase the ecological footprint in the G7 countries. Moreover, the study explores that the elasticity of the EF due to SE vary significantly across low and high regimes, as explored by the estimated environmental taxes and financial development threshold values.

The study is structured as follows: Section 2 describes the literature review, Section 3 explains the econometric models, variables, and statistical techniques, and Sections 4 and 5 describe the analysis of findings and conclusion, respectively.

2. Literature Review

There is an emerging literature that examines the effect of SE on EF (Bento et al., 2018; Khurshid et al., 2024). This encourages firms in the SE to migrate towards a formal economy. In contrast, environmental taxes increase the cost of doing business in the formal economy and force them to move to SE partially or fully. To mitigate the unintended consequences of environmental taxes, there is a case for discounted green finance. As a result, the following sections analyse the emerging literature on the nexus of SE, environment, environmental taxes and financial development.

2.1. Shadow Economy and Environment

There are a few studies that have provided an analysis of the relationship between SE and environmental degradation. Chaudhuri & Mukhopadhyay (2006) report that environmental pollution is caused due to the outsourcing of polluting products from the formal to the informal sector. In this process, the formal sector avoids environmental taxes and complies with the emission limit. These findings are supported by Baksi & Bose (2016), stating that SE tends to be associated with the manufacturing of pollutant goods. Canh et al. (2019) conclude that SE is a significant carbon emitter in high-income countries and a low carbon emitter in middle and low-income countries.

Huynh (2020) suggests that government expenditures reduce the SE impact on pollution and vice versa for taxes. Chu et al. (2023) report that SE has an inverse relationship with renewable energy usage for high and middle-income countries, these findings suggest SE may be using polluting energy and encouraging them to use formal sector renewable energy, which could lessen the adverse impact on environmental degradation.

In contrast, Silva et al. (2023) suggest that CO_2 emissions and SE are negatively correlated. Camara (2022) reported a significant reduction in carbon emissions due to the presence of SE. However, Yu et al. (2022) reported a non-linear association between SE and carbon emissions. Nguyen & Nguyen (2023) suggest that SE improves the forest area in the short-run, whereas it increases deforestation in the long-run. Moreover, studies (Çabaş et al., 2024; Magazzino, 2024; Magazzino et al., 2025) suggest that other socio-economic variables, including population, life expectancy and GDP, drive ecological footprint.

Table 1: Literature on SE and Environmental Degradation

Authors	Variables	Sample	Relationship between SE and Environmental degradation

Elgin & Oztunali (2014)	SE, CO2, Sulfur Dioxide	Turkey	Inverted U-shaped
Mirzaei et al. (2016)	SE, Environmental Pressure, Political and Administrative Corruption	MENA Countries	Positive
Köksal et al. (2020)	SE, Ecological Footprint	Turkey	Positive
Chu & Hoang (2022)	SE, Ecological Footprint	OECD Countries	Inverted U-shaped
Dada & Ajide (2021)	SE, Environmental and Institutional Quality	Nigeria	Positive
Pham Tran (2022)	SE, Environmental Pollution, Institutional Quality, Economic Growth	Vietnam	Insignificant
(Dada et al., 2022)	SE, Environmental Sustainability, Trade Openness, Financial Development, Urbanization	Africa	Positive
Dada et al. (2023)	SE, Environmental Degradation, Governance, Urbanization	African Countries	Negative
Nguyen & Nguyen (2023)	SE, Air Pollution	148 Countries	Positive
Gamal et al. (2024)	SE, Environmental Pollution, Corruption	Developing Countries	Positive
Ahmad and Hussain (2024)	SE, Environmental Pollution	Egypt	Positive
Wang et al. (2024)	SE, Environmental Sustainability, Governance	Developing Couties	Positive

It is well established in the literature that SE has implications for environmental degradation and there is a large presence of the informal sector in developed as well as developing countries. Table 1 shows that the approaches and samples of countries used vary, and the findings are inconclusive. Therefore, there is a gap in the literature and a case to examine the links between SE and EF. To study the linkage, the following hypothesis is proposed:

H1: SE has a significant impact on the ecological footprint.

2.2. The Moderating Role of Financial Development

The literature suggests that financial development is a prerequisite for economic growth, often associated with formal and informal economic activities. Therefore, it is crucial to understand the links between SE and financial development. Bose et al. (2012) suggest that banking sectors' depth and efficiency reduce the size of SE. This relationship is validated by Bayar & Ozturk (2016) for the economies in transition. Contrary to these findings, Berdiev & Saunoris (2016) reported a non-linear association between financial development and SE across the globe. The growth of the financial institution's efficiency leads to a fall in SE in the early stage but reverses with the financial market maturity, resulting in the U-shaped relationship between SE and financial efficiency (Canh & Thanh, 2020). Their findings are corroborated by Abu-Lila et al. (2021) for Jordan. Similarly, Rahman et al. (2023) for embracing financial technologies that promote financial inclusion. On the contrary, Safuan et al. (2021) recorded an inverted U-shaped relationship between financial development and SE, suggesting variation in findings at the country level.

