




Fossil fuel efficiency as a pathway to decarbonisation and the role of international trade: A perspective of the LCC hypothesis

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Received: 23 September 2024 / Accepted: 14 May 2025
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Abstract

The continued global dependency on fossil fuel sources in the face of increasing international trade may hamper the goal of decarbonisation. To condense climate risk and attain net zero, efficiency measures are proposed. This study unambiguously investigates the environmental quality implications of fossil fuel efficiency in the face of the international trade based on the Load Capacity Curve (LCC) hypothesis for Canada from 1965 to 2022. The application of a dynamic ARDL simulations method uncovers the following findings: (i) fossil fuel efficiency engenders load capacity factor (*lnLCF*) in the short run (SR) and long run (LR). This suggests a dampening trend of environmental externalities as fossil fuel efficiency increases. (ii) the connection between income expansion and *lnLCF* follows an inverted U-type pattern, thus invalidating the LCC hypothesis in Canada. (iii) the effect of international trade is positive but only significant in the SR. (iv) urban development is positively linked to *lnLCF* but its effect is perhaps significant only in the LR. These findings corroborate the responses of the *lnLCF* to a 1% positive and negative counterfactual shocks in fossil fuel efficiency, income expansion, international trade, and urban development. Moreover, the findings are robust to the results of the nonparametric multivariate quantile-on-quantile regression model. Therefore, the policy take of these results is that to achieve net-zero emissions targets by 2050, environmental policies ought to promote not only fossil fuel efficiency but also the growth of income expansion, trade, and urbanization.

Keywords Canada · Load capacity curve hypothesis · Fossil fuel efficiency · Dynamic ARDL simulations

1 Introduction

Global scale expansion in anthropogenic activities and the dominance of fossil energy-based production are escalating concerns about environmental degradation and associated climatic shifts characterized by extreme weather events. Consequently, the subject of environmental quality has taken the center stage of intensive analyses at most national and transnational policy discussions relating to economic expansion, energy, health, and security. Understandably, the premium placed on the environment debate

Extended author information available on the last page of the article

draws motivation from prompts such as the nexus it bears with general disease ecology and population health, global environmental changes (GECs), and socioeconomic adjustments, consisting of production and cultural shifts. In addition, a number of empirical evidence have identified harmful agricultural practices such as the use of herbicides and other non-biodegradable chemical solutions as not only destructive to soil systems but also supplementary to the pollution of adjoining water bodies (Iorember et al., 2022). On a broader scale, mineral exploration and exploitation and other forms of industrial production, as well as unrecycled domestic urban waste, are actively intensifying water pollution. According to Usman et al., (2020a), the outcome of these activities has unbearable consequences on bio-sustainability such as loss of aquatic species, decline in food diversity, decrease in productivity of water bodies, and increase in incidence of morbidities that are waterborne. Furthermore, in many parts of the world, increased water stress and a declining availability of land for arable and grazing activities resulting from environmental degradation have become dominant elements of large-scale armed conflicts with daunting economic and humanitarian crises as concomitant effects (see Ali et al., 2021).

In Canada, a wide range of environmental issues have been isolated in the specialized literature, including rising temperature, road salt contamination, air pollution, and monumental shifts in patterns of precipitation. In addition, McKittrick et al., (2018) recount that the country's environmental space is haunted by threats from oil sands and pipelines, increased extreme weather incidents, and climate change indicated by the melting of glaciers and permafrost. Among many key climate variables, temperature is a barometer of climatic shifts in reaction to emissions of greenhouse gases (GHGs) arising from anthropological activities. According to Davis et al., (2022), Canada's temperature growth levels have been on a very alarming upward trajectory, approaching twice the global average. While it is projected that the global mean annual increase in temperatures will hit 5.6 degree Celsius within the present century, forecasts relating to Canada indicate a rise of about 7.5 degree Celsius if current emissions levels do not abate. This only signals a momentous alteration in the weather configuration of the country and the landscape and patterns of environmental outcomes. Meanwhile, most empirical studies have identified the combined impact of expressed ecological stress on population health, economic production, and general human security in Canada. For instance, Greaves (2021) submits that climate-related changes have posed security threats to Canada's environmental quality. These threats manifest in harm and loss of lives due to life-threatening weather events like floods, heatwaves, and wildfires. This also include catastrophic environmental losses and damages to many homes and communities as well as infrastructures and health.

The association between economic growth, the attendant evolution of economic activities, and environmental quality, via emissions, has long been theorized. Consequently, models of the connection between economic expansion and ecological protection have occupied the research space for a long time. Pata and Caglar (2021) assert that interest in discussions about the association between economic production and the environment dates back three decades, specifically of increased scholarly and public policy attention on mitigating the debilitating consequences of energy use. It has been demonstrated that increased fossil energy consumption and the application of other naturally-based resources to optimize economic expansion have created, and are sustaining a scenario of steep uptrend in emissions levels and a matrix of environmental changes (Rehman et al., 2022). Meanwhile, economic growth has been supported by emitting energy sources. With the increasing awareness of the debilitating impact of greenhouse emissions on the environment, advances towards carbon neutrality including fossil-energy consumption efficiency

have been made. The question as to whether these efforts are successful at enhancing environmental quality has been subjected to empirical validation.

On the measurement of environmental protection and sustainability, carbon-related (CO₂) emissions have been extensively explored as great alternative measure (see Balcilar et al., 2023). It could be observed, however, that other than air pollution, CO₂ emissions do not offer comprehensive coverage of the full range of ecological decay emanating from demands of production. Therefore, Wackernagel and Rees (1998) developed the ecological-footprints as more composite and representativeness of air, land, and water degradation resulting from the demand placed on nature to support economic growth. The ecological footprint (EF) is indeed acknowledged to present a better option for measuring total environmental viability. However, Pata and Tanriover (2023) have adroitly divulged that both CO₂ emissions and EF are demand-side elements and so, do not account for the regenerative capacity of the environment expressed by biocapacity. Recently, Siche et al., (2010) developed the load capacity factor (LCF) to contemporaneously incorporate biocapacity and EF in a single framework as a measure of ecological sustainability. The value of LCF equals to or larger than 1 indicates that the environment is sustainable. On the flip side, if the value LCF is obviously smaller than 1, it signals deficits in the replenishing potentials of the environment. Ali et al. (2023) used both LCF and CO₂ emissions to determine how technological innovation, consumption of green energy, and debt affect ecological sustainability in the MINT region. The study found that foreign debts and clean energy access improve LCF. While Yang et al. (2024) validated the LCC-Hypothesis (LCC-H) in the BRICS, a study by Usman et al. (2024) fails to validate the LCC-H for China. In the case of Canada, the available studies employ a panel data analysis. For example, Teng et al. (2024) employed data from the USA, France, China, Canada, and Russia and found that renewable energy promotes LCF for these countries. Similarly, Işık et al. (2024) revealed that while governance factors promote LCF, economic factors dampen LCF among G7 nations.

Given this background, the study's focus is to probe how Canadian fossil fuel energy efficiency influences the nation's environmental sustainability. In achieving this, we control for per capita income, trade, and urbanization. Therefore, this study portrays some novelties, which are highlighted as follows: First, we adopt the LCF to test the validity of a LCC-H for Canada, for the first time in the literature. Second, given Canadian's net-zero emission targets amidst fossil fuel energy generation and consumption, this study will provide insights as to whether efficiency in fossil fuels can help mitigate the concentration of CO₂ in the atmosphere over time. Third, we apply not only the DARDL simulations method but also Multivariate QQR method to capture the influence of shocks in fundamentals over time. The study seamlessly aligns with a number of SDGs, i.e. 7, 9, 12 and 13.

Therefore, the study's structures are as follows: The 2nd section unveils the review of related studies. The 3rd section is related to the materials and methods employed. In the 4th section, the study analyzes the data and discuss the outcomes. The 5th section contains actionable policy-based suggestions and the 6th section is simply the concluding statement.

