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Drivers of eco-efficiency and the criticality of environmental policy stringency in OECD countries

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ABSTRACT

Existing studies show that environmental policies can improve eco-efficiency, but their moderating effect has been ignored in the literature. In this study, we investigate how the multidimensional reality of environmental policy stringency influences the interplay between export diversification and eco-efficiency in the nine most economically diversified OECD (Organisation for Economic Co-operation and Development) economies. Adopting balanced panel data from 1995 to 2020, empirical results based on Method of Moments Quantile Regression indicate that environmental policy stringency and technological innovation improve the eco-efficiency of OECD countries. Export diversification, energy utilisation, and financial deepening, on the other hand, are found to have negative relationships with eco-efficiency in OECD countries. The results also indicate that the relationship between economic growth and eco-efficiency follows a U-type pattern, confirming the environmental Kuznets curve hypothesis. Furthermore, the marginal effect of export diversification on eco-efficiency increases as environmental policy stringency increases, suggesting that a simultaneous increase in export diversification and environmental policy stringency can improve eco-efficiency. The implication of these findings is that export diversification policies must be combined with more stringent environmental policies and programs to facilitate eco-efficiency and ecological sustainability.

1. Introduction

For both economic and environmental reasons, efficient use of the Earth's ecological resources is increasingly vital for present and future generations. It is critical that resources are used efficiently across the supply chain running from resource extraction to transport, manufacturing, consumption, recovery and disposal (Musah et al., 2024). Beyond enhancing human well-being through improving environmental sustainability, economic sustainability and other market-based benefits are also (in)directly linked with the use of Earth's resources through industries' competition for access to resources, stimulation of employment and innovation, and promotion of the secure supply of vital resources through resource recycling and recovery (European Environmental Agency, 2020). Importantly, according to the European Environmental Agency (2020), any quantification of resource efficiency primarily rests on identifying the extent and nature of input resources and the associated economic outputs. In particular, the efficient use of natural capital, i.e. biocapacity and its components, and critical material resources such as non-metallic minerals (including construction and industrial minerals), metals, biomass (including wood and food), and fossil energy sources, are of vital importance (Dai and Du, 2023).

According to Hickel (2020), traditional methods of calculating the Human Development Index (HDI) do not adequately consider ecological dimensions, despite the fact that natural capital is fundamental to comprehensively understanding the HDI. Given that the HDI conventionally accounts for life expectancy, education, and per capita income indicators, Hickel (2020) affirms that the relevance of economic indicators, for example per capita income, in the HDI should intuitively necessitate consideration of ecological indicators given that former is a

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vital driver of the latter. Hickel's interpretation provides direct justification of Dasgupta's (2007) findings regarding the quantification of the economy from the perspective of natural capital. However, several factors have been investigated as critical drivers of natural capital or ecological indicators (Wackernagel et al., 2002; Rosa et al., 2004; Vačkář, 2012; Hassan et al., 2019; Chen et al., 2020; Sarkodie, 2021). In particular, beyond macroeconomic indicators (including gross domestic product and sector-level value added), socioeconomic, energy-related and technological factors have been studies as critical influences on countries' ecological footprints (Dietz et al., 2007; Bekun et al., 2019; Alola et al., 2021; Espoir et al., 2024).

Meanwhile, literature documenting the drivers of ecological efficiency remains scarce. Thus, this study examines the drivers of ecological efficiency as measured by gross domestic product (GDP) per ecological footprint per capita. This is further considered with reference to the carbon component of ecological footprint, such that the investigation affords a more comprehensive and comparative understanding of the productive and "greenish" nature of the demand side of natural capital (Villanthenkodath et al., 2024; Espoir et al., 2024). Besides investigating indicators reflecting energy use, export diversification, technological innovation, and financial deepening, another vital objective of this study is to test the moderating capability of environmental policy stringency. In line with this objective, the study samples the top nine Organisation for Economic Co-operation and Development (OECD) countries in terms of economic diversification as measured by the Global Economic Diversification Index (GEDI, 2023). The choice to study OECD countries in particular is informed by the fact that about 33.7 percent of global greenhouse gas emissions from the energy sector in 2022 originated in OECD countries, which are mainly in Europe and North America.[1] These countries have diversified their economic activities, opened up to international trade, and increased government revenues (not including natural resources or commodity revenues). Concerns about CO_2 emissions have intensified due to the climate change crisis. In OECD countries, several environmental policy measures, including both market and non-market policy instruments, have been deployed to reduce the environmental consequences of energy-related emissions resulting from increased economic growth (Yıldız et al., 2024).

Given this background, the main research questions in this study include: How do export diversification and environmental policy stringency affect eco-efficiency in OECD countries? To what extent do variables such as technological innovation, energy utilisation, and financial deepening affect eco-efficiency in OECD countries? How does environmental policy stringency moderate the impact of export diversification on eco-efficiency in OECD countries? Is the environmental Kuznets curve hypothesis confirmed for OECD countries? Therefore, our study makes several important contributions to the literature. First, it provides a novel conception of how environmental policy stringency influences the effect of export diversification on eco-efficiency in the most economically diversified OECD countries. Prior empirical studies have mostly focused on the direct effect of either export diversification (Dai and Du, 2023; Fang and Fang, 2023; Ersin et al., 2024) or environmental policy stringency (Lee and Park, 2017; Wolde-Rufael and Mulat-Weldemeskel, 2023; Olasehinde-Williams and Akadiri, 2024), while the moderating effect has been ignored. Therefore, in this study we uncover the marginal effect of export diversification on eco-efficiency at different levels of environmental policy stringency. This helps to form an understanding of how simultaneous increases in export diversification and environmental policy stringency trigger an increase or a decrease in eco-efficiency. Second, our study uses two indicators of eco-efficiency, one of which considers all components of ecological efficiency and one of which only considers the carbon component. These indicators enable us to properly capture various aspects of eco-efficiency. Third, we use Method of Moments Quantile Regression which controls not only for distribution, but also cross-country unobserved heterogeneity. For the purpose of robustness, we employ an Ordinary Least Squares (OLS) approach with Driscoll-Kraay Standard Errors (RDK). This approach is generally robust to autocorrelation and cross-sectional dependence within the specified lags. These empirical approaches allow the results of our investigation to inform valuable recommendations for policy-related pathways towards advancing countries' green development and environmental sustainability.

To enhance ease of reading, this study is structured such that the study's theoretical framework and model specifications are presented in Section 2, while the empirical methods and data used are described in Section 3. The results are discussed in Section 4, and the conclusion, along with a discussion of the limitations of the study and policy recommendations based on its findings, is presented in Section 5.

2. Theoretical framework

This section justifies the selection of variables for this study. A twin indicator of eco-efficiency was adopted to synchronically capture both economic and ecological aspects of ecological sustainability (Atchike et al., 2024). Being broadly reflective of ecological sustainability, eco-efficiency is a sophisticated indicator that is difficult to ascertain. In this study, we define eco-efficiency as increased economic growth combined with reduced environmental degradation (Tamburino and Bravo, 2024). To accommodate economic growth and its ecologically damaging impacts, we opted to use an eco-efficiency indicator comprising all components of countries' ecological footprints, and an eco-efficiency indicator comprising only the carbon component. This is because considering the carbon component alone permits us to reveal how the diverse moderating impacts of environmental policy stringency can interact with export diversification. This allows us to postulate some policy propositions for decision-makers.

Export diversification is among the critical drivers of economic growth; its economic impact has been assessed in detail by existing studies. However, very few studies have examined the two divergent standpoints on the ecological impact of export diversification. First, export diversification is likely to decrease ecological deterioration by ameliorating energy use (Dai and Du, 2023). Export diversification enables countries to increase the number of partners they trade with, slicing up the production and emission of pollutants from fossil fuels (Ahmad and Satrovic, 2023a). Export diversification can also be expected to decrease ecological sustainability as the intention to diversify exports by initiating trade in new products can induce an incremental increase in anthropogenic emissions. Diversifying exports can cause expansion of the manufacturing sector of the exporting country, potentially intensifying the use of carbon-intensive machinery and thus significantly degrading ecological quality (Dalwai et al., 2024). Increased use of machinery can increase energy consumption and stoke the over-utilisation of natural resources, paving the way for fossil-fuel-based pollutant emissions (Ahmad and Satrovic, 2024). Second, export decentralization can also advance ecological sustainability by facilitating the use of modern low-carbon technologies (Fang and Fang, 2023). Low-carbon technologies also reduce energy intensity and pave the way for pollution reduction, advancing ecological quality. Also, due to the "learning by doing effect," total products may be upgraded to favour the technique effect over the scale effect, thereby accelerating eco-efficiency (Udeagha and Ngepah, 2023).

The implementation of environmental policies is specified as a primary determinant of eco-efficiency in the present study because it propagates energy efficiency and its attendant positive impacts on ecological sustainability (Ahmad and Satrovic, 2023b). However, positive shocks resulting from increasing the stringency of environmental policy may result in a hike in the level of CO_2 emissions, worsening eco-efficiency. There are thus two opposing strata of research assessing

[1] See https://globalenergyprize.org/en/2023/07/21/oecd-countries-provide-one-third-of-energy-sectors-greenhouse-gas-emissions/.

of the ecological impacts of environmental policy stringency. In the present study, the "stringency" of environmental policies refers to their effect on reducing pollution and helping countries to tackle ecological challenges (Albulescu et al., 2022; Liu et al., 2023). As such, the implementation of stricter environmental legislation is among a number of vital approaches to improving eco-efficiency and both developed and developing countries are considering the imposition of stricter environmental policies to address the disastrous impacts of ecological deterioration. In addition, countries with more rigorous environmental regulations may smoothen the implementation of green solutions by promoting renewable energy (Li et al., 2023; Dai and Du, 2023). To reduce ecological pressure, governments are implementing more rigorous environmental policies that aim to ensure eco-friendly consumption and production patterns. As their principal target is to deal with pressing concerns about ecological quality, environmental regulations are inflicted to relax negative effects on eco-efficiency by increasing research and development (R&D) budgets (Wolde-Rufael and Mulat-Weldemeskel, 2021). In summary, the imposition of more rigorous environmental policies can directly and indirectly contribute to resolving ecological concerns. Considering direct impacts, businesses punished for eco-unfriendly behaviour are encouraged to reduce their harmful environmental impacts by reducing anthropogenic greenhouse gas emissions. With regard to indirect impacts, the imposition of stricter environmental regulations induces a behavioural change leading toward greener production and consumption (Satrovic et al., 2024a). Second, the application of more stringent environmental policies increases manufacturing costs and may lower productivity by requiring businesses to put in place environmental protection equipment and adopt more rigorously eco-friendly manufacturing practices (Olasehinde-Williams and Akadiri, 2024). More rigorous environmental policies may thus imply higher burdens on firms and other economic agents, preventing future investments on their part. Countries with more rigorous environmental legislation relocate their polluting industries to developing countries and shift to manufacturing processes that emit less anthropogenic emissions within their own national borders, thus fostering the importation of emission-intensive items (Levinson, 2023; Sohag et al., 2024).