Shujah-ur-Rahman et al. (2019) suggests that financial development reduces the use of energy consumption and ultimately improves environmental quality. These findings are supported by Dada et al. (2023), stating that a stronger financial system reduces the negative influence of SE on environmental degradation. Another study by Dada et al. (2024) reported that financial development positively moderates the nexus between energy, poverty and EF. The literature suggests dynamics of financial institutions' development (access, depth, and efficiency) that moderate the impact of SE on environmental degradation has not been investigated so far. Therefore, the hypothesis H2 is proposed.

> *H2: Financial institutions' development dynamics (access, depth and efficiency) significantly moderate the impact of SE on ecological footprint.*

2.3. The Moderating Role of Environmental Taxes

Fiscal tools such as environmental taxes are used to promote sustainable economic practices (Doğan et al., 2022; Dumortier & Elobeid, 2021). Amaddeo et al. (2025) highlighted a positive effect of the European Trading System of emissions on energy prices. In theory, the taxes are designed to increase the cost of environmentally polluting activities (Baranzini et al., 2017; Liu, 2013). Doğan et al. (2022) suggest that environmental taxes, compared to other net-zero strategies (such as tradable permits and controls), promote green development. Similar findings are reported by He et al. (2019) for Nordic and G7 countries, and these findings are corroborated by Dogan et al. (2022), who proposed environmental taxes for a reduction in carbon emissions.

The adverse impact of environmental taxes is that they reduce profit for the enterprises, and SE become more attractive (Aldy et al., 2010). Schneider (2012) reports that the difference between the labour cost (earnings) and after-tax earnings in the official sector induces workers to operate in the informal sector and thus reduces the tax revenue and negates the benefit for the environment. However, Dreher et al. (2009) found that taxation is not significant nor its an impact on SE or causes environmental degradation. Nevertheless, Liu (2013) contradicts and empirically establishes the adverse impact of tax evasion on environmental protection funds. The study proposed that efficient use of green revenue promotes environmental quality through carbon taxes, and economic growth results in the double dividend hypothesis. Markandya et al. (2013) tested the double dividend hypothesis and reported that environmental taxes not only reduce environmental degradation but also improve social and economic indicators in line with the earlier findings of Pearce (1991). His findings suggest that the replacement of labour taxes with energy taxes promotes the transition of informal labour to the tax net, which increases tax revenue and reduces carbon emissions in Spain. However, distortion caused by SE gives rise to the double-dividend hypothesis because of the environmental tax. This phenomenon suggests a possible association between environmental taxes, carbon emissions and SE. Therefore, based on the literature, the study tests the following hypothesis, H3.

- *H3: Environmental taxes moderate the relationship between SE and ecological footprint.*

2.4. Theoretical and Conceptual Framework

The theoretical framework of the study aligns with several environmental and economic theories. According to the Environmental Kuznets Curve (EKC), an increase in economic activities gives rise to an inverted U-shape relationship with environmental degradation (Grossman & Krueger, 1995). The EKC inverted U-shaped relationship between SE and pollution is empirically tested and verified. The EKC is further segregated into scale, composition, and technique effect (Bouvier, 2004), which provide a primary foundation to the SE-environment nexus. The economic and fiscal policies (environmental taxes) encourage businesses toward green transition and reduce incentives to operate informally and adopt environmentally friendly technologies (OECD, 2010; Parry et al., 2012; Ullah et al., 2025). However, Williams & Schneider (2013) suggest that increasing income (direct) and commodity taxes (indirect) promote the incidence of tax evasion and give rise to SE. This behaviour could be explained by the optimal tax theory that suggests excessive taxation leads to the transition of workers from formal to informal sectors; therefore, polluting taxation policies could have unintended consequences (Doligalski & Rojas, 2023). However, according to the double dividend hypothesis, environmental taxes are beneficial in reducing both environmental and economic inequalities (Pearce, 1991). Straub (2005) theorizes that SE can be reduced through financial incentives. However, to benefit from financial incentives, informal entities need to declare their assets and income which will not only increase tax revenue but also enable them to access external finance (Bose et al., 2012; Berdiev & Saunoris, 2016). In addition, financial depth usually stimulates economic activities by offering more investment and credit. Whilst, financial access and efficiency tends to tends to ensure environmental regulations and utilize capital more effectively. These theories provide the rationale to empirically test the nexus between SE, financial institutions development (depth, access and efficiency), environmental taxes and EF. Accordingly, the study examine the impact of SE on ecological footprint, assuming that apart from the official sector, the informal economic activities tend to affect environmental performance, following the EKC hypothesis. However, environmental taxes and financial institutions can determine the size of the SE by influencing them to work in or away from the official economy, and thus can affect environmental quality.