2 Review of literature

The theoretical support for this study is rested on the LCC-H put forward via empirically-based work of Siche et al., (2010). In its simplest form, environmental sustainability is worse-off by growth in the short run (SR) but that structural shifts and technological

advancement propel long-run (LR) relations between growth and the environment to be increasingly sustainable. According to Iormom et al (2025), the LCF curve promotes the argument that scale economics at the early phase of income expansion would worsen environmental protection/sustainability but once a turning point is attained, their association becomes rather bearable. Therefore, this hypothesis is analogous with the EKC but the difference is anchored on the U-shaped curve in the LCF analysis. This implies that, at the early phase of development, an upsurge in per-capita income causes deficits in the replenishing potentials of the environment until a certain threshold is attained, afterward, an upsurge in per-capita incomes promotes LCF thereby leading to environmental sustainability.

In recent times, a few studies tested the income-growth nexus within the procedure of the LCC-H. A study by Pata and Samour (2022) divulges that the LCC-H is confirmed for France's case while controlling for nuclear-powered energy and renewable/unpolluted energy. In a study of G-7 countries from 1986 to 2018, Dogan and Pata (2022) initiated evidence in support of the U-shaped curve, suggesting that ecological conditions are deteriorated by growth only up to a threshold, beyond which they both vary positively. Further, their study found increased unpolluted energy, research and development as well as information and communication penetration to be coincident with enhanced environmental outcomes. Similarly, Pata and Kartal (2022) proved that both the EKC and the LCF curve assumptions are valid in the connection of nuclear energy, unpolluted energy, and ecological performance in South Korea. They found nuclear energy to improve environmental quality but argued that renewable energy consumption had insignificant LR influence on the environment. On the contrary, Alola et al., (2023) fail observably to support the LCC-H in India. However, their study demonstrated that the efficiency of energy consumption from renewable and nonrenewable promotes environmental quality in India.

Furthermore, researchers have actively discussed the subject of economic growth, energy use, and environmental quality within different methodological and theoretical frameworks for a long time and this research discipline has remained topical in the specialized literature. Using the panel ARDL on data relating to Mexico, Venezuela, and Columbia from 1970 to 2020, Nahrin et al., (2023) found income expansion and energy resources to be associated negatively with pollution in the SR and perhaps positively in the LR. The study confirmed the existence of a 2-way causal connection between energy utilization and ecological degradation. Kong et al., (2022) also explored the empirical connection between income expansion, renewables, and carbon neutrality in MENA nations. The study confirmed the case of the EKC in high-income nations of the MENA region but could not validate the same among middle-income nations. Further, a unidirectional causality, running from government effectiveness and renewables to net-zero carbon is established while a feedback loop effect is reported between income expansion and net-zero carbon.

In a forward-looking study of Venezuela from 1980 to 2025 in the EKC procedure, Robalino-López et al., (2015) found a positively impacted influence of GDP on ecological degradation. Ali et al., (2022) found electricity consumption, hydroelectric production, and GDP to be significant and positively associated with CO₂ emissions in a study that primarily aimed to gauge how causal association happens between CO₂-related kind of emissions, combustible renewables, and waste, electric usage, thermal electric generation, hydro-electric and natural gas-based sources, energy usage and GDP. The study however found electricity production from coal, combustible renewable waste, and energy usage to be negatively associated with carbon emissions. Riti and Shu (2016) investigated the link between renewables, energy use effectiveness, and ecological sustainability in Nigeria using the traditional ARDL method. Their study's finding suggests that renewables lower

ecological degradation. However, the study fails to validate the EKC assumption with increased income expansion aggravating ecological quality in the LR.

From the foregoing, it is averred that the subject of income expansion elements, energy, and environment sustainability has attracted research interest over time, and it is still an ongoing discourse. The sub-discipline of the LCC hypothesis is also relatively new and has been shown to be more comprehensive in the measurement of environmental sustainability. Robust as this framework is, its application in the economic growth, energy efficiency, and ecology nexus in Canada is scant. The extant literature has also not settled on the basic and defined theoretical expectation from this association, giving the conflicting conclusions expressed by different empirical findings. This study uniquely improves the literature because it moves to close the isolated gap by domesticating the discourse on the LCC-H in Canada. The entire analysis holds great promise given the economic, energy, social, and security policy relevance of ecological sustainability.

3 Methods

This study typically uses robust time series and econometrics-inclined methods to isolate the contribution of fossil fuel efficiency and international trade to environmental sustainability in Canada. The formal framework for empirical analysis involves the distributional properties of the series. Further, the study probes the LR equilibrium connection and parameter estimates. The robustness of the estimates is also checked.

3.1 Data

The annual/yearly data spanning from 1965 to 2022 is used for this study. The variables comprise LCF which is measured in global hectares (gha) per capita. This is used as a measurement of environmental sustainability. The main independent variable is fossil fuel efficiency (FFE). The control variables include income expansion, international trade (TO), and urban development (UR). To achieve homoscedasticity, the natural logarithms of variables are perhaps taken. Table 1 describes variables used, their unit of measurements and sources.

Figure 1 reports the plots of individual series to scrutinize whether these series have some issues pertaining to not only drift but also seasonality, trend, and structural breaks. As correctly divulged, the $\ln LCF$ and $\ln TO$ are associated with fluctuations, which can

Table 1 Variables' descriptions/definitions

Var	Notation	Measurement/definition	Source
Load Capacity Factor	LCF	$\frac{\text{Biocapacity per capita}}{\text{ecological footprint per capita}}$ (gha)	GFN (2025)
Income expansion	GDP	Per capita GDP (constant 2011 international-\$)	OWD (2025a)
Fossil Fuel Efficiency	FFE	$\frac{\text{GDP per capita}}{\text{fossil fuel consumption per capita}}$ (2011 international-\$ per kWh)	OWD (2025a, b)
International Trade	TO	Trade (percentage of GDP)	WDI (2025a)
Urban Development	UR	Urbanization (percentage of total population)	WDI (2025b)

Authors' computation

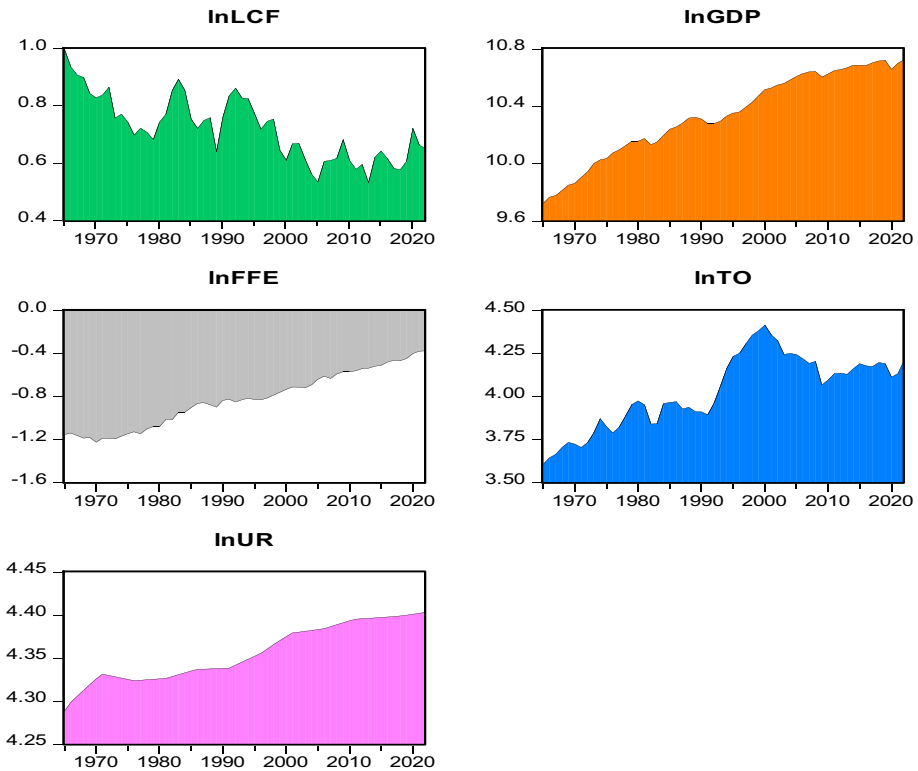


Fig. 1 Time plots of the variables

be traceable to structural breaks as a result of macroeconomic policy dynamics in a way to mitigate not only ecological footprints but also stimulate $\ln TO$. Particularly, the $\ln LCF$ has no clear-cut trend as the plot is characterized by upward and downward trends. However, it can be seen that starting from the early 1990 s, the $\ln LCF$ experienced a downward trend. This could be attributed to an excessive demand pressure on the resources to stimulate income expansion and improve the people's living standards. The $\ln GDP$ and $\ln UR$ trend upward over time, while the trend of $\ln FFE$ is negative over time. This implies that income per capita is rising along with the urban population in Canada. Also, the degree of $\ln TO$ was low but rising slowly before 1990. However, in the early 1990 s, significant rises in the degree of $\ln TO$ is detected, suggesting some favourable foreign trade policies.