Alongside the pivotal role of environmental policy stringency in attempts to address ecological pressure, both developed and developing countries across the globe have recognized that technological innovation is vital to the achievement of eco-efficiency (Musah et al., 2024). Technological innovation is an effective tool for limiting ecological pressure. Pronounced technological innovation is likely to help capture anthropogenic emissions that have already been released into the atmosphere. Technological innovation is also beneficial in curtailing anthropogenic emissions from energy generation by augmenting energy efficiency or producing green energy to power ecological sustainability. As an effective mechanism for boosting energy efficiency, technological innovation is also critical in encouraging businesses to switch from carbon-intensive to net zero sectors. Fostering innovation and technological change has the specific objective of allowing the expansion of carbon-intensive industries while inflicting limitations that can switch worsening impacts on eco-efficiency to the beneficial ones (Villanthenkodath et al., 2024). As far as the innovation–ecological deterioration nexus is concerned, it is worth mentioning that business sectors and governments are investing in R&D to offer eco-friendly alternatives which may contribute to attaining the objectives of ecological sustainability (Chen et al., 2022a; Gao et al., 2023). Technological innovation fosters the implementation of green technology and thus serves as an effective mechanism for improving eco-efficiency. Environmental management can be induced by technological innovation, reducing the overconsumption of natural resources (Ullah et al., 2023; Bashir et al., 2023). On the demand side, technological innovation can provoke behavioural changes by helping individuals control their energy utilisationuse and minimize waste. As such, technological innovation is a vital approach to realizing ecological sustainability targets (Atchike et al., 2024). In recent studies, increases in R&D expenditure have been positively related to environmental quality. Usman (2023) revealed that an increase in expenditure on renewable R&D provides an avenue to the development of new technologies, and hence reduced CO_2 emissions in G7 countries. Similarly, Usman et al. (2024) found that investment in green energy technology, measured in terms of expenditure on R&D for renewable technologies, are associated with the dampening of energy security-related uncertainties in the United States. However, a study by Usman et al. (2024) found that the positive effect of R&D expenditure on renewable technologies only has significant effect on reducing negative environmental impacts when environmental degradation is measured by CO_2 emissions, rather than ecological footprint.

The environmental Kuznets curve (EKC) hypothesis is that increased economic activity curtails ecological quality in the initial stages of growth, while in the later stages of growth increased economic activity is associated ecological improvement, manifesting an inverted U-type pattern between economic activity and ecological deterioration (Hakkak et al., 2023; Musah et al., 2024; Satrovic et al., 2024b). The EKC hypothesis is substantiated if the coefficient between ecological deterioration with economic activity is positive and the coefficient with its squared term is negative. The authenticity of the EKC is based on the premise that increases in economic activity demand the use of more natural resources and represent increased pressure on ecological sustainability, but that economic activity in fact mitigates ecological deterioration at higher developmental levels (Chen et al., 2022b; Voumik and Rahi Dey, 2023). Anthropogenic emissions from burning non-renewable energy sources (such as coal and oil) represent a significant threat to the environment; hence energy utilisation is likely to impede the eco-efficiency of OECD economies. Financial deepening eases the interplay between investors and the business sector and hence supports economic activity. Furthermore, financial services are easily attainable and affordable, and thus attract investment in eco-friendly sectors and facilitate eco-efficiency. On the flip side, the growth of economic activity may induce further utilisation of natural resources, resulting in a loss of biodiversity and an increase in ecological deterioration. Moreover, there is mixed evidence on the ecological impact of financial deepening (Hussain et al., 2022; Li et al., 2023; Anu et al., 2023; Rehman et al., 2023).

3. Data description and empirical methods

3.1. Data description

The present study assesses the influence of environmental policy stringency (IMEP) on the relationship between export diversification and eco-efficiency from 1995 to 2020. Data availability for this period permitted a balanced panel as appropriate data on export diversification were first published in 1995 whereas data on IMEP are available for the 1995–2020 period. The nine most highly-ranked OECD countries in terms of economic diversification in 2021 were selected for investigation (GEDI, 2023). As an indicator of eco-efficiency, gross domestic product per capita (EPR) divided by ecological footprint measured in terms of the global hectares per capita (all components) was selected as a response variable. This measure captures the economic and ecological effects of various independent variables. To guarantee the robustness of our outcomes, we further introduced an alternative proxy for eco-efficiency, namely EPR divided by ecological footprint measured in terms of global hectares per capita (carbon component). These broad indicators of eco-efficiency were calculated by the authors based on data gathered from the Global Footprint Network (GFN, 2022). The independent variables include economic growth (gross domestic product per capita in constant 2015 US$; EPR), its squared term, energy utilisation (primary energy consumption in millions of tonnes of oil equivalent; UTE), technological innovation (gross domestic spending on research and development; GRD), the export diversification index (EXDI), the environmental policy stringency index (IMEP); and twin features of financial deepening (FD), namely the financial development index (FDL) and the financial markets index (FMA). Table 1 presents the studied variables and highlights the measurement unit for each variable. A detailed statistical profile of the studied variables by country is provided in Table 2.

As Table 2 shows, average eco-efficiency (comprising all ecological footprint components) was 5295.57 constant 2015 US$/global hectare for Belgium, 6847.22 for Germany, 9067.18 for Ireland, 6383.97 for Italy, 6832.32 for Japan, 6999.34 for the Netherlands, 8276.40 for the United Kingdom, and 5876.88 for the United States in the studied period. The average for the whole sample was 5876.88 (Table 3). The average across the whole sample for the alternative proxy for eco-efficiency (capturing only the carbon component of ecological footprint) was 10974.46 constant 2015 US$/global hectare (Table 3). Table 2 shows that the minimum average value across the studied period was reported for the United States, whereas Ireland scored highest for CEC. Average economic growth across the sample was 40,206.67 per capita (constant 2015 US$), with the highest mean value recorded for the United States and the lowest for Italy (Table 3). As for technological innovation, the maximum mean value was recorded for Japan, and the minimum mean value is for Italy. Ireland scored highest for average export diversification (EXDI) across the studied period, while the United States scored lowest. Japan had the highest average score for environmental policy stringency, whereas the United States had the lowest. Table 3 provides summary statistics and a correlation matrix for the entire sample.

Economic growth had the highest standard deviation, and the financial development index (as a proxy for financial deepening) had the lowest. The kurtosis and skewness coefficients show that our panel data diverge from a normal distribution: only the financial deepening and IMEP indicators exhibit negative skewness whereas all other variables are positively skewed. Table 3 lists the correlation coefficients between the variables. The information presented in Table 3 highlights the statistically significant and positive relationships between eco-efficiency (comprising all components of ecological footprint) and economic growth, export diversification, environmental policy stringency, and proxies for financial deepening. The data also show a negative statistically significant correlation between TEC and energy utilisation and a statistically insignificant negative correlation between TEC and technological innovation. Finally, the data in Table 3 demonstrate that EPR, UTE, GRD, EXDI, and IMEP are moderately correlated with eco-efficiency (comprising only the carbon component of ecological footprint).

Table 1
Delineation of the examined variables.

Delineation	Label	Source
Economic growth – gross domestic product - GDP per capita (constant 2015 US$)	EPR	WB (2023)
Energy usage – primary energy consumption, million tonnes of oil equivalent	UTE	BP (2023)
Technological innovation – gross domestic spending on research and development - R&D	GRD	OECD (2023)
Export diversification index	EXDI	UNCTAD (2023)
Implementation of environmental policies – environmental policy stringency index	IMEP	OECD (2022)
Financial deepening 1 – financial development index	FDL	IMF (2022)
Financial deepening 2 – financial markets index	FMA	IMF (2022)
Ecological efficiency (all components) – EPR/ecological footprint per capita (constant 2015 US$/global hectare)	TEC	GFN (2022)
Ecological efficiency (carbon component) – EPR/carbon footprint per capita (constant 2015 US$/global hectare)	CEC	GFN (2022)

3.2. Empirical methods

In the light of the above-described theoretical mechanisms, our study determines baseline models that evaluate the direct interplay between associated variables and eco-efficiency. Notably, Eq. (1) specifies the following framework:

$$EE_{it} = f\left(EPR_{it}, EPR^2{}_{it}, UTE_{it}, GRD_{it}, EXDI_{it}, IMEP_{it}, FD_{it}\right) \tag{1}$$

Where *EE* denotes the dependent variables measured by twin facets of eco-efficiency, which comprise all components of ecological footprint (TEC) and only the carbon component of ecological footprint (CEC). *EPR* and EPR^2 are economic growth and its squared term, *UTE* is energy usage, *GRD* represent technological innovation, *IMEP* is the environmental policy stringency index, *EXDI* is the export diversification index, *FD* depicts financial deepening, $i = 1, 2, \ldots, N$ denotes country and $t = 1, 2, \ldots, T$ denotes time. To address the heteroscedasticity concern, and provide panel data that coincide with the assumption of normality, the natural logarithm of each variable is calculated. Eq. (2) sets up the following log-linear expression of Eq. (1):

$$LEE_{it} = \omega_0 + \omega_1 LEPR_{it} + \omega_2 EPR^2{}_{it} + \omega_3 LUTE_{it} + \omega_4 LGRD_{it} + \omega_5 LEXDI_{it} + \omega_6 LIMEP_{it} + \omega_7 LFD_{it} + \varepsilon_{it} \tag{2}$$

In Eq. (2), the predicted elasticities of the drivers $\left(EPR, EPR^2, UTE, GRD, EXDI, IMEP, FD\right)$ of eco-efficiency in OECD economies are denoted as $\omega_1 - \omega_7$, while ω_0 serves as an intercept. L signifies the natural logarithm. To measure financial deepening, this study incorporates two indicators, namely financial development index (FDL) and financial markets index (FMA). ε_{it} signifies the error term.