3. Methodology

3.1. Variables and empirical models

The study adopts Chu & Hoang (2022) and Dada et al. (2021, 2023) models by incorporating the environmental taxes and financial development proxies of access, efficiency and depth. To study the nexus between SE, financial institutions' dynamics, environmental taxes and ecological footprint, the study developed the linear regression equation (1) and incorporated the interactions between (SE*FIA, SE*FIE, SE*FID, SE*ET) in equations (2-5) below.

$$EF_{it} = \alpha_0 + \beta_1 SE_{it} + \beta_2 FIA_{it} + \beta_3 FIE_{it} + \beta_4 FID_{it} + \beta_5 ET_{it} + \varepsilon_{it} \dots (1)$$

$$EF_{it} = \alpha_0 + \beta_1 SE_{it} + \beta_2 FIA_{it} + \beta_3 FIE_{it} + \beta_4 FID_{it} + \beta_5 SE^* FIA_{it} + \beta_6 ET_{it} + \varepsilon_{it} \dots (2)$$

$$EF_{it} = \alpha_0 + \beta_1 SE_{it} + \beta_2 FIA_{it} + \beta_3 FIE_{it} + \beta_4 FID_{it} + \beta_5 SE^* FIE_{it} + \beta_6 ET_{it} + \varepsilon_{it} \dots (3)$$

$$EF_{it} = \alpha_0 + \beta_1 SE_{it} + \beta_2 FIA_{it} + \beta_3 FIE_{it} + \beta_4 FID_{it} + \beta_5 SE^* FID_{it} + \beta_6 ET_{it} + \varepsilon_{it} \dots (4)$$

$$EF_{it} = \alpha_0 + \beta_1 SE_{it} + \beta_2 FIA_{it} + \beta_3 FE_{it} + \beta_4 FID_{it} + \beta_5 SE^* ET_{it} + \beta_6 ET_{it} + \varepsilon_{it} \dots (5)$$

In the above equations, $i = 1, \dots., N$ represents number of countries and $t = 1, \dots., T$ indicates time. EF is ecological footprint; SE shadow economy; FIA financial institutions access; FIE institutions financial efficiency; FID financial institutions depth; ET environmental taxes and ε_{it} is the error term. All the coefficients $\beta_1 \dots \dots \beta_6$, are long-run variances in the dependent variables.

3.2. Data description

The study use annual panel data from 1995 to 2020 for the G7 countries. The environmental data starts from 1995, and the SE data is available until 2020; therefore, the period chosen is dictated by the data availability. Table 2 summarises the variables and data sources.

Table 2: Variables detail

Variables	Symbol	Unit	Sources
Ecological Footprint	EF	Ecological Footprint constant person capita	Ecological Footprint Network
Financial Institutions Access	FIA	Score	IMF
Financial Institutions Efficiency	FIE	Score	IMF
Financial Institutions Depth	FID	Score	IMF
Shadow Economy	SE	% to GDP	Elgin et al. (2021) (World Bank)
Environmental Taxes	ET	Environmental taxes to total tax revenue	OECD

Note: *The higher score represents higher financial institutions (banks, insurance companies, mutual and pension funds) development. STATA 19.5 version is used for analysis.*

The size of SE can be measured by direct (survey, questionnaire, tax audit) and indirect (transactions approach, currency demand, physical input etc.) techniques (Sabra et al., 2015). The justification for using the Multiple Indicators and Multiple Causes (MIMIC) approach is widely used in the literature which measures the relative size of SE (hidden variable), using three indicators (GDP growth rate, labor force participation, currency as a ratio of M0[4] and M1[5]) and six causes (business freedom, unemployment rate, GDP per capita, government effectiveness, share of direct taxation and government size) overtime by formally constructing structural model and the measurement model (Elgin et al., 2021). Environmental taxes are net of the environmental taxes revenue, consisting of tax base (tax bases of resources, pollution, transport and energy), tax rates and exemptions applied in the environmental domains, such as estimated air and water emissions, ozone-depleting gases, waste management, noise and biodiversity management. EF accounting measures the availability of nature and the extent to which it is utilised by human beings. This is composed of human activities that impact biodiversity and natural resources, such as forest, farming, fishing, mining, and manufacturing (emissions). It is measured in per capita EF,

[4] currency outside the banks (World Bank, 2024).
[5] IMF, IFS and Haver Analytics

using global hectares (gha) unit (Global Ecological Footprint, 2024). For financial development, the study used the IMF proxy, proposed by Svirydzenka (2016), which considered banks, mutual funds, insurance companies and pension funds. The higher score (index) of financial access, depth and efficiency indicates higher financial development and vice versa. To normalize All the variables are transformed into logarithm form to reduce homogeneity, skewness (with extreme outliers) and to enhance normal distribution in the data (Ali et al., 2022). Moreover, Fig. 3 visually plots the data to examine outliers, showing a symmetric distribution of data without having significant outliers. Minimal outliers are observed in the shadow economy (lnSE) and financial institution development (lnFIA). In addition, Fig. 4 represents the residuals distribution, indicating that the residuals are normally, distributed and fit for a regression model. Overall, these analysis suggests subsequent econometric analysis.