3.2 Building the empirical models

This study is focused on investigating the efficacy of $\ln FFE$ in deriving the environment towards sustainability, considering other control variables such as $\ln GDP$, $\ln TO$, and $\ln UR$. Therefore, the study has the following model:

$$\ln LCF = f(\ln GDP, \ln GDP^2, \ln FFE, \ln TO, \ln UR) \tag{1}$$

where from Eq. (1), $\ln LCF$ denotes the log of load capacity factor, which measures environmental quality. $\ln GDP$ and $\ln GDP^2$ correspond to the log of income expansion and its square. $\ln FFE$ is the log of $\ln FFE$, while $\ln TO$ and $\ln UR$ represent the log of international trade and urban development. Equation (2) can be transformed into an econometric model as follows:

$$\ln LCF_t = \alpha_0 + \alpha_1 \ln GDP_t + \alpha_2 \ln GDP_t^2 + \alpha_3 \ln FFE_t + \alpha_4 \ln TO_t + \alpha_5 \ln UR_t + \mu_t \tag{2}$$

where all the variables retain their previous definitions. t perhaps represents the period of the study, α_0 is known as the intercept, and μ_t denotes the residual term. Conventionally, within the EKC framework, $\ln GDP$ is regarded as the main driver of environmental degradation. The $\ln GDP^2$ determines the pattern and shape of the EKC, i.e. whether such a country has an inverted U-shape EKC or a U-shape EKC. Another factor that determines $\ln LCF$, a measure of ecological sustainability, is the level of $\ln FFE$. Generally, energy consumption is a major channel of environmental degradation through CO₂ emissions. However, recent literature has argued that once energy consumption is efficient, it can stimulate and protect the environment through energy savings and technologies. Hence, several policies have been hinged on energy efficiency to achieve net-zero emissions targets, particularly in the developed world. In addition to the above discussion, rapid $\ln UR$ and $\ln TO$ across the world may also contribute to the surge in emissions. This is likely to occur through an increase in energy consumption. To this extent, it is expected that the coefficients of $\ln GDP$ and $\ln GDP^2$ to be negatively and positively associated with the $\ln LCF$, implying a U-shape LCC. The $\ln FFE$ is presumed to be positively related to the $\ln LCF$, which implies an improvement in environmental quality. Both $\ln TO$ and $\ln UR$ are expected to be negative, which implies dampening environmental quality.

3.3 Main model specification

The study estimates Eq. (2) by using the dynamic-ARDL simulations (DARDL) model, which came into existence via the work of Jordan and Philips (2018). The model is undoubtedly a modification of the standard ARDL model of Pesaran et al. (2001), which can accommodate a multifaceted case where there are multiple (several) lags of first-difference variables. Hence, it captures out-of-sample counterfactual shock effects in exogenous variables over time by automatically providing their plots. These plots help in understanding the LR and the associated SR influence of the negative and positive shocks in exogenous variables. The expression of the DARDL model mathematically is:

$$\begin{aligned} \Delta \ln LCF_t = & \rho_0 + \sigma_0 \ln LCF_{t-1} + \delta_{1,i} \Delta \ln GDP_t + \theta_1 \ln GDP_{t-1} + \delta_{2,i} \Delta \ln GDP_t^2 + \theta_2 \ln GDP_{t-1}^2 \\ & + \delta_{3,i} \Delta \ln FFE_t + \theta_3 \ln FFE_{t-1} + \delta_{4,i} \Delta \ln TO_t + \theta_4 \ln TO_{t-1} + \delta_{5,i} \Delta \ln UR_t + \theta_5 \ln UR_{t-1} + \mu_t \end{aligned} \tag{3}$$

where Δ is a change in a specific variable, which also corresponds to the first-difference operator. ρ_0 is the intercept. $\delta_i, i = 1, \dots, 5$ correspond to the short-run slope coefficients while $\theta_j, j = 1, \dots, 5$ correspond to the LR slope coefficients. Also, μ_t is the residual term. Figure 2 highlights the flow chart of the models employed.

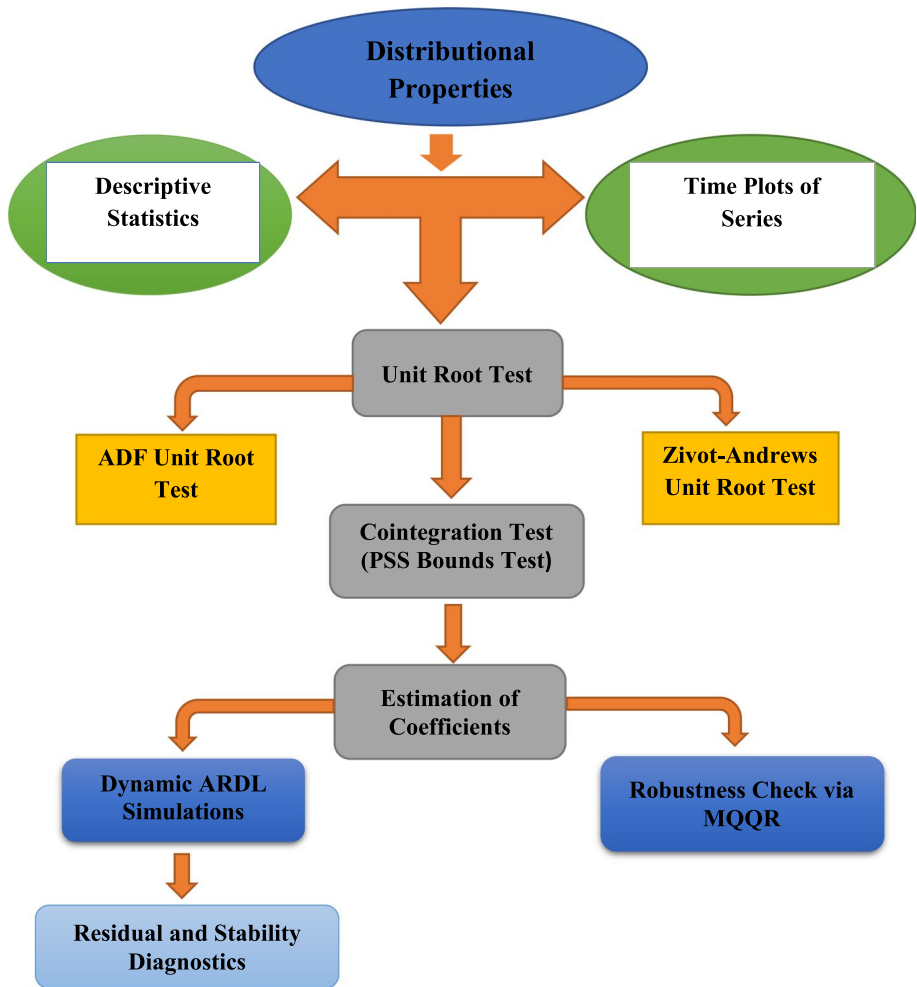


Fig. 2 Flow Chart of the Models

4 Results

4.1 Statistical descriptions

The statistical descriptions of the log series divulged in Table 2 observe that the $\ln GDP$ highest mean value i.e. 10.339. This is followed by $\ln UR$ with 4.356 and $\ln TO$ with 4.033. The $\ln FFE$ and $\ln LCF$ have the lowest value in absolute terms. Furthermore, the values of standard deviation suggest that every variable exhibits low variance as each variable has a standard deviation value close to zero. Also, while $\ln LCF$, $\ln FFE$, and $\ln UR$ have positive skewness, $\ln GDP$, and $\ln TO$ have negative skewness. This means that variables such as $\ln LCF$, $\ln FFE$, and $\ln UR$ are positively skewed while values such as $\ln GDP$ and $\ln TO$ are negatively skewed. Although, the absolute value of each of the variables is approximately zero. For

Table 2 Statistical description of variables

	<i>lnLCF</i>	<i>lnGDP</i>	<i>lnFFE</i>	<i>lnTO</i>	<i>lnUR</i>
Mean	0.723	10.339	-0.822	4.033	4.356
Med	0.723	10.329	-0.827	4.067	4.347
Max	0.998	10.726	-0.373	4.416	4.404
Min	0.534	9.723	-1.223	3.608	4.289
Std. Dev	0.111	0.297	0.257	0.213	0.032
Skew	0.321	-0.389	0.028	-0.184	0.028
Kurt	2.292	2.021	1.798	1.979	1.666
JB	2.208	3.776	3.498	2.844	4.308
(<i>p</i> -value)	(0.331)	(0.151)	(0.174)	(0.241)	(0.116)
Observation	58	58	58	58	58

JB is simply the Jarque–Bera test of normality

the kurtosis, it is observed that each variable exhibits a platykurtic distribution. However, the results of the normality test proposed by Jargue and Bera (1980) reveal that the null hypothesis of the normal distribution cannot be rejected. This implies that the variables are all normally distributed.