Despite the fact that eco-efficiency is a holistic approach to measuring ecological sustainability, studies to date have overlooked the assessment of its determinants. To fill this void, the present study accommodates a twin measure of eco-efficiency. Given that eco-efficiency refers to the ratio of EPR to ecological footprint (all components/carbon component), it embraces the joint assessment of both economic and ecological impacts as posited by several previous studies (Wang et al., 2023; Apostu et al., 2023; Sun and Sui, 2023; Zheng et al., 2022). These prior studies yield intuitions about the anticipated signs of assessed regression parameters. In particular, several prior studies (Chen et al., 2022b; Voumik and Rahi Dey, 2023; Hakkak et al., 2023; Musah et al., 2024) have highlighted the non-linear interplay between income and ecological deterioration. These studies support an inverted U-shaped pattern for their selected samples of countries. The theoretical formulation of EKC is assumed to follow an inverted U-shaped pattern, signalling that at the introductory stages of economic emancipation countries usually favour GDP growth over ecological protection – entailing a hike in ecological pressure. At the advanced stages of economic emancipation, countries maintain ecological quality as a top priority, resulting in increased ecological sustainability. Given the fact that OECD countries intensively develop on the design and implementation of policies to tackle ecological concerns, we expect that EPR reduces eco-efficiency in the introductory stages of the developmental process but acts to ensure improvements in eco-efficiency in the later stages of development, predicting the following signs of elasticities: $\frac{\partial LEE_{it}}{\partial LEPR_{it}} < 0$ and $\frac{\partial LEE_{it}}{\partial LEPR2_{it}} > 0$). Empirical evidence on the interplay between export diversification and eco-efficiency has been deficient in previous studies, which have yielded inconclusive findings on the ecological impact of the export diversification index (EXDI). In particular, one stratum of research elucidates that export diversification increases environmental deterioration (Wang et al., 2020; Zhang et al., 2022; Saleem et al., 2022; Udeagha and Ngepah, 2023). On the flip side, export diversification has been found to assist in the transformation towards eco-friendly technologies (Shahzad et al., 2020; Magazzino et al., 2022; Dai and Du, 2023; Fang and Fang, 2023; Satrovic et al., 2024a). Export

Table 2
Illustration of summary statistics (by country).

Country	Stat.	TEC	EPR	UTE	GRD	EXDI	IMEP	FDL	FMA	CEC
Belgium	Mean	5295.57	38209.22	62.17	2.16	0.37	2.31	0.63	0.45	8467.37
	Stad. dev.	683.82	3334.81	3.01	0.45	0.03	0.77	0.07	0.10	1322.72
	Max	6481.58	43107.20	66.64	3.35	0.42	3.44	0.73	0.63	11912.05
	Min	4298.53	31329.90	55.89	1.65	0.33	1.11	0.47	0.22	6668.81
	Skewness	0.197	−0.674	−0.542	1.271	0.350	−0.464	−0.912	−0.501	0.722
	Kurtosis	1.782	2.376	2.439	3.784	2.105	1.693	3.246	2.972	2.882
France	Mean	6847.22	34968.98	253.46	2.16	0.30	3.08	0.73	0.64	12102.84
	Stad. dev.	937.58	2397.54	15.15	0.08	0.04	1.17	0.09	0.12	1970.53
	Max	8654.02	38832.00	272.76	2.30	0.35	4.89	0.83	0.78	17252.22
	Min	5569.07	29745.10	211.14	2.02	0.24	1.39	0.51	0.32	10016.06
	Skewness	0.433	−0.756	−0.772	−0.211	−0.299	−0.188	−1.049	−1.402	1.169
	Kurtosis	2.055	2.867	3.326	2.065	1.592	1.600	3.014	4.204	3.396
Germany	Mean	7139.39	37411.25	334.35	2.63	0.30	2.64	0.72	0.71	10919.15
	Stad. dev.	1229.94	3700.25	13.34	0.32	0.02	0.68	0.05	0.11	2278.35
	Max	9641.30	43284.60	353.01	3.17	0.35	3.47	0.78	0.81	16727.07
	Min	5370.45	31628.20	296.41	2.14	0.26	1.44	0.52	0.27	7772.26
	Skewness	0.500	0.052	−0.878	0.120	0.486	−0.794	−2.214	−3.002	0.778
	Kurtosis	2.224	1.700	3.531	1.807	2.385	2.002	8.763	12.330	3.019
Ireland	Mean	9067.18	49813.40	14.95	1.28	0.63	2.05	0.72	0.59	15611.18
	Stad. dev.	3392.16	13082.11	1.40	0.18	0.05	0.78	0.05	0.07	7098.33
	Max	18346.75	79074.50	16.96	1.61	0.70	3.00	0.82	0.75	35144.22
	Min	4574.91	28309.80	11.46	1.05	0.55	0.53	0.64	0.47	7446.74
	Skewness	0.991	0.639	−0.850	0.814	−0.472	−0.646	0.443	0.732	1.089
	Kurtosis	3.581	2.919	3.299	2.300	1.899	1.854	2.059	3.306	3.551
Italy	Mean	6383.97	31633.93	170.57	1.17	0.37	2.81	0.72	0.69	10518.09
	Stad. dev.	696.97	1433.36	12.79	0.17	0.01	1.01	0.09	0.13	1676.69
	Max	7729.84	34081.10	189.17	1.51	0.38	4.06	0.79	0.81	15378.74
	Min	5672.16	29265.10	142.11	0.93	0.35	1.33	0.48	0.34	9017.08
	Skewness	0.638	−0.021	−0.294	0.364	−0.367	−0.195	−1.959	−1.822	1.423
	Kurtosis	1.848	1.832	2.206	1.883	1.947	1.387	5.513	5.138	4.356
Japan	Mean	6832.32	33052.72	498.60	3.07	0.40	3.09	0.78	0.67	9388.11
	Stad. dev.	939.70	1788.28	38.57	0.22	0.02	0.68	0.10	0.15	1133.31
	Max	9011.28	36138.50	538.60	3.37	0.46	4.06	0.93	0.87	12628.94
	Min	5359.87	30171.20	409.62	2.56	0.37	1.75	0.57	0.31	7799.86
	Skewness	0.455	0.172	−0.610	−0.794	0.431	−0.390	−0.600	−0.952	1.118
	Kurtosis	2.561	1.882	2.071	2.606	2.422	2.190	2.475	2.903	4.122
Netherlands	Mean	6999.34	42669.52	90.40	1.90	0.34	2.58	0.78	0.72	10769.20
	Stad. dev.	970.57	3935.67	4.08	0.20	0.02	0.85	0.05	0.11	2046.82
	Max	9170.34	48443.70	100.55	2.32	0.37	3.75	0.87	0.85	15471.14
	Min	5453.49	33696.70	83.83	1.62	0.31	1.39	0.66	0.36	8514.47
	Skewness	0.797	−0.763	0.473	0.611	0.058	−0.299	−0.226	−2.008	1.046
	Kurtosis	2.878	2.787	2.649	1.952	2.311	1.391	2.087	6.994	2.901
United Kingdom	Mean	8276.40	41834.61	213.28	1.84	0.28	2.43	0.85	0.79	12834.64
	Stad. dev.	1897.96	3719.42	17.69	0.43	0.04	1.02	0.06	0.11	3633.87
	Max	12271.73	47491.60	233.35	2.93	0.35	3.86	0.96	0.93	21589.03
	Min	6104.08	33759.70	169.58	1.53	0.23	1.00	0.69	0.48	9369.05
	Skewness	0.849	−0.657	−0.657	1.348	0.029	−0.207	−0.955	−1.523	1.160
	Kurtosis	2.387	2.706	2.380	3.321	1.382	1.564	3.802	4.551	3.144
United States	Mean	5876.88	52266.39	2229.73	2.70	0.26	1.89	0.89	0.89	8159.59
	Stad. dev.	1187.94	5080.79	61.64	0.24	0.01	0.71	0.04	0.04	1979.44
	Max	8279.26	60698.00	2327.08	3.47	0.28	3.03	0.92	0.93	13224.34
	Min	4299.23	41820.70	2093.01	2.41	0.23	1.08	0.75	0.71	5823.67
	Skewness	0.323	−0.393	−0.368	1.539	−0.442	0.329	−2.141	−2.738	0.819
	Kurtosis	1.883	2.404	2.483	5.524	2.722	1.584	6.924	10.933	2.958

diversification can thus be seen as a primary factor in harming ecological sustainability or boosting the eco-efficiency of OECD countries (i.e. $\frac{\partial LEE_{it}}{\partial LEXDI_{it}} < 0$ or $\frac{\partial LEE_{it}}{\partial LEXDI_{it}} > 0$).

In terms of the ecological impact of environmental policy stringency, previous studies have also offered ambiguous conclusions, such that Albulescu et al. (2022), Liu et al. (2023), Li et al. (2023) and Dai and Du (2023) endorse a positive effect of environmental policy stringency on eco-efficiency, whereas Wolde-Rufael and Mulat-Weldemeskel (2021) suggest that more rigorous environmental regulations curtail the eco-efficiency of emerging countries in the preliminary stages of growth. Based on such previous findings, environmental policy stringency may improve or harm the eco-efficiency of OECD countries (i.e. $\frac{\partial LEE_{it}}{\partial LIMEP_{it}} < 0$ or $\frac{\partial LEE_{it}}{\partial LIMEP_{it}} > 0$). Technological innovation plays a central role in the eco-efficiency of many countries. By upholding energy efficiency and fostering the development of net zero sectors, technological innovation is likely to boost the eco-efficiency of OECD countries (i.e. $\frac{\partial LEE_{it}}{\partial LGRD_{it}} > 0$) as affirmed by Chen et al., (2022a), Gao et al. (2023), Ullah et al. (2023), and Atchike et al. (2024). Energy utilisation is among the critical determinants of environmental degradation, posing a severe threat to the environment, and as such is expected to reduce the eco-efficiency of OECD countries (i.e. $\frac{\partial LEE_{it}}{\partial LUTE_{it}} < 0$) as several studies have claimed (Bashir et al., 2023; Sun et al., 2023a; Sun et al., 2023b; Satrovic et al., 2024b). Studies to date have also provided mixed findings on the ecological impact of financial deepening, claiming that it may increase ecological quality (i.e. $\frac{\partial LEE_{it}}{\partial LFD_{it}} > 0$) or curtail eco-efficiency (i.e. $\frac{\partial LEE_{it}}{\partial LFD_{it}} < 0$). The beneficial ecological impact of financial deepening aligns with Hussain et al. (2022) and Li et al. (2023), whereas Zhang et al. (2022), and Rehman et al. (2023) have described financial deepening as worsening eco-efficiency.