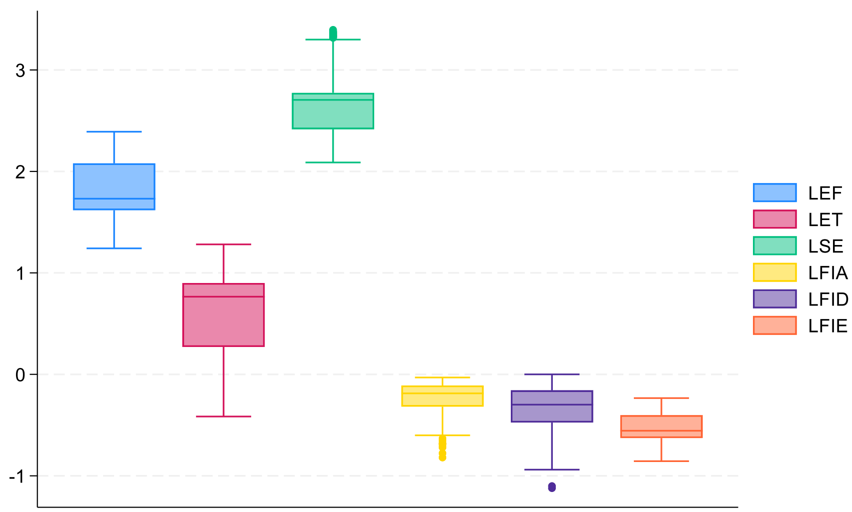

Figure 3: Boxplots for outliers in variables
Note: dashes inside the box indicate the mean of the variable.

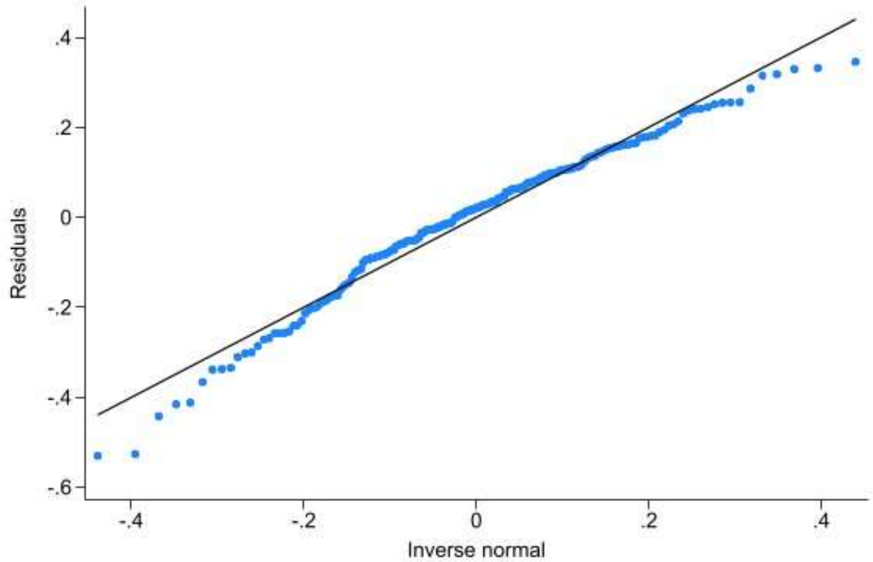

Figure 4: Residuals

3.3. Methodological techniques

The study uses a comprehensive framework to investigate the relationship between SE and EF, considering CSD, slope heterogeneity, stationarity, cointegration and potential nonlinearity. Initially, the study tested for multicollinearity (using the variance inflation factor (VIF)) and serial correlation, and proceeded with the empirical analysis in several steps. (1) Testing for CSD and slope heterogeneity; (2) identifying stationarity problem by using second-generation unit root tests (CIPS and CADF); (3) examining cointegration; (4) estimating the long-run relationship; (5) robustness checks; (6) investigating for threshold effects; (7) and examining causal relationships among the variables. The selection of each approach is based on its appropriateness for specific econometric challenges inherent in the panel data, as defined below.

and cointegration among the variables by applying the second-generation, which considers CSD. After exploring cointegration among the variables, FMOLS and DOLS tests are applied to examine the impact of explanatory variables on EF. However, the FMOLS and DOLS are limited in considering CSD and potential endogeneity. Therefore, the study employs the Augmented Mean Group and system GMM to consider AMG and potential endogeneity. For robustness, the study also uses the Hansen (1999) test to examine nonlinearity and regime-dependent effects. Finally, to examine the causal relationship among the variables, a panel causality test is used.

