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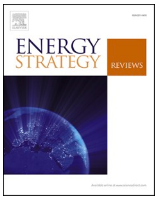

Probing environmental resilience facets of sustainable energy, natural resources, and sustainable innovation among EU member states

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ABSTRACT

By integrating the novel load capacity curve (LCC) with advanced panel quantile techniques, this study offers the first thorough assessment of the key factors of ecological resilience among selected European Union (EU) economies. Recognizing the need to ensure the global temperature increases below 1.5 °C, countries have undertaken enthusiastic initiatives in improving ecological resilience and tackling fatal ecological consequences. However, these initiatives are susceptible to the dynamic increase of natural resources consumption that outpaces the regenerative capacity of the ecosystem among our sample of ten EU states. In this vein, the present study scrutinizes the ecological facets of sustainable energy, demographic factor, and trade globalization under the prism of LCC framework. The empirical findings from the 1991–2021 sample of ten EU member states via Method of Moments Quantile Regression (MMQR) failed to validate the notions of LCC as there is an inverted U-shaped pattern between economic growth and load capacity factor (FCLC). Furthermore, the study evidenced that natural resource use and demographic factor show a significant negative relationship with the ecological resilience in our sample of ten EU member states, whereas sustainable energy, sustainable innovation, and trade globalization enhance FCLC. For moderation effects, sustainable innovation mitigates the negative effect of natural resources. Thus, the EU economies should balance socio-economic and ecological frameworks to rebound the ecological reserve state. By promoting sustainable energy, innovations, and inclusive growth, they can keep the total demand on nature below the biologically regenerative capacity of productive areas to achieve Sustainable Development Goal (SDG-15).

List of abbreviations

BE	Growth of the economy
CADF	Cross-sectional augmented Dickey-Fuller
CCR	Load capacity factor - carbon component
CGB	Trade globalization
CMN	Contribution of materials from nature to economic growth
CSEC	Cross-sectional dependence
DET	Sustainable innovation
EC	European Commission
ECR	Overall load capacity factor
EEA	European Environment Agency
EKC	Environmental Kuznets Curve
EMN	Earnings from natural resources
ETDK	Regression estimation technique by Driscoll and Kraay
EU	European Union
FCLC	Load capacity factor
FinTech	Financial technology
GFN	Global Footprint Network
HRGS	Slope heterogeneity
IRENA	International Renewable Energy Agency
KOF	KOF Swiss Economic Institute
L	Logarithm
LCC	Load Capacity Curve
MN	Materials from nature
Mod	Moderator
NTA	Natural asset
OECD	Organization for Economic Co-operation and Development:
PPL	Demographic factor
MMQR	Method of Moments Quantile Regression
SDG	Sustainable Development Goals

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(*continued*)

STE	Sustainable energy
URSP	Cross-section Im, Pesaran and Shin unit root
WB	World Bank
Δ	Delta

1. Introduction

Ecological resilience is a concept that is well known as an ecosystem's ability to absorb external shocks while maintaining its core structure and function. The concept has evolved widely in the last five decades, particularly amid Earth's challenging and rising global temperature. Ecological resilience is the ultimate concept that policymakers utilize today to combat global warming. In the European Union (EU) alone, the concept of ecological resilience has influenced policy initiatives, government-level strategies, and socio-economic factors. Several policies related to ecological resilience have been implemented in the EU area. For example, the land restoration law which mandates the restoration of at least 30% of habitats in poor condition by 2030 and is expected to reach 90% by 2050 [1]. These policies underscore a commitment to reversing environmental degradation and fostering sustainable land usage. However, despite the efforts, the EU is still experiencing environmental challenges. For instance, the EU is experiencing an accelerating climate change, with temperatures reaching a record high in 2024. Moreover, 80% of EU habitats are also in poor condition, which leads to declining biodiversity thus reflecting the need to increase the general ecological integrity of the bloc [2]. Also, air pollution remains one of the single most significant environmental health risks in the region, which contributes to respiratory diseases. Given this circumstance, understanding factors influencing the ecology in the EU is considered crucial.