Equation (2) can be augmented to integrate the indirect impact of

Table 3
Illustration of summary statistics and correlation matrix (entire sample).

Stat./Var.	TEC	EPR	UTE	GRD	EXDI	IMEP	FDL	FMA	CEC
Mean	6968.7	40206.67	429.72	2.1	0.36	2.54	0.76	0.68	10974.46
Stad. dev.	1870.87	8597.19	653.5	0.66	0.11	0.94	0.1	0.16	3757.08
Max	18346.75	79074.5	2327.08	3.47	0.7	4.89	0.96	0.93	35144.22
Min	4298.53	28309.8	11.46	0.93	0.23	0.53	0.47	0.22	5823.67
Skewness	2.155	1.43	2.267	0.088	1.63	−0.053	−0.393	−0.695	2.585
Kurtosis	10.904	5.892	6.536	2.009	5.229	2.057	2.953	2.877	13.283
TEC	1								
EPR	0.568[a]	1							
	0.000								
UTE	−0.225[a]	0.401[a]	1						
	0.001	**0.000**							
GRD	−0.025	0.036	0.452[a]	1					
	0.702	**0.587**	**0.000**						
EXDI	0.428[a]	0.239[a]	−0.407[a]	−0.361[a]	1				
	0.000	**0.000**	**0.000**	**0.000**					
IMEP	0.483[a]	0.030	−0.194[a]	0.304[a]	0.058	1			
	0.000	**0.645**	**0.003**	**0.000**	**0.375**				
FDL	0.148[b]	0.342[a]	0.500[a]	0.249[a]	−0.258[a]	0.242[a]	1		
	0.023	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**			
FMA	0.230[a]	0.355[a]	0.491[a]	0.248[a]	−0.329[a]	0.298[a]	0.912[a]	1	
	0.000	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**		
CEC	0.961[a]	0.514[a]	−0.307[a]	−0.147[b]	0.457[a]	0.443[a]	−0.010	0.093	1
	0.000	**0.000**	**0.000**	**0.025**	**0.000**	**0.000**	**0.879**	**0.155**	

Note: p values in bold, a – p > 0.01; b – p > 0.05; c – p > 0.10.

export diversification via the channel of environmental policy stringency. Equation (3) is estimated with the moderation of LIMEP and LEXDI as follows:

$$LEE_{it} = \omega_0 + \omega_1 LEPR_{it} + \omega_2 LEPR^2{}_{it} + \omega_3 LUTE_{it} + \omega_4 LGRD_{it} + \omega_5 LEXDI_{it} + \omega_6 L\,Mod_{it} + \omega_7 LFD_{it} + \varepsilon_{it} \tag{3}$$

In Equation (3), *Mod* depicts the interaction term of export diversification and environmental policy stringency. It is expected that the enforcement of stricter environmental policies enables economies to enlarge their export baskets by manufacturing green products to impose improved eco-efficiency (i.e. $\frac{\partial LEE_{it}}{\partial (LIMEP_{it} * LEXDI_{it})} > 0$), as asserted by Liu et al. (2023).

Given the unique features of panel data, the assessment of cross-sectional dependence (DPNCS) and slope heterogeneity (HTRS) precedes the estimation of the regression parameters to avoid biased outcomes. To achieve this, our study makes use of the DPNCS test devised by Pesaran (2021) to circumvent the cross-sectional dependency dilemma. The mathematical formula for the DPNCS test is shown in Eq. (4):

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij} \right) \tag{4}$$

Such that T signifies the selected timeframe, N stands for the OECD economies, and $\widehat{\rho}_{ij}$ refers to the correlation. Notably, $\widehat{\rho}_{ij}$ is defined in Eq. (5):

$$\widehat{\rho}_{ij} = \widehat{\rho}_{ji} = \frac{\sum_{t=1}^{T} \varepsilon_{it}\varepsilon_{jt}}{\left(\sum_{t=1}^{T} \varepsilon_{it}^2 \right)^{\frac{1}{2}} \left(\sum_{t=1}^{T} \varepsilon_{jt}^2 \right)^{\frac{1}{2}}} \tag{5}$$

Under the null hypothesis, there is no cross-sectional dependence in the sample of OECD economies, whereas H_1 assumes that the selected panel data are subject to DPNCS concerns. To unveil the potential heterogeneous behaviour of the slope coefficients, the present study employs Pesaran and Yamagata's (2008) HTRS test based on the following expressions (Eqs. (6) and (7)):

$$\widehat{\Delta}_{HTRS} = \sqrt{N} \bullet \sqrt{2k} \bullet \left(N^{-1} \bullet \widehat{S} - k \right) \tag{6}$$

$$\widehat{\widehat{\Delta}}_{HTRS} = \sqrt{N} \bullet \left(\frac{2k \bullet (T-k-1)}{T+1} \right)^{\frac{-1}{2}} \bullet \left(N^{-1} \bullet \widehat{S} - 2k \right) \tag{7}$$

In the aforementioned equations, $\widehat{\Delta}_{HTRS}$ depicts HTRS whereas $\widehat{\widehat{\Delta}}_{HTRS}$ refers to the adjusted HTRS test. The null hypothesis is that the behaviour of slope coefficients is homogeneous, whereas the alternative hypothesis is that HTRS concerns are persistent. To accommodate DPNCS and HTRS concerns while assessing the stationary properties of the variables, our study prioritizes a second-generation unit root test, namely the Im, Pesaran and Shin test (CIPS) devised by Pesaran (2007), over first-generation tests that might perform poorly if these concerns are present. The mathematical expression of the CIPS test statistics is set out in Eq. (8):

$$CIPS = N^{-1} \sum_{i=1}^{n} CADF \tag{8}$$

Such that CADF depicts the Cross-sectional Augmented Dickey-Fuller (CADF) statistic expressed as (Eq. (9)):

$$\Delta Y_{it} = \rho_i + \rho_i Y_{-1} + \rho_i X_{t-1} + \rho_i T + \sum_{j=1}^{n} \rho_{ij} \Delta Y_{-j} + \theta_{it} \tag{9}$$

In Eq. (9), Y_{it} symbolizes the selected panel data, Δ is the first difference and θ_{it} stands for the error term. To assess the long-run connection between selected variables, this study builds upon the Westerlund (2005) cointegration assessment where no cointegration (COIN) is declared under H_0, while the alternative hypothesis declares the presence of COIN interplay between selected variables. Unlike traditional panel data estimators that do not accommodate DPNCS and HTRS concerns and are likely to present inconsistent empirical findings in the case of outliers and heavy-tailed data, the novel Method of Moments Quantile Regression (QREG) approach of Machado and Silva (2019) accommodates these concerns. Another important feature of the QREG technique is that it analyses the heterogeneous effect of each independent variable on the conditional quantiles of eco-efficiency. This method performs better than traditional mean-based estimators, which only examine the mean effects of independent variables on eco-efficiency (Balcilar et al., 2023; Usman, 2023). In addition, it is worth mentioning that QREG deals with concerns relating to outliers and does not necessitate the fulfilment of distributional premises. The specification of the QREG technique can be posited as (Eq. (10)):

$$Q_{Y_{it}}(\tau \vee X_{it}) = \alpha(\tau)' X_{it} + \beta_i, i = 1, \ldots, N, t = 1, \ldots, T \tag{10}$$

Such that Y_{it} signifies twin proxies for eco-efficiency, X_{it} depicts $LEPR, LEPR^2, LUTE, LGRD, LEXDI, LIMEP, LFD$, $\alpha(\tau)$ are unknown parameters, and β_i stands for the individual effects. In this study Model 1 is specified as Eq. (11); Model 2 as Eq. (12); Model 3 as Eq. (13); and Model 4 as Eq. (14):

$$Q_{LTEC}(\tau \vee X_{it}) = a_{1\tau}LEPR_{it} + a_{2\tau}LEPR^2{}_{it} + a_{3\tau}LUTE_{it} + a_{4\tau}LGRD_{it} + a_{5\tau}LEXDI_{it} + a_{6\tau}LIMEP_{it} + a_{7\tau}LFDL_{it} + \beta_i \tag{11}$$

$$Q_{LTEC}(\tau \vee X_{it}) = a_{1\tau}LEPR_{it} + a_{2\tau}LEPR^2{}_{it} + a_{3\tau}LUTE_{it} + a_{4\tau}LGRD_{it} + a_{5\tau}LEXDI_{it} + a_{6\tau}LIMEP_{it} + a_{7\tau}LFDM_{it} + \beta_i \tag{12}$$

$$Q_{LTEC}(\tau \vee X_{it}) = a_{1\tau}LEPR_{it} + a_{2\tau}LEPR^2{}_{it} + a_{3\tau}LUTE_{it} + a_{4\tau}LGRD_{it} + a_{5\tau}LEXDI_{it} + a_{6\tau}LMod_{it} + a_{7\tau}LFDL + \beta_i \tag{13}$$

$$Q_{LTEC}(\tau \vee X_{it}) = a_{1\tau}LEPR_{it} + a_{2\tau}LEPR^2{}_{it} + a_{3\tau}LUTE_{it} + a_{4\tau}LGRD_{it} + a_{5\tau}LEXDI_{it} + a_{6\tau}LMod_{it} + a_{7\tau}LFDM_{it} + \beta_i \tag{14}$$

Based on Eqs. 11–14, Mod = $LIMEP \times LXEDI$. In order to obtain robust outcomes, this study opts for an alternative estimator – namely the Driscoll-Kraay estimator (RDK) – and re-evaluates our baseline models. This approach is robust to autocorrelation and cross-sectional dependence, as demonstrated by Balcilar et al. (2023) and Usman (2023). In addition, the fitness of our findings is further judged by incorporating an alternative proxy for eco-efficiency. The adjusted model specifications are expressed below in Eqs. (15)–(18):

$$Q_{LCEC}(\tau \vee X_{it}) = a_{1\tau}LEPR_{it} + a_{2\tau}LEPR^2{}_{it} + a_{3\tau}LUTE_{it} + a_{4\tau}LGRD_{it} + a_{5\tau}LEXDI_{it} + a_{6\tau}LIMEP_{it} + a_{7\tau}LFDL_{it} + \beta_i \tag{15}$$

$$Q_{LCEC}(\tau \vee X_{it}) = a_{1\tau}LEPR_{it} + a_{2\tau}LEPR^2{}_{it} + a_{3\tau}LUTE_{it} + a_{4\tau}LGRD_{it} + a_{5\tau}LEXDI_{it} + a_{6\tau}LIMEP_{it} + a_{7\tau}LFDM_{it} + \beta_i \tag{16}$$

$$Q_{LCEC}(\tau \vee X_{it}) = a_{1\tau}LEPR_{it} + a_{2\tau}LEPR^2{}_{it} + a_{3\tau}LUTE_{it} + a_{4\tau}LGRD_{it} + a_{5\tau}LEXDI_{it} + a_{6\tau}LMod_{it} + a_{7\tau}LFDL_{it} + \beta_i \tag{17}$$

$$Q_{LCEC}(\tau \vee X_{it}) = a_{1\tau}LEPR_{it} + a_{2\tau}LEPR^2{}_{it} + a_{3\tau}LUTE_{it} + a_{4\tau}LGRD_{it} + a_{5\tau}LEXDI_{it} + a_{6\tau}LMod_{it} + a_{7\tau}LFDM_{it} + \beta_i \tag{18}$$

Where L $CEC = \frac{LEPR}{L\ ecological\ footprint\ global\ hectare\ per\ capita\ (carboncomponent)}$. Therefore, Fig. 1 clearly demonstrates the theoretical framework for this study.