4.2 Unit root test results

As a fundamental move in a time series analysis, the study examines the stationarity status of employed series to obtain valid and robust results. Thus, the AD-F test by Dickey and Fuller (1979) and Phillips-Perron (PP) test by Phillips and Perron, (1988) are employed. Table 3 reports the unit root (UNR) test results. It is divulged that the working series have no unit root at their 1st differences which is the opposite of level test results with the exception of *lnGDP* and *lnLCF*. Note that these tests invariably failed to consider breaks in the series, which could occur because of structural changes. This failure can render

Table 3 Unit-root tests outcomes

Variables	AD-F		PP	
	t-St	<i>P</i> -val	Adj. t-St	<i>P</i> -val
<i>LnLCF</i>	-2.753	0.071	-2.715*	0.071
Δ <i>lnLCF</i>	-6.570***	0.000	-7.492***	0.000
<i>lnGDP</i>	-2.766	0.069	-2.615*	0.095
Δ <i>lnGDP</i>	-6.065***	0.000	-6.065***	0.000
<i>lnGDP</i> ²	-2.553	0.108	-2.422	0.140
Δ <i>lnGDP</i> ²	-6.143***	0.000	-6.143***	0.000
<i>lnFFE</i>	0.696	0.991	0.819	0.993
Δ <i>lnFFE</i>	-5.791***	0.000	-8.130***	0.000
<i>lnTO</i>	-1.749	0.403	-1.856	0.351
Δ <i>lnTO</i>	-5.354***	0.000	-5.354***	0.000
<i>lnUR</i>	-0.199	0.932	-1.628	0.461
Δ <i>lnUR</i>	-3.824***	0.004	-3.822***	0.004

*** and * simply signify 0.01 and 0.10 levels of statistical significance

the outcomes of the test spurious. Therefore, addressing the methodological-based issue prompted the use of the unknown and indefinite structural-break test advanced by Zivot and Andrews (1992) to confirm the order of integration. The Zivot-Andrews test results uncover that all the variables have no at their first differences except $\ln UR$ as presented in Table 4. Conclusively, the results are in harmony with the mixed order of integration which justifies the suitability of the ARDL model's family in this study.

4.3 Results of the bounds testing cointegration

The ARDL-bounds testing method is explored to investigate the cointegration linkage among the study-outlined variables. According to the results in Table 5, there is an LR relation in the estimated model since the F-statistic value calculated is greater than Narayan's (2005) 5% level of significance upper critical value. Also, the t -statistic value in absolute terms is greater than the tabulated (critical) value. Thus, the $\ln LCF$ is found to move together with $\ln GDP$, $\ln FFE$, $\ln TO$, and $\ln UR$ in the LR over the investigated period for Canada.

4.4 LR and SR results

After meeting the pre-requisites for the NARDL test, i.e., maximum integration order of variables is $I(1)$ with an explained variable particularly possesses not only $I(1)$, but also the employed variables are cointegrated, the study proceeds with the empirical analysis to obtain the SR and LR impact of fundamental variables on $\ln LCF$ in Canada. Table 6 divulges the outcome of the DARDL analysis. The estimated error-correction-term is -0.781 and statistically significant. This indicates that any SR disequilibrium

Table 4 ZA unit-root test outcomes

Variables	t-St	BP
$\ln LCF$	-4.191	1999
$\Delta \ln LCF$	-7.230***	1995
$\ln GDP$	-2.642	2009
$\Delta \ln GDP$	-6.936***	1993
$\ln GDP^2$	-2.658	2009
$\Delta \ln GDP^2$	-6.958***	1993
$\ln FFE$	-4.031	1981
$\Delta \ln FFE$	-6.619***	1988
$\ln TO$	-3.468	1992
$\Delta \ln TO$	-6.031***	2001
$\ln UR$	-5.888***	1997
$\Delta \ln UR$	-3.591	1992
Critical values		
10%	-4.58	
5%	-4.80	
1%	-5.34	

*** and ** signify 0.01 level of statistical significance

Table 5 Cointegration test outcomes

		Critical values of Narayan (2005)		
		0.10	0.05	0.05
F-Stat.	5.353**	↘	↗	↘
		2.39	3.58	2.85
		4.16	3.93	5.41
		Critical values of Pesaran et al. (2001)		
		0.10	0.05	0.05
t-Stat.	-5.505***	↘	↗	↘
		-2.57	-3.86	-2.86
		-4.19	-3.43	-4.79

*** and ** signify statistical significance at 0.01 and 0.05 levels. ↘ and ↗ simply imply lower and upper bounds of the test

Table 6 Dynamic-ARDL simulations outcomes

Variables	Coef	SE	t-stat	Prob
$\Delta \ln GDP_t$	10.210	9.868	1.035	0.306
$\ln GDP_{t-1}$	9.170***	3.218	2.849	0.006
$\Delta \ln GDP_t^2$	-0.582	0.474	-1.228	0.225
$\ln GDP_{t-1}^2$	-0.491***	0.163	-3.001	0.004
$\Delta \ln FFE_t$	0.533**	0.222	2.392	0.021
$\ln FFE_{t-1}$	0.626***	0.174	3.591	0.004
$\Delta \ln TO_t$	0.248*	0.136	1.826	0.074
$\ln TO_{t-1}$	0.053	0.076	0.693	0.491
$\Delta \ln UR_t$	1.779	3.688	0.483	0.631
$\ln UR_{t-1}$	1.310**	0.968	2.276	0.030
Constant	-47.072**	18.688	-2.519	0.015
ECT_{t-1}	-0.781***	0.141	-5.505	0.000
Simulations	10,000			
R^2	0.656			
F-stat (Prob.)	7.816*** (0.000)			

***, **, and * signify statistical significance at 0.01, 0.05, and 0.10 levels

can be adjusted through the employed fundamentals and hence, the system invariably converges to the LR equilibrium path at the speed of 78.1% every year. Also, it is found that economic activities enhance ecological sustainability by increasing the $\ln LCF$ over the study period for the case of Canada. This study demonstrates that a 1% increase in income expansion yields a 9.2% increase in ecological sustainability in the LR. Although the impact of SR income expansion is positive, it is not statistically significant.

Furthermore, the $\ln GDP^2$ has a reduction impact on $\ln LCF$, which is against the position theorized by the load capacity curve. This indicates that $\ln GDP^2$ delinks $\ln LCF$ and $\ln GDP$ at the higher level of income only in the LR. Specifically, a 1% increase in $\ln GDP^2$ causes $\ln LCF$ to decrease by 0.49% in the LR with the SR influence proving insignificant. Thus, the LCC-hypothesis is not validated for Canada. This outcome indicates an inverted U-type connection between the $\ln LCF$ and income expansion.

In Canada, $\ln FFE$ improves ecological quality. As expected, the relationship between $\ln FFE$ and $\ln LCF$ is inelastic in the SR and LR. If $\ln FFE$ increases by 1%, the $\ln LCF$ increases by about 0.53% and 0.63% in the SR and LR. Also, the influence of $\ln TO$ on the $\ln LCF$ is positive in the SR and LR but significant in the SR only. A 1% increase in $\ln TO$ increases $\ln LCF$ by about 0.207%. Furthermore, the current study also considers the nexus between $\ln UR$ and the Canadian $\ln LCF$. In Table 6, it is uncovered that a positive influence of $\ln UR$ on the $\ln LCF$ both in the LR and SR. While the SR influence is not statistically significant, a 1% increase in $\ln UR$ is connected to about a 1.31% surge in the LR Canadian $\ln LCF$.