Past literature has studied ecological resilience in relation to sustainable innovation, natural resources, and sustainable energy [3–6]. Despite the number of studies conducted in the past, several gaps are still found in existing literature. Firstly, although prior studies have explored the impacts of technological innovations and natural resources in view of ecological resilience, only a few studies have comprehensively examined their collective influence on the subject matter using a dual-load capacity factor approach. The relevance of following this relates to its potential methodological gains as it captures both the biocapacity and carbon-specific dynamics. Secondly, past studies also primarily focused on either emerging economies and many of those with specific regions without adequately addressing cross-sectional dependence and slope heterogeneity among countries, thus leading to bias results. Thirdly, studies focusing on sustainable innovation in advanced economic bloc like the EU are limited and most extant studies have not uniquely assessed its role in moderating the natural resources-ecological resilience nexus.

The Environmental Kuznets Curve (EKC) conceptually explains a relationship between economic progress and environmental pressure [7]. The curve demonstrates that the relationship between the two follows an inverted U-curve where environmental pressure initially increases when economic development increases, but the pressure will reach an extreme point and start to decline due to cleaner and more environmentally friendly technology. In practice, EKC is typically measured using metrics such as emissions or pollution intensity. On the contrary, the Load Capacity Curve (LCC) focuses on comparing the economic progress and environmental sustainability, not focusing on environmental degradation as in the EKC case. Thus, in LCC, the relationship between economic growth and environmental sustainability follows a U-curve, where environmental sustainability initially decreases as economic growth increases. However, as technology increases, the country can manage its environment better, resulting in a sustainability rebound. However, what more interesting from the LCC concept is that it is more forward thinking for not only focusing on today's degradation but, more importantly, on the ability of the economy to manage its environmental quality in the long run.

Therefore, this study provides new insights into the existing literature on whether economic growth truly improves long-term ecological sustainability in view of sustainable innovations. It provides unique perspective by implementing the Load Capacity Curve (LCC) framework for the EU bloc in contrast to the traditional Environmental Kuznets Curve (EKC) approach (Objective 1). This procedure creates a two-way understanding of the research inquiry by considering both the demand and supply sides of natural capital vis-à-vis two indicators of ecological resilience, namely, the overall load capacity factor and its carbon-specific components. This study also offers a more robust and in-depth analysis of how key macroeconomic variables (sustainable energy, natural resources, demographic factor, trade globalization, and sustainable innovation) interact with ecological resilience (Fig. 1) by addressing cross-sectional dependence and heterogeneity in block-level analysis of the EU countries via advanced second-generation techniques that are panacea to the identified methodological limitations (Objective 2). The study also provides important insights into policy formulation based on the outcomes of moderating impact of sustainable innovation on natural resources-ecological resilience relations (Objective 3). Unlike other examinations conducted in past literature, the present research addresses the gap in understanding the differentiated impacts across various levels of ecological resilience using quantile regression technique.

This study examines the response of the indicators of ecological resilience to key macroeconomic factors across ten EU countries from 1991 to 2021. Ecological resilience was examined in view of sustainable innovation while incorporating pressing forces like resource intensity, natural capital earnings, economic growth, population, trade globalization and sustainable energy [8,9]. To have a robust synthesis of ecological resilience, two load capacity factor (FCLC) indicators were adopted. By these strategies, the current study provides deep insights into the pressing question of how impactful are sustainable innovations on the ecological resilience of an economically buoyant blocs such the EU.

The choice of the 10 EU members builds on the following grounds: studied countries have extended feasible actions to support sustainable innovation as it fortifies better usage of resources from nature and advances the transition towards more circular EU. Additionally, aside from the fact that the EU is an advanced economy, with a global relevance as a sustainability frontrunner, the EU is a critical case study considering the bloc's unique ambitious green transition policies like the European Green Deal. Sustainable innovation represents a keystone in attaining the targets of European Green Deal. Specifically, 6 out of 10 selected countries are eco-innovation leaders in 2024 with Austria ranked 3rd, Sweden 5th, Italy 6th, France 7th, Germany 8th, and Netherlands 9th [10]. The focus on the investigative laboratory is further explained by the considerable production capabilities. Particularly, BE in the selected countries (36919.26 US$) outstrips the average BE of European Union (33456.23 US$), Euro area (36794.27 US$) and global average BE (11100.29 US$) in 2021 [11]. It is also plausible to note that the sampled countries report substantially lower contribution of materials from nature to BE (0.32) than high income countries (2.45), OECD members (1.44) and World (3.03) in 2021 [11]. An additional reason that justifies the selection of underlying countries is their commitment to switch to sustainable energy sources.