4. Empirical results and discussion

4.1. Preliminary results

Slope homogeneity results are displayed in Table 4. Assessment of the interplay between the selected variables indicates that the null hypothesis of no slope heterogeneity (HTRS) is rejected at the 1% significance level. Thus, the assumption of slope homogeneity is rejected in favour of slope heterogeneity.

The data in Table 4 demonstrate that the slope parameters are heterogeneous for the selected OECD countries. Pursuant to the significance of delta and adjusted delta test statistics, the assumption of slope homogeneity is rejected, suggesting that the selected models encounter HTRS. OECD countries are subject to dynamic macro-economic changes, and these are likely to have a prominent impact on eco-efficiency; in turn, this leads to heterogeneous slope parameters. Table 5 presents the outcomes of cross-sectional dependence (DPNCS) and unit-root tests.

To avoid inconsistency in our findings, we used the Pesaran (2021) test to check our panel data for cross-sectional dependence. As Table 5 shows, all our variables are subject to DPNCS concerns: H_0 (no DPNCS) is strongly rejected with p values less than 1%. These findings suggest that eco-efficiency, economic growth, energy utilisation, technological innovation, export diversification, the implementation of environmental policies, and financial deepening are cross-sectionally dependent. Given the strong interconnectedness between OECD economies, any instability in environmental legislation or other explanatory variables in one sample economy might provoke repercussions in other sample economies. Keeping in mind that our sample is subject to both DPNCS and HTRS, it was necessary to inspect stationary properties by using second-generation unit root tests. A synopsis of CIPS test is provided in Table 5, showing that all first differences are stationary. From the results shown in Tables 5 and it is clear that LEPR, LEPR2, LUTE, LGRD, LEXDI, LIMEP, LFDL, LFMA, LTEC, and LCEC are I (1). This prompted us to assess cointegration relationships between the variables, as depicted in Table 6.

The data in Table 6 confirm long-run association between the selected variables. Based on the outcome of Westerlund's (2005) cointegration test, it can be concluded that the assumption of no cointegration is rejected at a 10% significance level. This means that economic growth, energy utilisation, technological innovation, export diversification, environmental policy stringency and financial deepening, as determinants of eco-efficiency, changed in conjunction over the long run during the 1995 to 2020 period. Establishing the long-run interplay between selected variables allowed us to estimate the regression parameters. The outcomes of the QREG and RDK techniques are detailed in Table 7 (odd quantiles) and Fig. 2 (even quantiles).

4.2. Coefficient estimations

The positive coefficient derived for environmental policy stringency shows that more stringent environmental policies provoke an upswing in eco-efficiency. The results of models without moderation (Models 1 and 2) unveil highly significant coefficients of LIMEP for the sample of nine OECD member countries. The coefficient derived for LIMEP suggests it has a positive effect on eco-efficiency, with stronger environmental policies resulting in improved eco-efficiency during the 1995 to 2020 period. These results suggest that increasing the cost of environmentally unfriendly behaviour may have positive effects on the environment. More stringent environmental legislation which aims to reduce pollution is shown to be critical to preventing the deterioration of eco-efficiency. Furthermore, countries that strengthen their environmental policies are also likely to reduce the cost of the energy transition by subsidizing research and development, and more stringent environmental policies also target the reduction of production- and consumption-based anthropogenic emissions to curtail their adverse eco-efficient impacts. This finding is similarly to that of Albulescu et al. (2022), who revealed that increased environmental policy stringency reduces CO_2 emissions and has a pronounced effect on improving environmental quality in European Union countries. Environmental policy stringency clearly plays an important role in increasing energy efficiency, which is vital for a more sustainable future. Our findings are also in harmony with those of Liu et al. (2023), who found that environmental policy stringency helps to curtail the carbon dioxide emissions of emerging economies. The present study demonstrates that more stringent environmental legislation leads to greater environmental quality, and hence contributes to environmental health. Our finding is also corroborated by Li et al. (2023), who draw attention to the beneficial environmental impact of environmental policy stringency in emerging economies by unveiling its significant impact in curtailing greenhouse gas emissions. The present study's findings highlight the fact that stringent environmental policies pave the way for improved eco-efficiency by contributing to the development of net zero technologies and increasing environmental standards. Similarly, Dai and Du

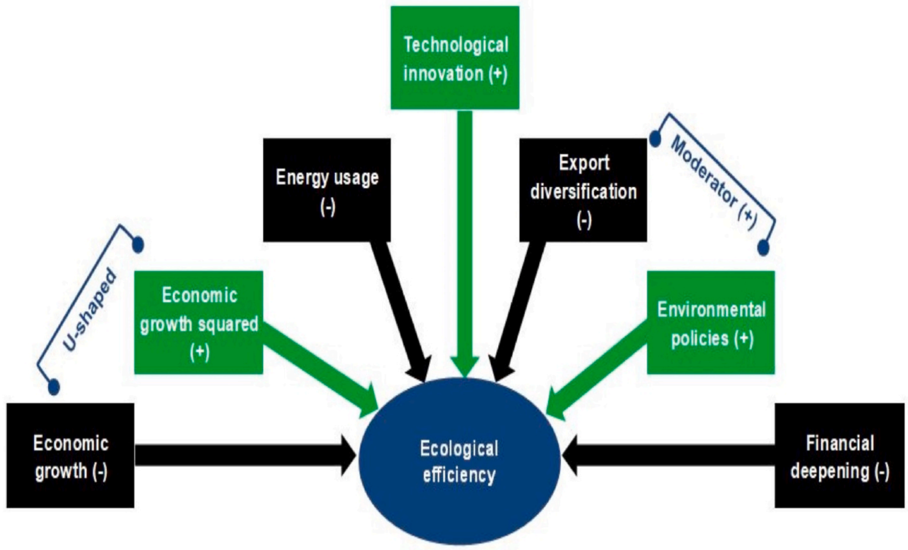

Fig. 1. Theoretical framework.

Table 4
Slope homogeneity assessment.

Stat./Model	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)	Model (8)
Δ	6.128a	6.168a	6.128a	6.168a	6.273a	6.105a	6.273a	6.105a
	0.000	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
Δ adj.	7.578a	7.628a	7.578a	7.628a	7.758a	7.550a	7.758a	7.550a
	0.000	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**

Note: p values in bold, a – p > 0.01; b – p > 0.05; c – p > 0.10; Δ – delta statistic, and Δ adj. – adjusted delta statistic.

(2023) found a negative impact of environmental policy stringency on ecological footprint, suggesting that more stringent environmental policies contribute to improving environmental quality in emerging economies.

Export diversification decreases eco-efficiency in OECD countries, as shown by a negative regression parameter. Table 7 and Fig. 2 outline this effect, showing that it is statistically significant for the middle and upper-middle quantiles. This statistically significant effect was found in models without interactive terms (Models 1 and 2) from quantiles 0.4 to 0.9, highlighting that export diversification is associated with lower eco-efficiency in the selected OECD members. As such, it may be concluded that export diversification does not pave the way for ecological sustainability and climate change mitigation. This may be because export diversification intensifies manufacturing and the overconsumption of natural resources, leading to an upswing in pollutant emissions. To increase their competitiveness in foreign markets, countries may be willing to diversify their exports by introducing new energy-intensive exports that lead to environmental pollution. In addition, the use of carbon-intensive machinery to produce certain exports might reduce eco-efficiency. Our results therefore align with those of Wang et al. (2020), who posited that export diversification increases the carbon dioxide emissions of developed countries. As such, export diversification is among the strongest determinants of environmental degradation; this calls for the urgent implementation of stricter environmental policies to tackle the detrimental environmental impact of export diversification. Similarly, Zhang et al. (2022) found that export diversification increased the level of environmental degradation in countries with high pollutant emissions. This is because export diversification intensifies energy use, causing an upswing in pollutant emissions. The findings of the present study can thus be corroborated with those of prior research, and suggest that initiatives should be undertaken to introduce modern low-carbon technologies and increase the use of renewable energy sources. Udeagha and Ngepah (2023) also confirmed that export diversification is not a feasible solution for reducing environmental degradation in emerging economies, finding a positive correlation coefficient between export diversification and environmental concerns for the 1970 to 2020 period.

Technological innovation increased the eco-efficiency of the selected OECD countries in the studied period. The empirical findings displayed in Table 7 and Fig. 2 show that the coefficients of correlation between technological innovation and eco-efficiency are statistically significant

Table 5
Assessment of cross-sectional dependence and unit root.

Var./Test	DPNCS		CIPS (intercept & trend)	
	Stat.	p value	Level	First diff.
LEPR	23.69a	**0.000**	−1.000	−3.365a
$LEPR^2$	23.65a	**0.000**	−0.955	−3.373a
LUTE	16.02a	**0.000**	−2.862b	−4.779a
LGRD	18.22a	**0.000**	−2.227	−3.545a
LEXDI	5.41a	**0.000**	−3.396a	−5.560a
LIMEP	28.18a	**0.000**	−3.554a	−5.508a
LFDL	17.11a	**0.000**	−3.474a	−5.628a
LFMA	20.73a	**0.000**	−3.793a	−5.892a
LTEC	28.33a	**0.000**	−2.359	−4.757a
LCEC	27.96a	**0.000**	−2.178	−4.764a

Note: p values in bold, a – p > 0.01; b – p > 0.05; c – p > 0.10.