Furthermore, the study applies a set of post-estimations for checking the reliability and robustness of the outcomes of the DARDL simulations model. The findings are divulged in Table 7. According to the outcomes, the estimated model does not have any serial correlation, conditional heteroscedasticity, ARCH effect, non-normality, and model misspecification problems. Additionally, as shown in Fig. 3, the CUSUM and CUSUM-squared plots at

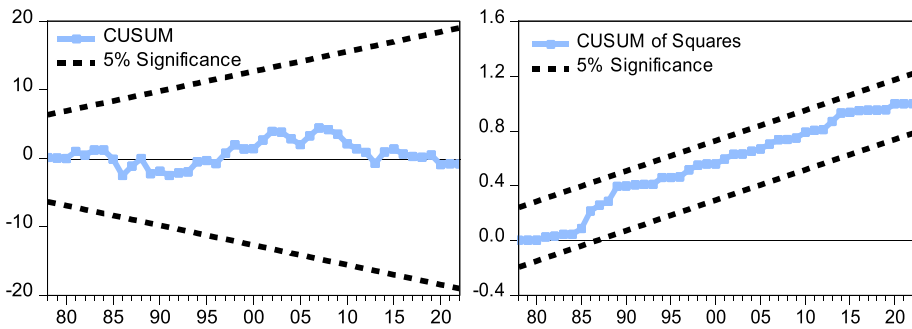


Fig. 3 Results of CUSUM and CUSUMSQ

0.05 bounds, indicates that the model is stable. Thus, the findings are robust and valid for policy direction.

Lastly, the DARDL simulations method is employed to analyze the impulse-response plots. These plots indicate the negative (positive) changes of the aforementioned exogenous variables on the *lnLCF* under a ceteris paribus condition. Figures 4–8 show the responses of the *lnLCF* to a 1% \mp counterfactual shock in *lnGDP*, *lnGDPSQ*, *lnFFE*, *lnTO*, and *lnUR*. As divulged in Figs. 4–8, the results corroborate the findings observed in the dynamic ARDL simulations model (see Table 7). Specifically, Fig. 3 demonstrates that positive (negative) shocks on *lnGDP* increase (decrease) LCF, which invariably supports environmental sustainability over the time horizon. However, the quadratic form of *lnGDP* fails to validate the U-shape between *lnLCF* and the quadratic form of *lnGDP* as outlined in Fig. 5. Moreover, Fig. 6 highlights that both positive (negative) shocks in *lnFFE* increase and decrease the *lnLCF*. This is an indication of environmental sustainability over the time horizon explored. The impulse-response plots in Figs. 7 and 8 indicate that a 1% positive change in both *lnTO* and *lnUR* first increases the *lnLCF* in the SR and then reduces it in the LR. On the other hand, a 1% negative change in *lnTO* and *lnUR* decreases the *lnLCF* in the SR and after the second year, the effect of a negative change tends to increase the *lnLCF*.

4.5 Robustness check

Following the empirical results, the study applies the novel nonparametric multivariate-quantile on quantile regression (M-QQR) proposed by Ozkan et al. (2023) and Alola et al. (2023). This method captures the quantile impact of exogenous variables across the conditional distribution of endogenous variables. From Fig. 9, a heterogeneous positive impact of *lnGDP* on ecological sustainability through *lnLCF* is revealed across the spectrum of

Table 7 Outcomes of diagnostic tests

Tests	<i>p</i> -values
Breusch-Godfrey (B-G) LM serial correlation	0.203
Breusch-Pagan-Godfrey (B-P-G) heteroscedasticity	0.913
ARCH	0.923
Ramsey RESET	0.117
Jarque–Bera normality	0.676
Authors' computation	

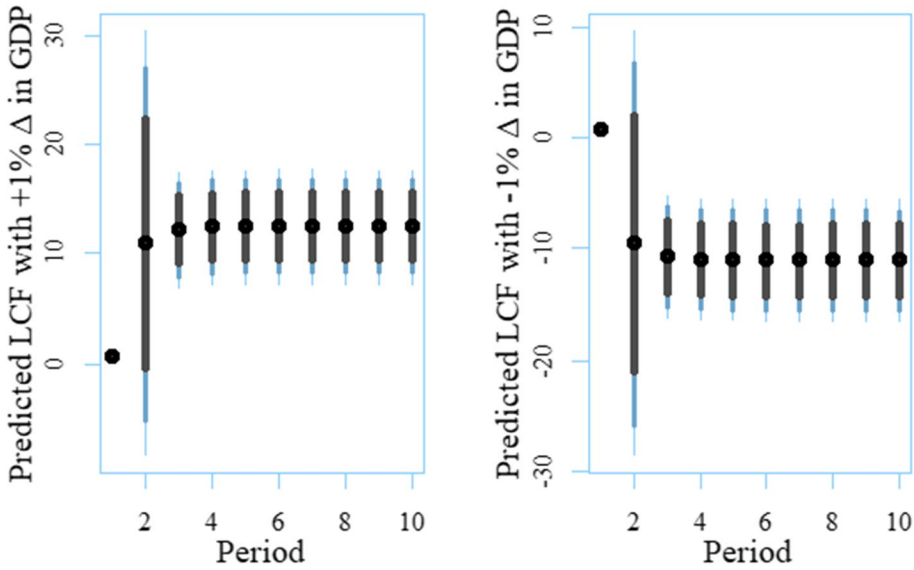


Fig. 4 ±1% changes in $\ln GDP$ and its influence on predicted $\ln LCF$

the relationship. Notably, the impact of income expansion is stronger in the lower quantiles and middle quantiles of the $\ln GDP$. Also, a stronger effect of $\ln GDP$ in the lower quantiles of the $\ln LCF$ is isolated. This confirms that income expansion exerts a stronger positive impact on environmental sustainability at lower quantiles of both variables. This finding