3.3.1. Cross-sectional dependency

The presence of economic, political, environmental, and social integration amongst G7 economies may cause issues of cross-sectional dependency (CSD) in the panel data, while ignoring it may cause biased estimations. Therefore, this study employs second-generation Pesaran (2015) CSD tests to identify CSD among the variables. The main (*H1*) hypotheses for CSD tests are as follows:

$$H_1: \rho_{ij} = Cov(v_{it}, v_{it}) \neq 0 \dots\dots\dots\dots (6)$$

Pesaran (2004) CSD proposed a simple CSD test to address the issue of CSD, which can be applied on stationary and unit root dynamic heterogenous panel data with short *T* and larger *N*. It can be empirically represented by Equations (10) and (11) for the imbalanced panel dataset as follow.

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \sim N(0,1)i,j \dots\dots\dots\dots (7)$$

$$= \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho_{ij}}\right)\left[\frac{(T-k)\widehat{\rho_{it}}^2 - (T-K)\widehat{\rho_{it}}^2}{Var(T-K)\widehat{\rho_{it}}^2}\right] \dots\dots\dots\dots (8)$$

Whereas $\widehat{\rho_{ij}}^2$ indicates cross-sectional (pairwise) correlations through the simple OLS technique

3.3.2. Unit root tests

Before estimating the relationship, the study examines stationarity among the variables by employing second-generation unit root tests, which consider CSD. The study used Cross-Sectionally Augmented Im-Pesaran (CIPS) and Covariate-Augmented Dickey Fuller (CADF), for reliable and consistent estimations (Pesaran, 2007). CADF is estimated as follows:

$$\Delta Y_{it} = \beta_i + \alpha_i y_{i,t-1} + b_i \bar{y}_{t-1} + d_i \Delta\bar{y}_t + v_{it} \dots\dots\dots\dots\dots\dots (9)$$

Equation (13) can be stated as below for a single lag.

$$\Delta Y_{it} = \beta_i + \alpha_i y_{i,t-1} + b_i \bar{y}_{t-1} + \sum_{j=0}^{p} d_{ij}\,\Delta\bar{y}_{i,t-j} + \sum_{j=1}^{p}\delta_{ij}\,\Delta y_{i,t-j} + v_{it} \dots\dots\dots\dots\dots\dots (10)$$

In the above equations, $\bar{y}_{t-j}$ and $\Delta y_{i,t-j}$ represents the lagged average and the first cross-sectional difference for each variable. The CIPS unit root test is estimated as follows:

$$CIPS = N^{-1}\sum_{i=1}^{N} CADF_i \ldots\ldots\ldots\ldots\ldots\ldots..(11)$$

3.3.3. Cointegration test

After identifying stationarity among the variables, the study tests for cointegration to explore the existence of long-run relationship. Westerlund's (2007) cointegration test is employed, which considers both heterogeneity and CSD among the variables and provides more reliable results by avoiding spurious estimates (Rahman et al., 2025; Westerlund, 2007). This approach provides four statistics (Gt, Ga, Pt, Pa), consisting of group and panel statistics. The significance of a group or panel of statistics determines the presence of cointegration among the variables.

3.3.4. Long-run relationship estimations

In order to estimate the coefficients of the relationship, the study employs FMOLS, DOLS and AMG. Proposed by Pedroni (2000), the FMOLS uses a modified least squares approach to control for the serial correlation, which we examined earlier, and potential endogeneity (Phillips & Hansen, 1990). However, this test cannot be applied without meeting the assumption of order I(*1*) integration among all the variables. Whereas DOLS, proposed by Stock & Watson (1993), estimates long-run relationship among the variables, cointegrated at order I(*1*). Numerically, this is represented as follows:

$$EF_{it} = \varphi_o + \varphi_1 Z_{it} + \sum_{j=-p}^{p} \Phi_j \, \Delta Z_{t-1} + n_t \ldots\ldots\ldots..(12)$$

Where Z_{it} is a vector of independent variables, while Δ is a lag operator.

Further, the AMG estimator accounts for CSD and slope heterogeneity in the panel data by including a common dynamic process (Eberhardt and Bond, 2009). For robustness, the study PCSE and GMM approaches to account for possible heteroskedasticity and endogeneity across the panel. The PSCE considers serial correlations, heteroskedasticity and contemporaneous correlation; whilst, GMM is used to address endogeneity and measurement bias, leading to provide estimator efficiency. In addition, a key contribution of the study is highlighting whether the effect of SE on EF differs across regimes, estimated by environmental taxes and financial institutions' dynamics. Hansen's (1999) panel threshold approach is used for estimating potential non-linearity in the models, which allows for estimating regime-dependent effects due to structural changes. The threshold value is described by reducing the residual sum of squares over a grid of candidate values.