Table 6
Outcomes of cointegration assessment.

Test/Model	Model (1)	Model (2)	Model (5)	Model (6)
Westerlund's (2005) test result	−1.306c **0.096**	−1.333c **0.091**	−1.400c **0.081**	−1.361c **0.087**

Note: p values in bold, a – p > 0.01; b – p > 0.05; c – p > 0.10.

Table 7
Elasticity assessment (RDK and QREG, LTEC- dependent variable).

Model	Var./Quat.	RDK		0.1 quantile		0.3 quantile		0.5 quantile		0.7 quantile		0.9 quantile	
		Elas.	p val.	Elas.	p val.	Elas.	p val.	Elas.	p val.	Elas.	p val.	Elas.	p val.
Model (1)	LEPR	−8.182a	**0.001**	−8.271c	**0.097**	−8.224b	**0.012**	−8.173a	**0.000**	−8.148a	**0.001**	−8.103b	**0.031**
	LEPR2	0.441a	**0.000**	0.448c	**0.050**	0.444a	**0.003**	0.440a	**0.000**	0.438a	**0.000**	0.434b	**0.012**
	LUTE	−0.792a	**0.000**	−0.667a	**0.000**	−0.734a	**0.000**	−0.804a	**0.000**	−0.840a	**0.000**	−0.903a	**0.000**
	LGRD	0.228a	**0.000**	0.195b	**0.035**	0.212a	**0.000**	0.231a	**0.000**	0.241a	**0.000**	0.257a	**0.000**
	LEXDI	−0.126a	**0.006**	−0.055	**0.671**	−0.093	**0.275**	−0.133b	**0.026**	−0.153b	**0.019**	−0.189c	**0.055**
	LIMEP	0.084a	**0.000**	0.076c	**0.057**	0.080a	**0.002**	0.085a	**0.000**	0.087a	**0.000**	0.091a	**0.003**
	LFDL	−0.100c	**0.057**	−0.085	**0.421**	−0.093	**0.177**	−0.101b	**0.034**	−0.106b	**0.044**	−0.114	**0.153**
Model (2)	LEPR	−7.144a	**0.003**	−6.542	**0.134**	−6.887b	**0.013**	−7.172a	**0.001**	−7.393a	**0.002**	−7.705b	**0.030**
	LEPR2	0.395a	**0.001**	0.370c	**0.065**	0.384a	**0.003**	0.396a	**0.000**	0.405a	**0.000**	0.418b	**0.010**
	LUTE	−0.814a	**0.000**	−0.724a	**0.000**	−0.775a	**0.000**	−0.818a	**0.000**	−0.851a	**0.000**	−0.898a	**0.000**
	LGRD	0.238a	**0.000**	0.207b	**0.015**	0.225a	**0.000**	0.239a	**0.000**	0.251a	**0.000**	0.267a	**0.000**
	LEXDI	−0.148a	**0.002**	−0.091	**0.454**	−0.124	**0.110**	−0.151b	**0.010**	−0.172a	**0.008**	−0.201b	**0.042**
	LIMEP	0.081a	**0.000**	0.073b	**0.037**	0.078a	**0.000**	0.082a	**0.000**	0.085a	**0.000**	0.090a	**0.002**
	LFMA	−0.080a	**0.000**	−0.072	**0.150**	−0.077b	**0.016**	−0.081a	**0.001**	−0.084a	**0.002**	−0.088b	**0.031**
Model (3)	LEPR	−8.182a	**0.001**	−8.271c	**0.097**	−8.224b	**0.012**	−8.173a	**0.000**	−8.148a	**0.001**	−8.103b	**0.031**
	LEPR2	0.441a	**0.000**	0.448c	**0.050**	0.444a	**0.003**	0.440a	**0.000**	0.438a	**0.000**	0.434b	**0.012**
	LUTE	−0.792a	**0.000**	−0.667a	**0.000**	−0.734a	**0.000**	−0.804a	**0.000**	−0.840a	**0.000**	−0.903a	**0.000**
	LGRD	0.228a	**0.000**	0.195b	**0.035**	0.212a	**0.000**	0.231a	**0.000**	0.241a	**0.000**	0.257a	**0.000**
	LEXDI	−0.210a	**0.006**	−0.131	**0.355**	−0.173c	**0.061**	−0.217a	**0.001**	−0.240a	**0.001**	−0.280a	**0.009**
	LMod	0.084a	**0.000**	0.076c	**0.057**	0.080a	**0.002**	0.085a	**0.000**	0.087a	**0.000**	0.091a	**0.003**
	LFDL	−0.100c	**0.057**	−0.085	**0.421**	−0.093	**0.177**	−0.101b	**0.034**	−0.106b	**0.044**	−0.114	**0.153**
Model (4)	LEPR	−7.144a	**0.003**	−6.542	**0.134**	−6.887b	**0.013**	−7.172a	**0.001**	−7.393a	**0.002**	−7.705b	**0.030**
	LEPR2	0.395a	**0.001**	0.370c	**0.065**	0.384a	**0.003**	0.396a	**0.000**	0.405a	**0.000**	0.418b	**0.010**
	LUTE	−0.814a	**0.000**	−0.724a	**0.000**	−0.775a	**0.000**	−0.818a	**0.000**	−0.851a	**0.000**	−0.898a	**0.000**
	LGRD	0.238a	**0.000**	0.207b	**0.015**	0.225a	**0.000**	0.239a	**0.000**	0.251a	**0.000**	0.267a	**0.000**
	LEXDI	−0.230a	**0.000**	−0.164	**0.209**	−0.201b	**0.015**	−0.233a	**0.000**	−0.257a	**0.000**	−0.291a	**0.006**
	LMod	0.081a	**0.000**	0.073b	**0.037**	0.078a	**0.000**	0.082a	**0.000**	0.085a	**0.000**	0.090a	**0.002**
	LFMA	−0.080a	**0.000**	−0.072	**0.150**	−0.077b	**0.016**	−0.081a	**0.001**	−0.084a	**0.002**	−0.088b	**0.031**

Note: p-values in bold, a– $p > 0.01$; b– $p > 0.05$; c– $p > 0.10$; Mod = IMEP*EXDI. For brevity, location and scale coefficients are not reported.

and positive across all quantiles. Models without moderation (Models 1 and 2) demonstrate that harnessing technological innovation can lead to improvements in eco-efficiency in OECD countries. This is because technological innovation opens the door not only to preventing future greenhouse gas emissions, but also to curtailing current greenhouse gas emissions. In addition, technological innovation drives the development and implementation of cleaner technologies that have lower or no greenhouse gas emissions (Ahmad and Satrovic, 2023b). Technological innovations also induce behavioural changes, influencing individuals to control their energy consumption and minimize waste. Similar results have been found by Chen et al. (2022a), who indicated that technological innovation is crucial for tackling ecological deterioration as it reduces the cost of modern low-carbon technologies. Similarly, Gao et al. (2023) found a negative relationship between technological innovation and carbon emissions, demonstrating that technological innovation boosts the environmental quality of developing countries. The findings of the present study underline the importance of boosting research and development budgets to spur the development of low-carbon technologies that can improve energy efficiency, and combining this with approach with strict environmental policies. Our findings are also consistent with Musah et al. (2024), who found that technological innovation is positively correlated with environmental sustainability and that this entailed that increased technological innovation encourages the transition from non-renewable to renewable energy sources, favouring environmental quality. Ullah et al. (2023) have also shown that technological innovation improves environmental quality by reducing greenhouse gas emissions.

The models devised in the present study also include economic growth and its quadratic term. The coefficient of LEPR is statistically significant across all quantiles in Model 1, whereas in Model 2 it is statistically insignificant for the 10th quantile. The parameter of $LEPR^2$ is statistically significant across various quantiles in both models. The negative coefficient of LEPR and positive coefficient of $LEPR^2$ signify that the interplay between economic growth and eco-efficiency follows a U-type pattern. These results confirm that the initial stages of economic growth reduce eco-efficiency, demonstrating that economic emancipation does not favour ecological sustainability (Satrovic et al., 2024a). In the later stages of growth, however, technological advancement results in a favourable ecological impact of economic growth. The assumption of a non-linear association between LEPR and eco-efficiency is confirmed by Chen et al. (2022b) in the case of China, supporting the EKC phenomenon. More recently, Voumik and Rahi Dey (2023) revealed that while increasing gross domestic product in the initial stages of growth is associated with harmful ecological impacts, in the later stages of growth it can have a beneficial ecological impact. Similarly, Hakkak et al. (2023) provided support for the EKC phenomenon in emerging economies. Our study aligns with that of Ahmad and Satrovic (2023a) by considering a sample of OECD countries; in their study, OECD countries' energy utilisation was negatively related to eco-efficiency and this relationship was statistically significant across all quantiles. Our findings on the adverse ecological impact of energy utilisation align with the previous findings of Bashir et al. (2023); Sun et al. (2023a), Sun et al. (2023b), and Villanthenkodath et al. (2024). Our empirical findings indicate a negative association between financial deepening and eco-efficiency in Model 1 that is statistically significant across the 0.4 to 0.8 quantiles. Similarly, Model 2 demonstrates the detrimental effect of financial deepening on eco-efficiency, which is statistically significant across the 0.2 to 0.9 quantiles. Analogous results have been found by Zhang et al. (2022), and Rehman et al. (2023).