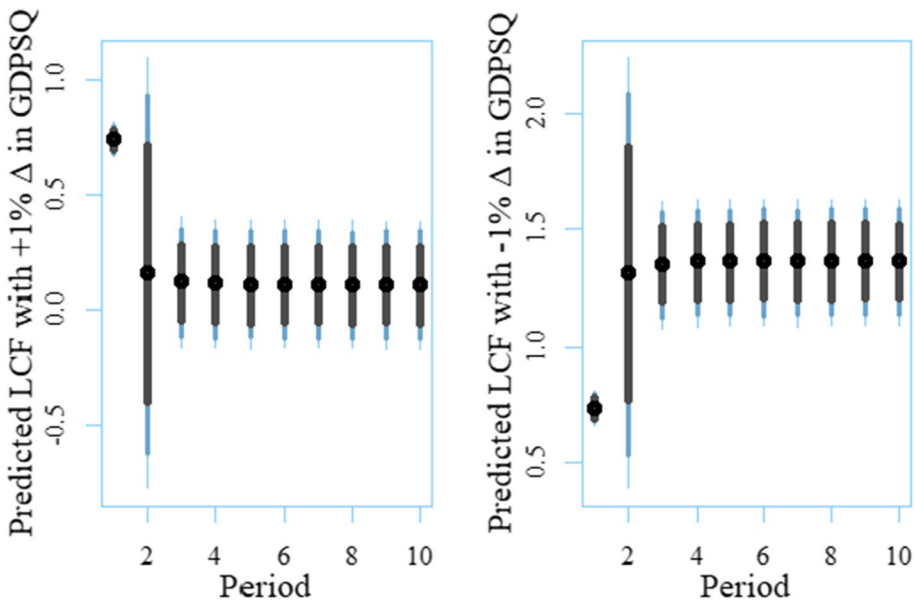


Fig. 5 ±1% changes in $\ln GDP^2$ and its influence on predicted $\ln LCF$

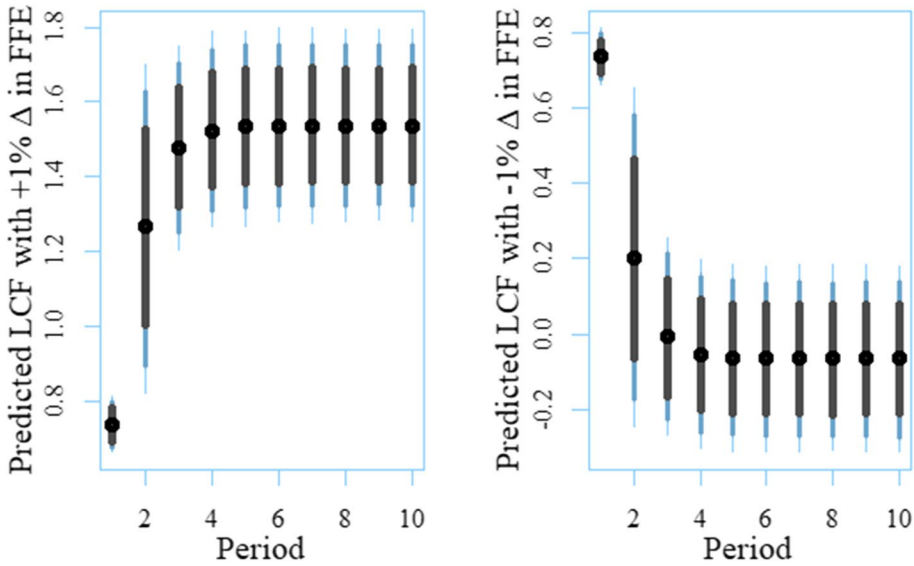


Fig. 6 ±1% changes in $\ln FFE$ and its influence on predicted $\ln LCF$

resonates with the estimates in Table 6 where a positive link between $\ln GDP$ and $\ln LCF$ was shown. It also aligns with the DARDL simulation plots in Fig. 5 which revealed that $\ln GDP$ exercise positive shocks on $\ln LCF$.

However, the MQQR values for the square of $\ln GDP$ ($\ln GDP^2$) in Fig. 10 are persistently negative, ranging between -0.25 and -0.75 . This suggests that the $\ln GDP^2$ delinks

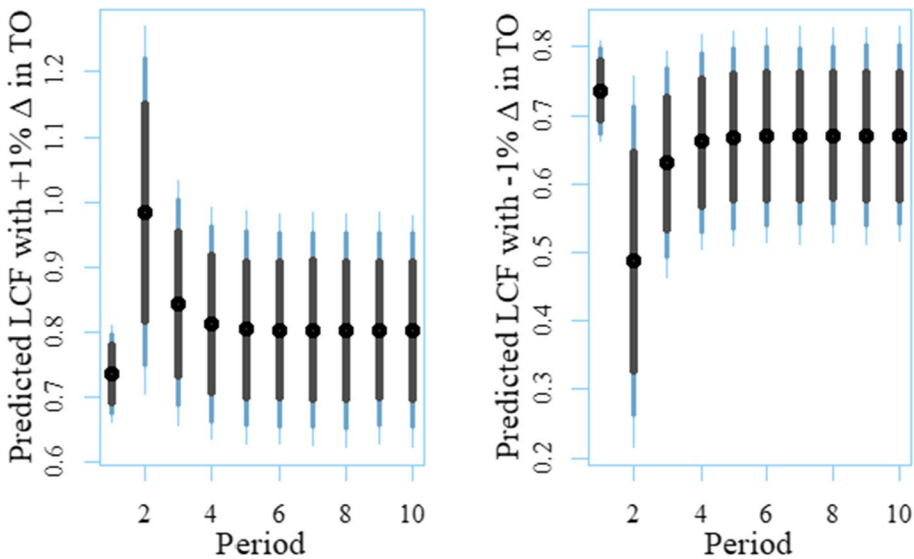


Fig. 7 ±1% changes in $\ln TO$ and its influence on predicted $\ln LCF$

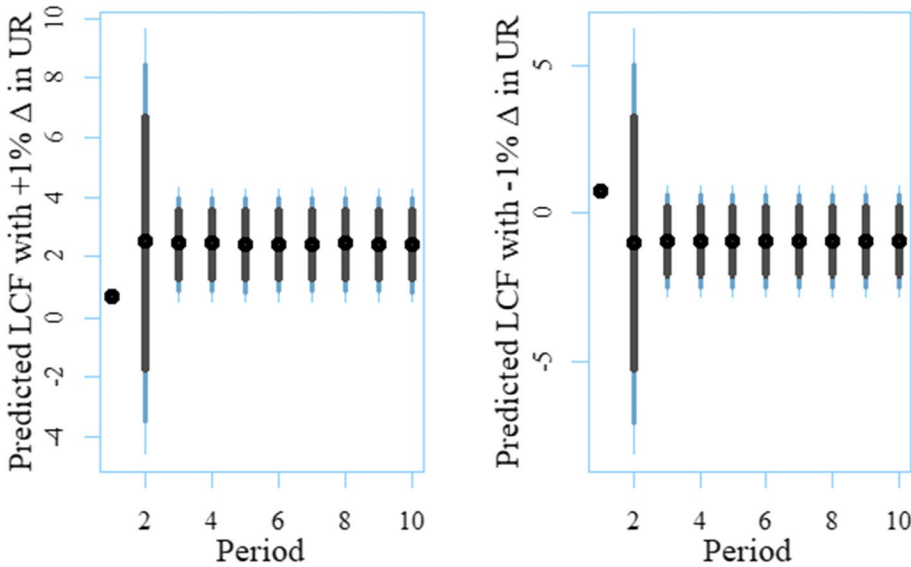


Fig. 8 $\pm 1\%$ changes in $\ln UR$ and its influence on predicted $\ln LCF$

the $\ln LCF$ and real income at the higher levels of income. The impact is stronger at lower and middle quantiles of $\ln GDP^2$ and $\ln LCF$. This result does not support the validity of the LCC-H in the case of Canada. The scenario mirrors the case of environmental regulation costs where such controls may force exponential growth in $\ln GDP$ to be dependent on resource-intensive energy alternatives with net negative marginal improvements in environmental sustainability. Canada has embarked on stringent environmental regulations such as carbon pricing and emission reduction targets (e.g., Canada’s Net-Zero Emissions targets by 2050) which may impose additional costs on energy production, reducing $\ln LCF$ by increasing alternative resource intensity.

Fig. 9 Impact of $\ln GDP$ on $\ln LCF$ based on $\ln LCF = \hat{f}(\ln GDP, \ln GDP^2, \ln FFE, I$

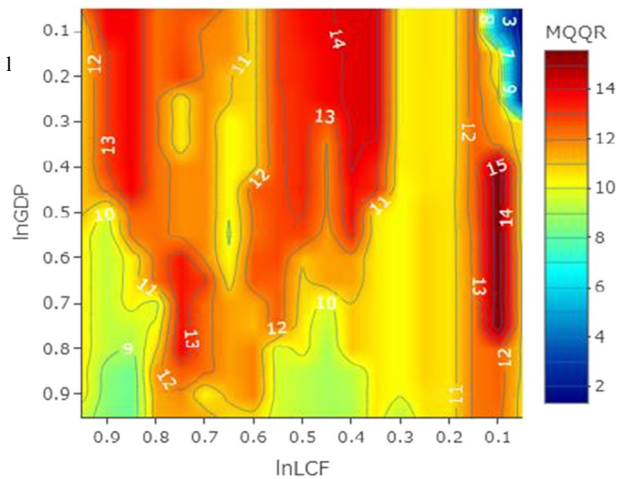


Fig. 10 Impact of $\ln\text{GDP}^2$ on $\ln\text{LCF}$ based on $\ln\text{LCF} = \hat{f}(\ln\text{GDP}, \ln\text{GDP}^2, \ln\text{FFE}, 1)$