Furthermore, the adoption of the LCC framework in this study adds to the contribution as this provides a main theoretical strength for the study. Two indicators of ecological resilience, namely, the overall load capacity factor (ECR) and its carbon-specific components (CCR) were utilized and this allows the study to separate drivers of general ecological balance from those affecting climate-specific pressures, providing deeper insight. Besides, in addition to the LCC hypothesis, the use of the MMQR techniques further adds to the contributions by aptly addressing

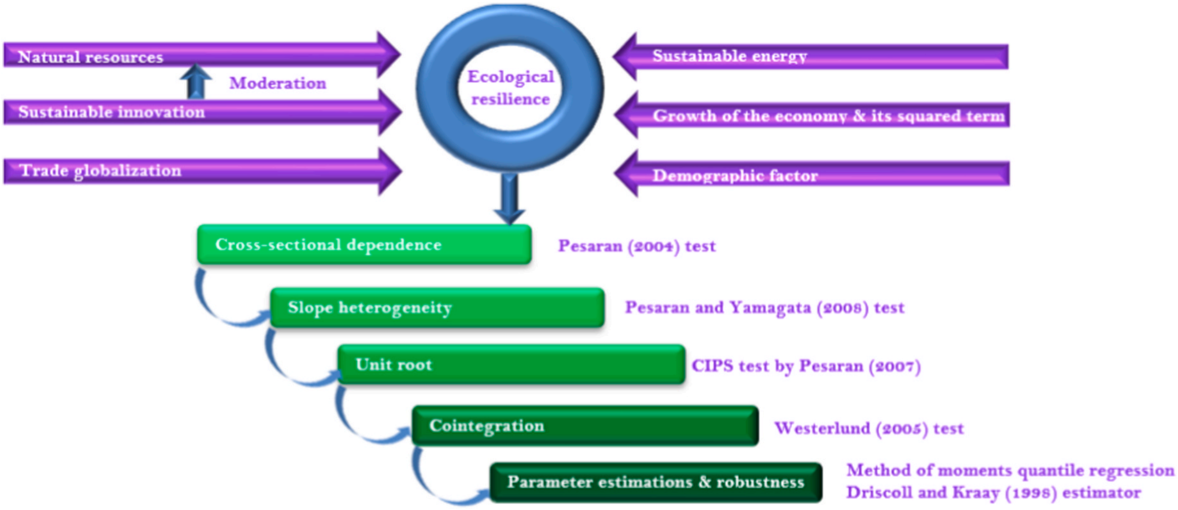

Fig. 1. Conceptual framework.

heterogeneity in EU ecological resilience.

This study is structured as follows. The first section is the introduction. The second section is a systematic literature review and detailed examination of past literature. The third section includes analysis. The final section concludes.

2. Literature review

This section examines the relevant literature by systematically comparing and contrasting multiple studies on environmental sustainability based on the framework of sustainable innovation, natural resources, and policy interventions. Some studies demonstrate that sustainable innovation positively affects environmental sustainability. For example, Wang et al [3] demonstrated that sustainable innovations combined with renewable energy use significantly improve environmental quality. However, Caglar et al. [6] and Voumik et al. [5] point out that even if the adoption of green technologies takes place, the immediate effects can sometimes be detrimental to the environment. This is believed to occur because many green technologies are still not fully efficient and produce sub-optimal results, especially in the period just after they have been adopted. Uche et al. [4] argue that without a much stronger policy push, green technology processes have environmental sustainability payoffs that are, at best, marginal. They noted that while green transitions vastly enhance ecological quality, green technologies have only marginal positive effects due to their underdeveloped status. Urbanization, economic expansion, and resource utilization negatively impact FCLC, with urbanization being the most damaging.

Another EU related study by Chen et al. [12] employs panel econometric techniques to analyze a comprehensive array of data, up to 19 years, across 27 countries in the bloc. The study demonstrates that the direct positive consequence of the energy transition is a considerable reduction of the ecological footprint. Similarly, Satrovic et al. [13] unveil that clean energy technology patents play a significant role in improving ecological sustainability. On the other hand, a greater bulk of attention is given to the assessments of natural resources in some other studies. It has been consistently argued that overdependence on such resources undermines the sustainability of the environment [14–16], as well as overall economic progress thereby lending support to the “resource curse” hypothesis [17].

In contrast, Atchike et al. [18] presented a more detailed perspective. They indicate that while coal and forest use are detrimental to sustainability, resources like natural gas and advancements in green energy can alleviate such conditions. Samour et al. [19] and Ozbay et al. [20] present differing results by extending the research scope to the evolution of finance and the finance sector's activities. According to Samour et al. [19] financial inclusion improves environmental quality. In contrast, Ozbay et al. [20] indicated that the actions of financial institutions and markets frequently undermine sustainability, highlighting the necessity for regulations that ensure finance promotes green initiatives.