Our study further determined the interaction term of environmental policy stringency (LIMEP) and export diversification (LEXDI) in Models 3 and 4. These moderated models assess the combined impact of LIMEP and LEXDI, reporting a positive coefficient of the interactive term. The statistically significant positive coefficient across all quantiles shows that this effect increases from the lower to the higher quantiles, suggesting that environmental policy stringency counteracts the harmful ecological impact of export diversification. The findings show that more rigid environmental legislation is necessary in OECD countries to regulate pollutant emissions, and that export sectors should be motivated to implement greener production technologies. The interplay between

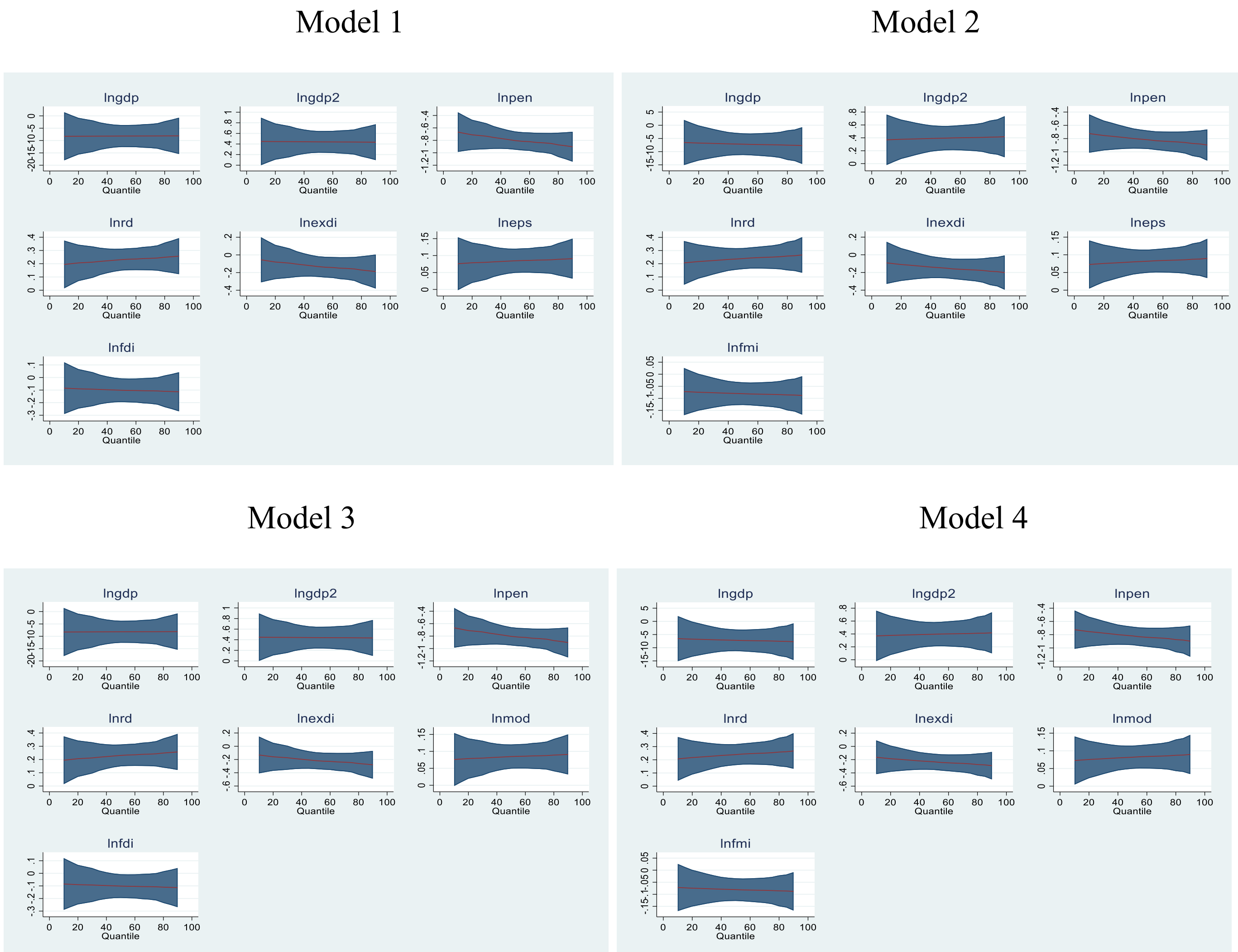

Fig. 2. Graphical representation of even quantiles. LTEC is the dependent variable.
Note: lngdp = LEPR, lngdp2 = LEPR2, lnpen = LUTE, lnrd = LGRD, lnexdi = LEXDI, lneps = LIMEP, lnfdi = LFDL, lnfmi = LFMA, lnmod = LMod.

LIMEP and LEXDI is stronger at higher quantiles, indicating that more stringent environmental policies tend to support the energy transition from fossil fuels to renewables in OECD member countries, leading to a reduction in emissions associated with international trade. These findings are congruous with those of Liu et al. (2023), who found that the imposition of more stringent environmental policies can lead to a reduction in trade-adjusted greenhouse gas emissions.

We used alternative model specifications to examine the robustness of our findings, by including an alternative proxy for eco-efficiency that considers only the carbon aspect of ecological footprint rather than all aspects. The empirical outcomes are reported in T able A1 and Fi gure A1 (Appendix) and indicate that energy utilisation, financial deepening, and export diversification have detrimental impacts on eco-efficiency in the models without moderating effects (Models 5 and 6). Our findings further reinforce the positive ecological impact of technological innovation and environmental policy stringency, affirming the non-linear association between economic growth and eco-efficiency. In models with moderating effects (Models 7 and 8), the positive coefficient of LMod exhibits an increasing effect, indicating that export diversification amplified eco-efficiency when it was integrated with environmental policy stringency in the sampled OECD economies during the studied period. Comparison of our baseline (Table 7 and Fig. 2) and alternative (Ta ble A1 and Fi gure A1) models leads us to conclude that our empirical results are robust, as the signs and significance levels of the regression coefficients match in both sets of models.[2]

We also employed the Driscoll-Kraay (RDK) econometric technique to measure the robustness of our findings. The outcomes tabulated in T ables 7 and A1 demonstrate that technological innovation and environmental policy stringency enhanced the eco-efficiency of the sampled OECD countries in the period from 1995 to 2020. In particular, a 1% rise in technological innovation was found to increase LTEC by 0.228% (Models 1 and 3) or 0.238% (Models 2 and 4), and LCEC by 0.355% (Models 5 and 6) or 0.391% (Model 7 and 8). Analysis of the coefficients of environmental policy stringency indicates that a 1% rise in LIMEP increases eco-efficiency by 0.084 (Model 1), 0.081 (Model 2), 0.089 (Model 5) or 0.073 (Model 6). The results of the RDK technique further indicate that energy utilisation, export diversification and financial deepening reduce the eco-efficiency of OECD countries, supporting a

[2] The results of the alternative models are provided in T able A1 and Fi gure A1 in the Appendix.

non-linear association between LEPR and eco-efficiency. By considering the indirect impacts of export diversification, our findings affirm that export diversification improves the eco-efficiency of OECD countries through the channel of stricter environmental policies, as the outcomes of the RDK technique do not differ in sign and significance from those of our principal QREG estimation technique.

5. Conclusion, policy recommendations, and limitations

5.1. Conclusion

Growing concern about climate change has led several governments across the world to identify and implement appropriate policies in response to this challenge. There have thus been global efforts to implement environmental policy frameworks that promote ecological sustainability without putting economic growth in jeopardy. To achieve this, and to secure enhanced eco-efficiency, a combination of stringent environmental policies and technological innovation should serve as the cornerstone of ecological policy frameworks, alongside policies focusing on export diversification, economic growth, energy utilisation, and financial deepening. However, the indirect impact of export diversification through the channel of environmental policy stringency and eco-efficiency has been totally ignored by existing studies. Accordingly, our study's primary objective is to unravel how the multidimensional reality of environmental policies influenced the interplay between export diversification and eco-efficiency in most diversified OECD countries over the period 1995 to 2020. To achieve this objective, we used Method of Moment Quantile Regression and produced results suggesting that environmental policy stringency and technological innovation are instrumental to the improvement of eco-efficiency in OECD countries. Energy utilisation, financial deepening, and export diversification, on the other hand, impede eco-efficiency. Furthermore, our results affirm that the relationship between economic growth and eco-efficiency follows a U-shaped pattern, thus supporting the EKC hypothesis.

5.2. Policy recommendations

Given the findings of this study, the following recommendations can be made to help governments and policymakers accelerate progress towards achieving environmental sustainability. First, there is a need to initiate more stringent environmental policies which effectively regulate pollutant emissions from industry and other sectors that are major contributors to countries' total emissions. This suggestion is corroborated with Haites (2018), Wolde-Rufael and Mulat-Weldemeskel (2023), and Adeshola et al. (2024). On this note, the social cost of carbon emissions should be adequately reflected by tightening environmental policy, for example by increasing taxes on pollution to discourage firms from emitting pollutants. Similarly, policies and programs such as cap-and-trade carbon markets and a carbon tax on the sale or use of fossil fuels should be implemented across OECD countries and closely monitored as suggested by Wolde-Rufael and Mulat-Weldemeskel (2023). Importantly, if the environmental rules are the same across OECD countries, industries may not be able to avoid their responsibilities by strategically relocating to a country with less stringent policies. However, governments and policymakers need to be cautioned not to jealously increase environmental taxes as high taxes can lead to increased cost of production and weakening of international competitiveness as noted by Lin and Li (2011). High environmental taxes can also exacerbate iniquality of income as noted by Oueslati et al. (2017).

Furthermore, climate change policies across OECD countries should be more comprehensive in nature. Notably, taxes on emissions should not be limited only to carbon taxes, which are designed mainly to reduce emissions by increasing the price of fossil fuels; rather, the scope of this taxation should be expanded to include all forms of emissions from resource use, energy generation, and transportation as suggested by European Commission (2019). Moreover, although environmental taxation can effectively reduce environmental degradation, governments and policymakers must not disregard the effective use of policy instruments such as tax credits and tax holidays, along with other subsidies to attract investment in green energy as demonstrated by Paramati et al. (2021). In addition, since technological innovation improves ecological sustainability, more funding should be directed to research, innovation and development. Advancing technological progress in this way may induce firms and industries to innovate and embrace green production and manufacturing. This suggestion concurs with the argument canvassed by Usman (2023). Finally, since export diversification is detrimental to eco-efficiency but its interaction with environmental policy stringency improves eco-efficiency, our results suggest that governments and policymakers should promote export diversification while at the same time increasing environmental policy stringency to achieve eco-efficiency in OECD countries. Increasing environmental policy stringency will lead to a reduction in trade-adjusted greenhouse gas emissions as firms and industries strategically re-position themselves to favour green production and manufacturing and thus avoid heavy environmental taxes. This suggestion is corroborated with Dai and Du (2023) who found a negative effect of environmental policy stringency on environmental degradation.

5.3. Limitations

This study is subject to some limitations. For example, further research is necessary to identify the appropriate threshold for environmental policy stringency, which is becoming a serious concern for many countries. Higher levels of environmental policy stringency can interfere with firms' and industries' operations, thereby reducing economic growth. There is therefore a need for further research on the threshold effect of environmental policy stringency in the relationship between export diversification and eco-efficiency. Moreover, this study's sample of nine OECD member countries based on their export diversification rankings may not be sufficient to generalize the findings. Therefore, it is suggested that further research should include more OECD member countries in the sample. Furthermore, since environmental degradation is a global challenge, we suggest that similar studies should be conducted for different regions such as Africa, Asia and Latin America, and that the results should be compared to enhance our understanding of the influence of environmental policy stringency on the relationship between export diversification and eco-efficiency.