Using multiple techniques allows the study to provide robust results, considering different assumptions for serial correlation, slope heterogeneity, CSD, error structure and potential endogeneity effects.

3.3.5. Granger Causality

Finally, Dumitrescu and Hurlin (2012) method is employed to determine the causal relationship between the variables. Unlike the Granger (1969) method, this approach changes across the panel data and cross-sectional units. Similarly, the alternative techniques in this test is more flexible because it assume that the causation between the two variables exists in at least one of the cross-sectional units; thus address the data's slope heterogeneity problems. The Z-bar statistic and Dumitrescu-Hurlin test used are as follows:

$$\check{Z}_{N,T}^{HNC} = \frac{\sqrt{N}}{\sqrt{Var(\hat{W}_{i,T})}}\left[W_{N,T}^{HNC} - E\hat{W}_{i,T}\right] \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$$y_{it} = \alpha + \sum_{k=1}^{k} \lambda_i^k i y_{it-k} + \sum_{k=1}^{k} \beta_i^k i y_{it-k} + \varepsilon_{it} \ldots\ldots\ldots (14)$$

4. Empirical Results

4.1. Descriptive statistics, VIF and CSD test

Descriptive statistics of the variables are estimated, shown in Table 1A, online Appendix 1. The standard deviation for all variables is between 0-1, with the lowest reported for financial institutions' efficiency and the highest for real interest rate; thus, suggesting that the data set is normally distributed. The VIF values range from 2.77 for environmental taxes to 1.2 for FIA; thus, reporting the non-existence of multicollinearity (Gujarati & Porter, 2003). Moreover, Table 1A shows the Pesaran (2015) CSD results, which are statistically significant and indicate the presence of CSD among all variables.

4.2. Unit root and slope heterogeneity test

To address the presence of unit roots among the variables reported in Table 2A (online Appendix), the study employs the CIPS and CADF unit root tests. The results suggest stationarity at first differences and indicate an I(*1*) integration order. Moreover, the slope of heterogeneity among the variables in the study models is examined. The results also indicate the presence of slope heterogeneity and serial correlation among the models, as reported in Table 3A (online Appendix). This suggests applying relevant tests to consider CSD, serial correlation and slope heterogeneity, such as AMG, PSCE, FMOLS and DOLS. Next, the study employed Westerlund's (2007) cointegration test to check for long-run cointegration among the variables. As shown in Table 4A (online Appendix), cointegration in the long-run exists, allowing us to estimate the coefficients.

4.3. Long-run estimations

Table 3 documents the findings of FMOLS and DOLS tests to estimate the long-run relationship among the variables. Environmental taxes have a negative relationship to EF, indicating that a 1% increase in environmental taxes significantly reduces EF by -0.434 to -0.831% in the G7 countries. This suggests that higher environmental taxes encourage businesses to adopt sustainable business practices and technology, decreasing carbon emissions and ecological impact. The findings corroborate earlier studies (Khan et al., 2021 and Shahbaz et al., 2024), exploring that green taxes reduce carbon emissions. The coefficients for SE in model 1–both FMOLS and DOLS—are positive and significant, implying that a 1% increase in SE raises EF by 0.7% to 1.22%. Thus, the findings validate the main H1 and Environmental Kuznets Curve, confirming that informal economic activities (SE) promote EF. It can be inferred that SE (mainly consisting of illegal and hidden businesses) avoids environmental regulations and government enforcement, and significantly contributes towards environmental degradation. Being outside the official financial sector, the informal businesses pursue profit at the cost of the environment, leading to polluted air, water and soil. These results are in line with Canh et al. (2019) findings, who reported a negative association between SE and carbon emission for lower-middle-income economies. Results reported the significant negative association of EF with the efficiency (efficient use of money) of financial institutions. The results suggest that increased depth of financial institutions (such as banks, insurance companies, mutual funds and pension funds relative to the economy or private credit relative to the GDP) promotes better investment in clean energy production and advanced technologies, which reduces EF. These results support earlier findings (Ahmad et al., 2022 and Xu et al., 2021) that financial depth promotes environmentally friendly technologies (renewable energy, electric vehicles) and green infrastructure (reforestation, sustainable farming).

Further, results in Table 3 depict that together SE and environmental taxes—moderating role of the environmental taxes in the impact of SE on EF—significantly reduce EF. This suggests that environmental taxes is effective in reducing the adverse ecological impact of the SE in which unregulated economic activities usually produce more waste emissions. Whereas, environmental taxes targeting the SE enforce strict regulations and thus reduce their EF. The findings support the double-dividend hypothesis[6] of Liu (2013) and Markandya et al. (2013) in G7 countries that environmental taxes reduce tax evasion and environmental degradation.