Xiao et al. [21] highlight FinTech's moderating role in reducing the ecological footprint. They show that digital financial tools can aggravate the effects of circular economy practices and technological innovations that can potentially diminish ecological impacts. In the paper, the authors moderate their environmental finance theory and combine it with a concept that few finance researchers have used: sustainable finance. They contend this combination results in a robust theory using FinTech to achieve enhanced environmental sustainability in the EU.

With regard to economic growth and the framework of policy, a number of studies (e.g., Ref. [13,19,22]) validate versions of the Environmental Kuznets Curve (EKC) or Load Capacity Curve (LCC), confirming that, the increase in environmental degradation is a by-product of the early stages of economic growth, and we cannot expect it to improve until the economy reaches a much higher level of development. Several studies have confirmed the Environment Kuznets Curve (EKC) framework across the European Union. The N-shaped EKC is a recent confirmation reaching back to 1990 and forward to 2019 across EU member states [22]. The N-shaped EKC paradigm holds that there is a much longer period of economic increase and environmental degradation before wealthier states enjoy any real environmental improvement.

Beyond the economic growth aspects, demographic factors are recently seen as other essential indicators in relation to ecological resilience and environmental sustainability. This relationship emerges from the rationale that population growth and housing patterns influence higher consumption of natural resources. The higher demand for natural resources is consequently followed by higher residuals, such as waste, pollution, and natural scarcity, due to people's exploitation of natural resources. Recent studies like those of Udemba et al. [23] and Voumik et al [24] show that population growth increases energy use and land conversion in such a way that it deteriorates the biocapacity equilibrium and ecological footprint. Consequently, this condition deteriorates environmental resilience in the long run. The role of demographics as a channel in imposing negative impact on the environment is also supported by the studies from Saud et al. [22] and Atchike et al. [18] through their LCC-based findings, where the role of clean technology is noted to be crucial in moderating the negative impact of demographics on environmental degradation.

In addition to demographics, globalization is also increasingly recognized as an essential macro indicator that affect ecological resilience. Globalization can have two side effects on environmental quality. On one side, the intensifying trade activities through globalization make countries exploit their natural resources for profit. This situation imposes a downward pressure on the environment, increasing pollution and environmental degradation. On the other hand, globalization also opens the door for knowledge transfer across countries, which can enhance clean technological development and eventually reduce the bad side effects. Some studies demonstrate that globalization has driven ecological development through wider access to clean technology, which resonates the role of LCC [25–28]. This positive impact occurs through the channel of innovation, which encourages technological diffusion and adoption among countries and thus strengthen their ecological resilience [12,13,25].

In summary, while there is consensus among studies that policy interventions—particularly those supporting sustainable energy, sustainable technology, and fiscal reforms—are essential for sustainability, their effectiveness and the approaches taken vary. Some research prioritizes the role of innovation and the speed of transition [3,4], while others underscore the importance of governance and financing structures [15,20], and others focus on the specifics of resource types and geopolitical factors [5,18]. These variations highlight the complex and context-specific nature of the global effort towards sustainable development. In this regard, we focused on probing the ecological resilience aspects of sustainable innovation, natural resources, and sustainable energy in the European Union.

2.1. Contributions & literature gap

It has been argued that the initial phases of adopting green innovation may not necessarily enhance ecological resilience due to inefficiencies. This study builds on the recently published studies like Caglar et al. [6] and Voumik et al. [5] to examine the veracity of this claim using an approach that provides unique perspective via the LC framework for the EU bloc in contrast to the traditional EKC approach. The LCC framework here provides a main theoretical strength for the study. This procedure creates a two-way understanding of the research inquiry by considering both the demand and supply sides of natural capital vis-à-vis two indicators of ecological resilience, namely, the overall load capacity factor (ECR) and its carbon-specific components (CCR). The study contributes to the growing debate on ecological resilience from a pragmatic case synthesis considering that the EU is among the leading blocs at the forefront of the global sustainable innovation drive. Moreover, none of the aforementioned studies have been known to inspect the indirect effect of sustainable innovation in moderating the impact of natural resources on ecological resilience under the umbrella of LCC for the EU bloc. Therefore, the current study applies the LCC hypothesis and Method of Moments Quantile Regression to address heterogeneity in EU ecological resilience.