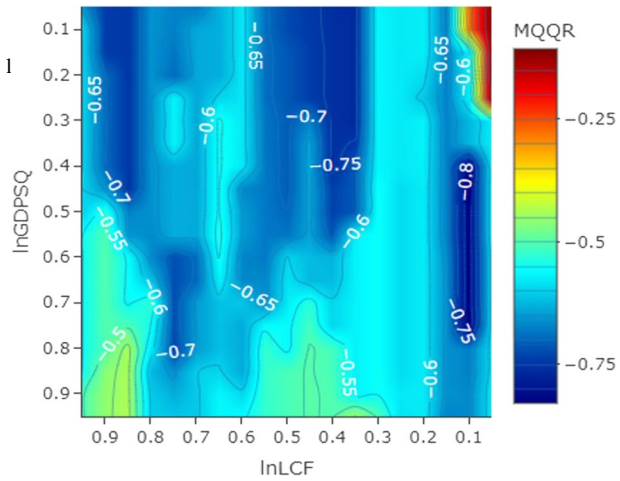
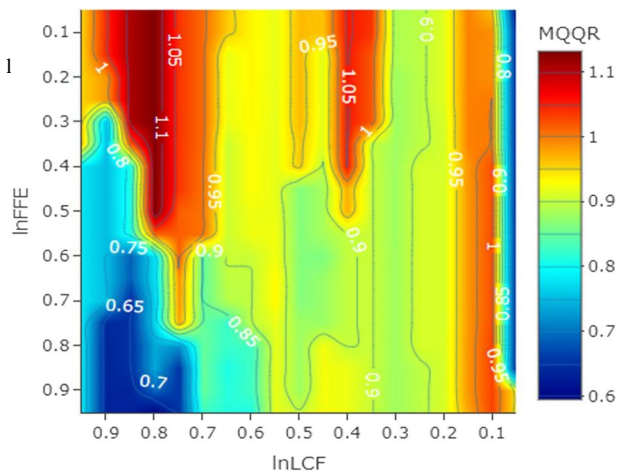


Fig. 11 Impact of $\ln\text{FFE}$ on $\ln\text{LCF}$ based on $\ln\text{LCF} = \hat{f}(\ln\text{GDP}, \ln\text{GDP}^2, \ln\text{FFE}, 1)$



In Fig. 11, the study finds the positively increasing impact of $\ln\text{FFE}$ on the respective quantiles of $\ln\text{LCF}$. This again supports the revelation of a positive effect of $\ln\text{FFE}$ on $\ln\text{LCF}$ in Table 6 and a positive shock of $\ln\text{FFE}$ on $\ln\text{LCF}$ in the DARDL simulation graph in Fig. 6.

The study presents the impact of $\ln\text{TO}$ and $\ln\text{UR}$ in Figs. 12 and 13. From the plots, it can be inferred that both $\ln\text{TO}$ and $\ln\text{UR}$ have a positive impact across the conditional distribution of the LCF. For $\ln\text{TO}$, a stronger impact is found in the middle quantiles of the $\ln\text{LCF}$ while for $\ln\text{UR}$, a stronger impact is found in the lower quantiles of the $\ln\text{LCF}$, confirming the earlier findings based on the DARDL simulation plots.

Fig. 12 Impact of $\ln TO$ on $\ln LCF$ based on $\ln LCF = \hat{f}(\ln GDP, \ln GDP^2, \ln FFE, I$

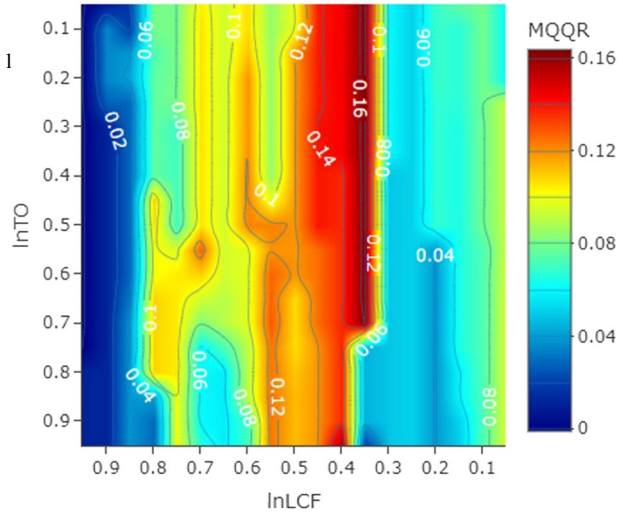
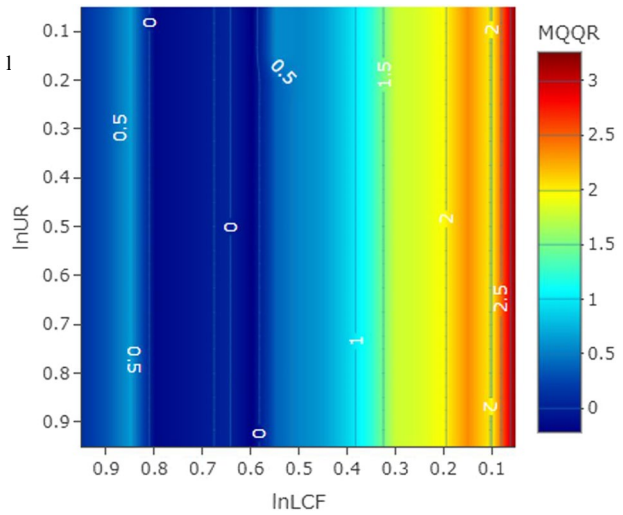


Fig. 13 Impact of $\ln UR$ on $\ln LCF$ based on $\ln LCF = \hat{f}(\ln GDP, \ln GDP^2, \ln FFE, I$



The summary of the study’s outcomes is generally divulged in Fig. 14, wherein the LCC-hypothesis is invariably invalidated in Canada. Also, the $\ln FFE$, $\ln TO$, and $\ln UR$ are environmentally friendly.

5 Discussion

The results divulge that income expansion enhances a sustainable environment via a rise in $\ln LCF$ in Canada with the insignificant presence of income expansion in the SR. This result plausibly reflects Canada’s strong environmental regulations and policies towards achieving net-zero emissions targets by 2050. Theoretically, this finding is enhanced by the Porter

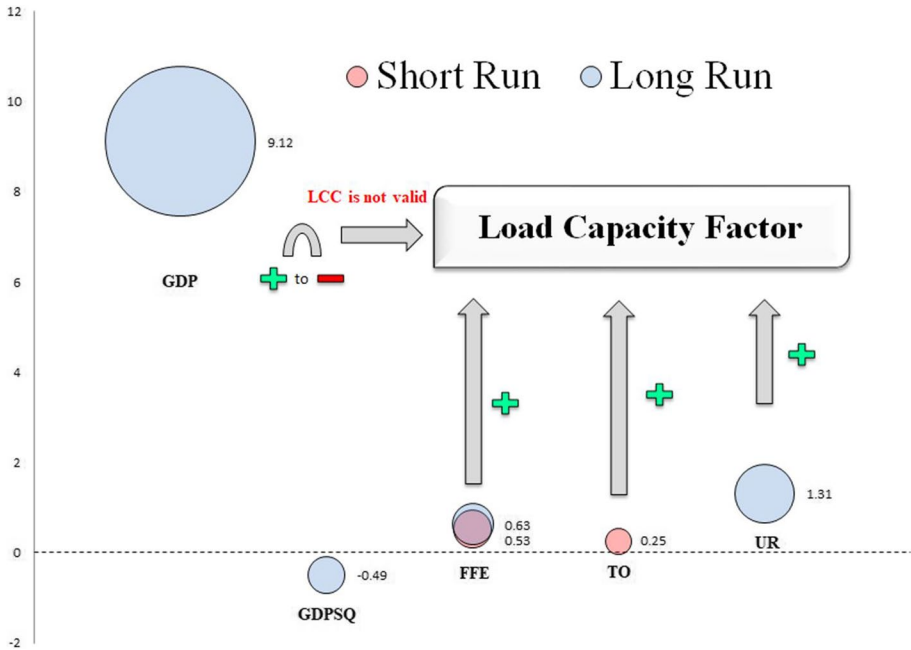


Fig. 14 Dynamic ARDL Results, Note: Summary of the significant short and long-term parameters estimated using the main model

Hypothesis, which indicates that strict environmental controls, obtainable in this context, can stimulate innovation and resource efficiency. This can simultaneously lead to income expansion and improved environmental performance as divulged by Porter and van der Linde1 (1995). Besides, the Canadian economy has performed well over the study period, growing most of the years except for 1982, 1991, 2009, and 2020 (Macrotrends, 2024). Environmental quality indicators have also improved significantly in Canada over the last decades. This means increased growth has provided the country with ample fiscal space to guarantee investments towards attaining most environmental policy targets. A positive link between $\ln GDP$ and the load capacity factor is also supported by the Energy Ladder Hypothesis, which argues that increased income expansion alters the energy mix in favour of cleaner sources. The outcome of this study is informative and instructive to policymakers and energy specialists in Canada as it helps to achieve decent environmental quality. From the empirical perspective, the outcome is also in agreement with extant studies. For example, Usman et al. (2020b) wherein divulge that real output promotes and/or facilitates only SR ecological improvement in the U.S. Also, Dogan and Turkekul (2016) uncover the environmental-friendly effect of real output in the U.S. Moreover, in the case of emerging economies such as South Africa, Uche and Ngepah (2024) found that income expansion promotes $\ln LCF$ in the middle and upper quantile, which is unswervingly congenial with the results in this study. On the other hand, Xu et al. (2022) reported that income expansion, clean-sourced energy, and non-clean-sourced energy resources are dampening $\ln LCF$ in Brazil.