CRediT authorship contribution statement

Elma Satrovic: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ojonugwa Usman:** Writing – review & editing, Writing – original draft, Visualization, Project administration. **Andrew Adewale Alola:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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

Appendix

Table A1
Robustness assessment (RDK and QREG, LCEC- dependent variable)

Model	Var./Quantile	RDK		0.1 quantile		0.3 quantile		0.5 quantile		0.7 quantile		0.9 quantile	
		Elas.	p val.	Elas.	p val.	Elas.	p val.	Elas.	p val.	Elas.	p val.	Elas.	p val.
Model (5)	LEPR	−11.651a	**0.000**	−8.548	**0.299**	−10.33b	**0.049**	−11.676a	**0.003**	−12.975a	**0.003**	−14.625b	**0.030**
	LEPR2	0.613a	**0.000**	0.468	**0.220**	0.552b	**0.023**	0.614a	**0.001**	0.675a	**0.001**	0.752b	**0.016**
	LUTE	−1.033a	**0.000**	−0.746a	**0.003**	−0.911a	**0.000**	−1.035a	**0.000**	−1.156a	**0.000**	−1.308a	**0.000**
	LGRD	0.355a	**0.000**	0.370a	**0.001**	0.361a	**0.000**	0.355a	**0.000**	0.348a	**0.000**	0.340a	**0.000**
	LEXDI	−0.254a	**0.000**	−0.127	**0.471**	−0.200c	**0.073**	−0.255a	**0.002**	−0.308a	**0.001**	−0.376a	**0.009**
	LIMEP	0.089a	**0.004**	0.074	**0.166**	0.082b	**0.015**	0.089a	**0.000**	0.096a	**0.001**	0.104b	**0.017**
	LFDL	−0.288a	**0.000**	−0.309b	**0.030**	−0.297a	**0.001**	−0.288a	**0.000**	−0.280a	**0.000**	−0.269b	**0.020**
Model (6)	LEPR	−11.563a	**0.000**	−9.225	**0.219**	−10.616b	**0.022**	−11.554a	**0.001**	−12.496a	**0.002**	−13.650b	**0.025**
	LEPR2	0.613a	**0.000**	0.505	**0.145**	0.570a	**0.008**	0.613a	**0.000**	0.656a	**0.000**	0.710b	**0.012**
	LUTE	−1.058a	**0.000**	−0.839a	**0.000**	−0.969a	**0.000**	−1.057a	**0.000**	−1.145a	**0.000**	−1.253a	**0.000**
	LGRD	0.391a	**0.000**	0.419a	**0.000**	0.402a	**0.000**	0.391a	**0.000**	0.380a	**0.000**	0.366a	**0.000**
	LEXDI	−0.286a	**0.000**	−0.171	**0.302**	−0.239b	**0.019**	−0.285a	**0.000**	−0.331a	**0.000**	−0.388a	**0.004**
	LIMEP	0.073b	**0.010**	0.047	**0.329**	0.062b	**0.035**	0.073a	**0.002**	0.084a	**0.001**	0.097b	**0.014**
	LFMA	−0.162a	**0.000**	−0.169b	**0.013**	−0.165a	**0.000**	−0.162a	**0.000**	−0.159a	**0.000**	−0.155a	**0.005**
Model (7)	LEPR	−11.651a	**0.000**	−8.548	**0.299**	−10.331b	**0.049**	−11.676a	**0.003**	−12.975a	**0.003**	−14.625b	**0.030**
	LEPR2	0.613a	**0.000**	0.468	**0.220**	0.552b	**0.023**	0.614a	**0.001**	0.675a	**0.001**	0.752b	**0.016**
	LUTE	−1.033a	**0.000**	−0.746a	**0.003**	−0.911a	**0.000**	−1.035a	**0.000**	−1.156a	**0.000**	−1.308a	**0.000**
	LGRD	0.355a	**0.000**	0.370a	**0.001**	0.361a	**0.000**	0.355a	**0.000**	0.348a	**0.000**	0.340a	**0.000**
	LEXDI	−0.343a	**0.000**	−0.200	**0.299**	−0.282b	**0.021**	−0.344a	**0.000**	−0.404a	**0.000**	−0.480a	**0.002**
	LMod	0.089a	**0.004**	0.074	**0.166**	0.082b	**0.015**	0.089a	**0.000**	0.096a	**0.001**	0.104b	**0.017**
	LFDL	−0.288a	**0.000**	−0.309b	**0.030**	−0.297a	**0.001**	−0.288a	**0.000**	−0.280a	**0.000**	−0.269b	**0.020**
Model (8)	LEPR	−11.563a	**0.000**	−9.225	**0.219**	−10.616b	**0.022**	−11.554a	**0.001**	−12.496a	**0.002**	−13.650b	**0.025**
	LEPR2	0.613a	**0.000**	0.505	**0.145**	0.570a	**0.008**	0.613a	**0.000**	0.656a	**0.000**	0.710b	**0.012**
	LUTE	−1.058a	**0.000**	−0.839a	**0.000**	−0.969a	**0.000**	−1.057a	**0.000**	−1.145a	**0.000**	−1.253a	**0.000**
	LGRD	0.391a	**0.000**	0.419a	**0.000**	0.402a	**0.000**	0.391a	**0.000**	0.380a	**0.000**	0.366a	**0.000**
	LEXDI	−0.359a	**0.000**	−0.218	**0.221**	−0.302a	**0.006**	−0.358a	**0.000**	−0.415a	**0.000**	−0.484a	**0.001**
	LMod	0.073b	**0.010**	0.047	**0.329**	0.062b	**0.035**	0.073a	**0.002**	0.084a	**0.001**	0.097b	**0.014**
	LFMA	−0.162a	**0.000**	−0.169b	**0.013**	−0.165a	**0.000**	−0.162a	**0.000**	−0.159a	**0.000**	−0.155a	**0.005**

Note: p-values in bold, a– $p > 0.01$; b– $p > 0.05$; c– $p > 0.10$; Mod = IMEP*EXDI. For brevity, the location and scale coefficients are not reported.

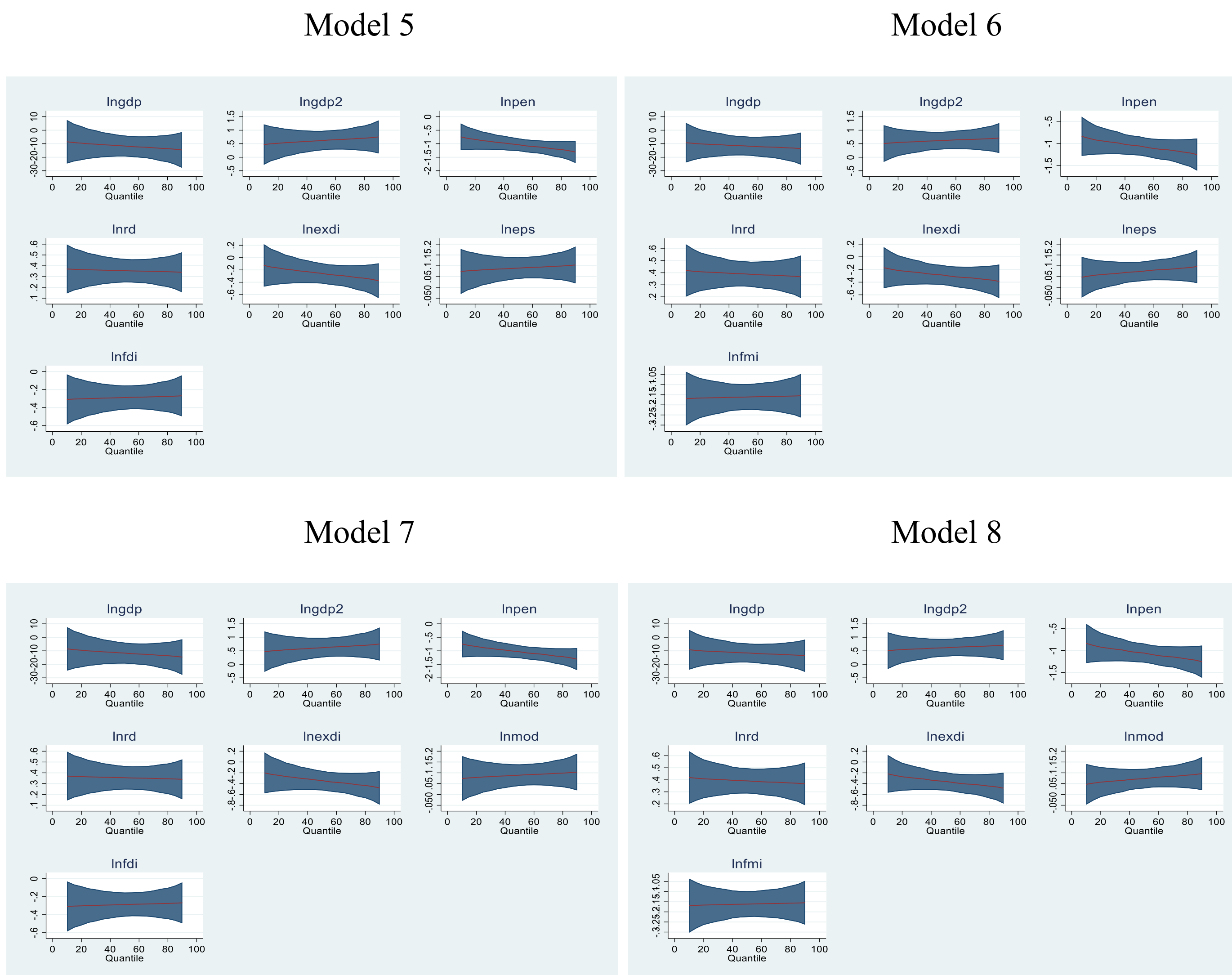

Fig. A1. Even quantiles (graphical representation, LCEC – dependent variable) Note: lngdp = LEPR, lngdp2 = LEPR2, lnpen = LUTE, lnrd = LGRD, lnexdi = LEXDI, lneps = LIMEP, lnfdi = LFDL, lnfmi = LFMA, lnmod = LMod

Data availability

Data will be made available on request.

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