2.2. Research objectives

The observations discussed above bring forward important research questions that call for further investigation. Correspondingly, the objectives of this study are formulated as follows:

Objective 1: To empirically test the Load Capacity Curve (LCC) hypothesis for selected EU states.

Objective 2: To examine the role of sustainable energy, natural resources, demographic factor, trade globalization, and sustainable innovation in fostering ecological resilience.

Objective 3: To give fresh insight into the moderating impact of sustainable innovation on natural resources-ecological resilience nexus.

These objectives are intrinsically linked to the underlying theory and facilitate the determination of policy insights employing a methodologically robust Method of Moments Quantile Regression.

3. Methodology

3.1. Data

The ongoing study delves into the response of ecological resilience to the escalation in several key macroeconomic indicators for the ten European Union – EU members incorporating (Austria, Belgium, France, Germany, Greece, Italy, Netherlands, Poland, Spain, and Sweden). Explanatory variables embrace: natural resources intensity, earnings from natural capital, growth of the economy, sustainable innovation, sustainable energy, population, and trade globalization examining the time-period from 1991 to 2021 (Table 1). The selection of the investigative laboratory from 1991 to 2021 was made on the data availability. Notably, the data on population were available starting from 1991, whereas the data on sustainable innovation were not available after 2021. The choice of the 10 EU members builds on the following grounds: first, studied countries have extended feasible actions to support sustainable innovation [10]. Second, the superior production capabilities of selected EU members which exceed those of the non-selected countries (Table 2). Third, the selected EU members report substantially higher earnings from materials from nature in comparison to non-selected EU members. Owing to the lack of DET balanced data for Bulgaria, Croatia, Cyprus, Estonia, Latvia, Lithuania, Romania, Slovenia, Malta, these countries were excluded from the present study. In addition, Czech Republic, Finland, Ireland, Slovakia, Denmark, Hungary, Luxembourg, and Portugal were omitted due to the unavailability of ECR, PPL, CCR, CMN, or EMN data in balanced form. The detailed specification of the ecological resilience and the selected explanatory variables is clarified in Table 1.

From the outcomes in Table 2, it can be noted that the average BE of the observed economies is 31995.69 with the substantial heterogeneity in income between the selected EU members. The average contribution of materials from nature (MN) to BE is 0.34, with some countries unveiling low to moderate contribution, while other countries substantially capitalize on earnings from natural resources. Our study further applies the correlation analysis and details the findings in Table 3.

As suggested in Table 3, there is positive and statistically significant relation between the growth of the economy, contribution of materials from nature to BE, population, trade globalization, and sustainable energy. There is also a positive association between ECR, trade globalization, earnings from natural capital, and sustainable innovation, but statistically insignificant. Moreover, ECR has a positive and statistically significant correlation with CMN, BE, STE, and population.

3.2. Theoretical framework and econometric model

The ecological impact of economic activities has been researched tremendously in past studies. As a leading framework, many of these studies [32,33] established on the Environmental Kuznets Curve (EKC) trajectory instituted by Grossman and Krueger [34]. Despite its popularity, EKC trajectory covers only the demand for natural assets and looks over the supply aspect. To handle this scenario, our research develops on the novel trajectory, namely load capacity curve (LCC) hypothesis which divulges a shape different from EKC. The adoption of the Load Capacity Curve (LCC) framework provides a primary theoretical strength for this study. By extending beyond the demand-side focus of the traditional EKC, the LCC incorporates both biocapacity (supply) and ecological footprint (demand) sides. Thus, the LCC provides a more holistic and in-depth evaluation of ecological resilience thereby better aligning directly with the ultimate goal of sustainability policy.

To probe into the ecological impacts of the growth of the economy (BE), contribution of materials from nature (MN) to BE; earnings from MN; sustainable innovation, sustainable energy, population, and trade globalization the study applies the trajectory of LCC hypothesis [35–37] and mathematically expresses the base model as detailed below (Eq.

Table 1
The description and source of explanatory and response variables.