Also, the $\ln GDP^2$ is found to dampen $\ln LCF$, which is against the position theorized by the LCC-H. By this, the LCC-H is not valid for Canada as the connection between income expansion and the $\ln LCF$ is found to be an inverted U-type. The plausible explanation for

not validating the LCC-H could be due to sustainable environmental regulations momentum after its first stage. In order to maintain environmental sustainability, consistent policies among environmental stakeholders, i.e. all agents and players are required. Thus, policy-makers are expected to act with caution in energy and environmental policy construction and implementation. While this finding is consented to by Alola et al. (2023) for India, the study advocates the need to reinforce the commitments toward the Canadian Environmental Protection Acts of 1999 and the Environmental Assessment Acts of 2012 in order to protect the environment. These acts both highlight commitments toward Canadian environmental protection without compromising sustainable income growth.

In Canada, $\ln FFE$ turns out to improve ecological quality. This indicates that energy transformation policies from conventional energy sources to unpolluted energy sources are not only avenues to promote a sustainable environment but also efficient use of fossil fuels may contribute significantly to laudable greening projects by the Canadian nation to achieve net-zero emission targets by 2050. This is congenial with the major conclusion of Alola et al. (2023), which is rooted in the Indian dataset and that of Usman et al. (2025) for the U.S. Moreover, the influence of $\ln TO$ on the $\ln LCF$ is positive in the SR and LR. However, this influence is significant in the SR only. This result suggests the worsening of ecological quality and sustainability. Therefore, this outcome echoes Alola et al. (2023) and Kartal et al., (2022) wherein a negative influence of $\ln TO$ is unveiled on the $\ln LCF$.

Furthermore, the study uncovered a positive influence of $\ln UR$ on the $\ln LCF$ both in the LR and SR. This result implies that as the Canadian economy is getting more urbanized, the country transitions towards the environmentally sustainable path in the LR. There are several factors to enhance the environment improvement effect of $\ln UR$. For example, the economic structure of the country, largely driven by investments in new technologies and innovations as well as massive funding of green-based energy activities may promote green growth. These technologies and innovations are likely to be adopted in the urban areas. Therefore, this finding is congenial with studies by Kongbuamai et al. (2022) for the N-11 and Nathaniel (2021) for Canada. Moreover, the result on the positive effect of $\ln UR$ on $\ln LCF$ is consistent with Lin and Ullah (2024) wherein urbanization is found to exert a 0.027% rise $\ln LCF$ in Pakistan.

6 Policy implications

The outcomes of this study propel the need for the following policy-based recommendations, which ought to be adeptly implemented to ensure accelerated progress toward the realization of the LR environmental goals in Canada:

6.1 Supporting green-based and sustainable growth policies

From the findings, $\ln GDP$ promotes $\ln LCF$, which suggests the attainment of a level whereby energy consumption is reduced due to improvements in technologies, making the environment protected, safe, and secure for future generations to experience a healthy environment. To this extent, the study suggests the need to promote an environment that drives sustainable growth through subsidies, tax credits, and holidays on green economic activities and projects. This helps to realize the Canadian LR environmental goals. Additionally, adequate investments in green energy projects should be undertaken to encourage the importation of advanced technologies to dampen the intensity of energy usage. Note

that promoting green-based environment and growth is not possible without the inclusion of all communities and individuals. Therefore, governments at all levels should advocate dialogue, participatory, and collaborative spirit among economic actors so that progress toward achieving a pollutant-free environment can be attained through shared responsibilities. In this case, governments need to exemplify several virtues such as transparency, accountability, and commitment of governments to policies regarding building a sustainable growth and environment, strengthening collaboration with partners and stakeholders by taking concrete actions toward having pollutant-free environment as well and seriously advocating gender equality to enable female counterpart deeply involved in the actions on climate change and energy transitioning.

6.2 Enhancing and encouraging efficient utilization of fossil fuels

The finding that $\ln FFE$ is instrumental to an increase in $\ln LCF$ suggests that policy initiatives and measures should enhance the efficient use of fossil fuels. This cannot be possible in the face of lack of energy efficiency practices. Awareness campaign program should be launched so that the best practices regarding energy utilization is known to the people. In other words, to achieve efficient use of fossil fuel, governments and policymakers need to launch an awareness campaign across the nooks and crannies of the country. Interestingly, the high level of educated individuals is an advantage for such a country like Canada where governments, private sector's actors and households can easily adopt the best practices as outlined by the policymakers. Moreover, given the high level of skills among workers in the Canadian economy, it becomes easier to apply high technologies and innovations imported from other advanced countries to help migrate to the path of greening the environment.

6.3 Supporting and promoting trade policies that are environmentally sustainable

The fact that $\ln TO$ positively interacted with the $\ln LCF$ suggests that trading goods and services across borders and beyond promotes environmental sustainability. The positive impact of $\ln TO$ is enhanced by ecosystem innovations cum strict laws pertaining to the environment, which have continued to discourage and stop highly polluted firms and industries from entering the country. On this note, governments and policymakers should make trade policies attractive to the trade actors while upholding and maintaining a strong and tight multilateral trading system, diversified trade, and trade inclusiveness. This can be realized by not only reducing tariffs but also providing subsidies on traded goods that have to do with greening the environment.

6.4 Stimulating a sustainable urban development

The finding also unveils that urban development patterns in Canada are positively related to boosting $\ln LCF$. Over the years Canada has recorded interesting policy statements concerning long-term planning for urban sustainability. One of the policies is the "New Deal Cities and Communities". In addition to government's effort to achieve urban sustainability, the study recommends the need to promote and stimulating urban green development

projects driven by green production, green lifestyle, and material base. At the level of municipals, Centre for sustainable communities can be established with the main objective of facilitating infrastructural development and implement climate change policies through awareness campaigns.

7 Conclusions

This study quantifies the environmental effect of *lnFFE* in the face of dynamic growth, trade, and rapid urban development in the Canadian economy over the period 1965 to 2022. The study applied the DARDL approach and the M-QQR approach for robustness, having met their underlying assumptions. The study provides some interesting findings: (i) *lnGDP* and *lnLCF* follows an inverted U-type pattern, suggesting that the LCC-hypothesis indeed does not hold for Canada. (ii) the SR and LR effects of *lnFFE* stimulate ecological sustainability through an increase in the LCF. (iii) Foreign trade drives environment quality through a rise in the *lnLCF* but the effect is only significant in the SR. (iv) *lnUR* pattern is associated with a dramatic surge in ecological sustainability through a rise in the LCF. These findings are validated by the responses of the *lnLCF* to 1% positive and negative counterfactual shocks in *lnGDP*, *lnTO*, *lnFFE*, and *lnUR*.

Like other studies, this study is perhaps faced with some weaknesses such as the inability of the findings to reflect industrialized and unindustrialized and emerging nations due to the heterogeneous nature of these nations. Given that the focus of this study is Canada, the findings may have little or no effect on developing nations where environmental awareness and regulations are not strong. Therefore, future studies can focus on developing/unindustrialized nations. Similarly, a comparative-based study can be conducted via a panel data analysis for industrialized and unindustrialized nations. Moreover, institutional factors may play a crucial role in promoting LCF. Hence, future studies can incorporate these factors and see how they moderate the growth of the economy.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data availability The dataset supporting the findings of this research is available upon reasonable request.

Declarations

Conflict of interest None.

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