The positive interaction terms between SE and financial institutions' access, depth and effeciency (lnSE*FIA, lnSE*FID and lnSE*FIE) indicate that increased financial institutions development improves EF. For instance, increasing access to financial institutions may empower industries to oversee environmental regulations or invest in resource-exploitative activities. These findings are supported by Canh & Thanh (2020), but they contradict the findings of Berdiev & Saunoris (2016) and Faryal et al. (2023).

For robustness, AMG, GMM and PSCE techniques are employed to address dynamic effects, potential endogeneity, CSD and panel cross-sectional correlation. These outcomes, reported in Table 5A (online Appendix), further validate our key findings. Environmental taxes is effective in reducing EF, particularly targeting the informal sector. However, the SE plays a critical role in affecting the negative interaction of financial institutions and environmental taxes with EF.

In addition, to explore how the variables affect EF across high and low regime economies and to determine the threshold value for SE, the study used the Hansen (1999) test. As shown in Table 6A (online Appendix), the predictors' contributions towards EF vary across regimes. Threshold value for SE with environmental taxes is -0.24, and SE with financial institutions dynamics (access and depth) are -0.155 and -0.583. The impact of SE in low-regimes (lnSE ≤ threshold value) is weak while in the high-regimes (lnSE ≤ threshold value) it is strong, indicating their increased adverse effects in the higher SE economies. Our outcomes are in line with those of Dada et al. (2023) who

[6] The theory of reducing labor taxes (direct taxes) in the formal sector and imposing green taxes to tackle the inefficiency of the tax system on the environmental degradation (Chaudhuri & Mukhopadhyay, 2006).

explored that a higher financial development moderates the SE's environmental impacts. These findings can be generalized for other countries with similar characteristics, such as income level, institutional framework, etc. For instance, the threshold values may also be appropriate for other highly developed countries with a significant SE; however, they may be different for countries with poor institutional quality and income. Moreover, these threshold values may be different for urban areas in the G7 countries, because comparatively urban areas experience higher informal manufacturing, transport and resource depletion. In addition, the marginal effect of the moderating variables is shown in the Online Appendix 2.

Table 3: Long-run estimations

	FMOLS					DOLS				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
lnET	-0.83* (0.06)	0.37** (0.26)	-0.79* (0.06)	-0.68* (0.06)	-0.59* (0.06)	-0.43** (0.19)	4.44* (1.23)	-0.75* (0.19)	-0.59* (0.08)	-0.60* (0.13)
lnFIA	0.03 (0.12)	0.13 (0.11)	-2.80** (1.22)	0.06 (0.10)	-0.02 (0.09)	0.06 (0.06)	0.07 (0.09)	-5.82** (2.51)	-0.05 (0.12)	-0.05 (0.20)
lnFID	-0.53* (0.14)	0.26 (0.13)	0.38** (0.15)	-1.49* (0.43)	-0.22*** (0.18)	-0.63* (0.16)	-0.39 (0.24)	0.01 (0.30)	-1.81* (0.3)	0.01 (0.22)
lnFIE	-0.70* (0.17)	-0.84* (0.15)	-0.6* (0.17)	-0.68* (0.15)	-2.55* (0.32)	-0.02 (0.15)	0.39 (0.27)	-0.11 (0.35)	-0.35** (0.19)	-2.66* (0.49)
lnSE	0.78* (0.04)	0.74* (0.03)	0.77* (0.04)	0.74* (0.03)	0.76* (0.03)	1.22* (0.45)	2.17* (0.74)	0.76* (0.05)	0.79* (0.03)	0.78* (0.05)
lnSE*ET		-0.43* (0.09)					-1.71** (0.42)			
lnSE*FIA			1.03** (0.45)					1.98** (0.96)		
lnSE*FID				0.68* (0.14)					0.81* (0.1)	
lnSE*FIE					0.81* (0.13)					0.94* (0.18)
R-sq	0.48	0.61	0.50	0.61	0.67	0.98	0.99	0.94	0.98	0.95
Adj R-sq	0.47	0.59	0.49	0.60	0.66	0.91	0.96	0.67	0.89	0.76

Note: **, ** and *** P<0.01, P<0.05 and P<0.1; significance level at 1%, 5% and 10% respectively. Values in parentheses represent standard error. The R^2 and adjusted R^2 measure the coefficient of proportion of variance in the dependent variable caused by the independent variables.*
Source: Author's own work

4.4. Granger Causality

Results in Table 4 reflect a unidirectional causality from SE towards EF and a bidirectional causality between environmental taxes and SE. The coefficient significance suggests that informal economic activities drive EF, whilst environmental taxes drive SE and vice versa for G7 economies. Moreover, a bidirectional causal relationship is reported between financial institutions' depth and EF. The findings suggest that environmental taxes, SE and financial institutions' depth are the critical factors in mitigating EF and should be part of policy development.

Table 4: Granger causality

Variables	lnEF	lnET	lnSE	lnFIA	lnFID	lnFIE
lnEF	--	3.91**	2.3	4.9*	2.33**	3.68
lnET	5.52*	--	4.23**	2.39	2.24	2.66
lnSE	6.41*	4.68**	--	1.75	4.01***	2.17
lnFIA	3.57	4.42**	1.62	--	0.72	4.1**
lnFID	8.85*	3.36	5.32**	0.29	--	2.32
lnFIE	2.59	3.89***	4.13**	3.67	3.35	--

Note: The test considers the null hypothesis of no causality.
**, ** and *** P<0.01, P<0.05 and P<0.1; significance level at 1%, 5% and 10% y of W-stat, respectively.*
Source: Author's own work

5. Conclusion

The shadow economy (SE) is an important facet of global economies, and the literature suggests that SE affects a broader spectrum of socio-economic systems. Its environmental and ecological impacts are rarely explored in the literature. This study investigates the SE impact on EF, while specifically focusing on the moderating role of environmental taxes and financial institutions development dynamics (access depth and efficiency). There is an unsettled debate in the literature about whether environmental taxes and financial development dynamics impact SE and its association with EF.

Using a large sample of annual observations from G7 economies over the period from 1995-2020, the study employed a comprehensive methodological framework. The study employed second-generation econometric techniques, including unit root tests (CIPS and CADF), Westerlund (2007) cointegration test, FMOLS, DOLS and AMG estimators, with PSCE and GMM for robustness. Moreover, the study employed Hansen's (1999) panel threshold test to examine the nonlinear and regime-dependent impact of the SE on EF, considering environmental taxes and financial institutions' development dynamics as threshold variables. Further, the study employed Dumitrescu and Hurlin's (2012) heterogeneous panel causality test.

The study's key findings reveal that there is a significant relationship between EF, SE, environmental taxes and financial development dynamics. Firstly, the positive impact of SE is explored, indicating that informal economic activities promote EF. Secondly, the negative impact of financial institutions' depth and efficiency on EF is also identified. Thirdly, the study also finds that using environmental taxes and financial institutions' dynamics moderates the relationship between SE and EF. The study explores that the SE effect on EF varies across low and high regimes, with threshold values for environmental taxes, financial institutions' depth and efficiency and of -0.24, -0.586, and -0.592, respectively. These outcomes indicate that the SE's environmental impacts are more stronger in countries with weak financial system and lower environmental taxations.

5.1. Policy implications

The study provides several policy implications based on empirical findings. The study reveals that environmental taxes are effective in moderating the role of SE in reducing EF above the critical threshold (-0.24). The G7 countries below this threshold level may not reduce the environmental consequences of the SE. Therefore, such countries should increase environmental taxes on SE to the given specific threshold to moderate SE's adverse environmental impact. Further, the findings reveal that in a low financial development regime (financial depth = -0.586 and efficiency = -0.545), SE has a more significant impact on EF. Policymakers should further enhance the financial institutions' development beyond the given threshold value to reduce the environmental impact of SE. Countries (US, Japan, France, Italy, UK, Canada) should introduce the carbon taxation policy at the industry-based level to promote sustainable practices and transition toward a formal sector economy. Also, policymakers in these countries should design a gradual roadmap for increasing environmental taxes to reduce informality and its environmental and economic consequences. In addition, the authorities may spread awareness among the public of the environmental consequences of the SE. Discouraging SE will not only increase tax revenue but also environmental quality.

5.2. Limitations and future directions

This study is limited to focusing on only the G7 countries and determining the threshold for only SE. Future studies may individually analyse the G7 countries, expanding to other markets and industries. Specifically, future studies should focus on the threshold values of other predictors, such as environmental taxes, and explore the role of institutional quality in their relationship. Further, future studies may use alternative proxies of financial institutions' development.

List of abbreviations

AMG = Augmented Mean Group
CADF = cross-sectionally augmented Dickey-Fuller
CIPS = cross-sectionally augmented Im, Pesaran and Shin
CSD = Cross-sectional dependency
DH = Dumitrescu and Hurlin
DOLS = Dynamic Ordinary Least Squares
EF = Ecological Footprint
ET = Environmental Taxes
FIA = Financial Institutions Access
FID = Financial Institutions Depth
FIE = Financial Institutions Efficiency
FMOLS = Fully Modified Ordinary Least Squares
G7 = Great Seven
GMM = Generalized Methods of Moments
OECD = Organisation for Economic Co-operation and Development
PSCE = Panel-Specific Covariance Estimation

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