Symbol	Name	Description/construction	Unit of measurement	Expected sign	Source
BE	Growth of the economy	Gross domestic product - GDP per capita	2015 US$	+/−	WB [11]
CMN	Contribution of materials from nature (MN) to BE	Total natural resources rents to GDP	ratio	+/−	WB [11]
EMN	Earnings from MN	CMN × GDP	2015 US$	+/−	WB [11]
DET	Sustainable innovation	Environment-related technologies/domestic innovations	ratio	+	OECD [29]
STE	Sustainable energy	Renewable energy/final consumption	ratio	+	WB [11]
PPL	Population	Civilian labor force aged 15-24 currently employed against the working age population	ratio	-	WB [11]
CGB	Trade globalization	Trade globalization index	index	+/−	KOF [30]
ECR	Ecological resilience 1	Biocapacity global hectare – gha per person/ecological footprint gha per person	ratio	dependent variable	GFN [31]
CCR	Ecological resilience 2	Biocapacity global hectare – gha per person/carbon footprint component of ecological footprint gha per person	ratio	dependent variable	GFN [31]

Table 2
Summary statistics and sample comparison.

Sample	Stat./Var.	BE	CMN	EMN	DET	STE	PPL	CGB	ECR	CCR
Selected EU members	Average	31995.69	0.34	2070000000	10.35	14.2	36.82	70.42	0.47	0.86
	St. Dev.	11383.97	0.65	2990000000	3.58	12.31	16.57	10.4	0.42	0.87
	Max	54458.4	5.71	24600000000	25.49	57.9	78.26	89	2	4.39
	Min	4735.93	0.02	49100000	1.76	0.9	11.87	41	0.15	0.24
	Skew.	−0.538	4.361	3.618	0.578	1.467	0.912	−0.38	2.315	2.419
	Kurt.	2.638	27.051	20.229	3.776	4.61	2.95	2.559	7.279	7.739
Non-selected EU members	Average	24132.2	0.66	1072153.99	11.52	16.31	34.66	75	0.69	1.49

Table 3
Correlation analysis.

Variables	BE	CMN	EMN	DET	STE	PPL	CGB	ECR	CCR
BE	1								
CMN	−0.301a	1							
	0.000								
EMN	−0.107c	0.896a	1						
	0.060	0.000							
DET	0.037	0.208a	0.228a	1					
	0.520	0.000	0.000						
STE	0.429a	0.067	0.001	0.280a	1				
	0.000	0.237	0.866	0.000					
PPL	0.545a	0.027	0.133b	−0.061	0.096c	1			
	0.000	0.633	0.020	0.282	0.093				
CGB	0.651a	−0.009	0.067	0.064	0.193a	0.445a	1		
	0.000	0.871	0.238	0.261	0.001	0.000			
ECR	0.284a	0.143b	0.048	0.070	0.831a	0.100c	0.039	1	
	0.000	0.012	0.402	0.222	0.000	0.080	0.494		
CCR	0.303a	0.135b	0.049	0.072	0.835a	0.073	0.050	0.987a	1
	0.000	0.018	0.393	0.204	0.000	0.199	0.379	0.000	

a, b, and c - 1%, 5% and 10% statistical significance, respectively; p values in dot-dash underline.

(1)):

$$ECRS_{it} = f(BE_{it}, BE2_{it}, NTA_{it}, DET_{it}, STE_{it}, PPL_{it}, CGB_{it}) \quad (1)$$

In Eq. (1), environmental resilience proxied by load capacity factor is symbolized by FCLC while BE stands for the growth of the economy. Moreover, the present study sets out the twin measures of natural assets (NTA); CMN - depicting the contribution of materials from nature to BE in base models and earnings from MN (EMN) in the alternative model specification. Sustainable innovation is signalized by DET, whereas STE gauges sustainable energy. The impact of population is captured by PPL, while the ecological impact of globalization is divulged by introducing trade globalization index (CGB). The selected regressors and regressands are natural log transformed, and the consecutive model is written as (Eq. (2)):

$$LECRS_{it} = \alpha_{it} + \beta_1 LBE_{it} + \beta_2 LBE2_{it} + \beta_3 LNTA_{it} + \beta_4 LDET_{it} + \beta_5 LSTE_{it} + \beta_6 LPPL_{it} + \beta_7 LCGB_{it} + \varepsilon_{it} \quad (2)$$

With reference to Eq. (2), L is the depiction of natural log, $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7$ are the coefficients to be estimated. By the means of these coefficients, the current research will witness which of the explanatory variables indeed influences ecological resilience of our sample of ten EU members signalized by *i*. The analysis is conducted for the period from 1991 to 2021, which is delineated by *t*. Random error terms are subsequently specified by ε_{it} and intercept by α_{it}.

The ideology of LCC trajectory is that economic expansion is negatively related to FCLC initially, whereas higher growth prospects divulge positive relation between BE and twin indicators of ecological resilience. Herein, this new evolved trajectory is established if the coefficient of BE is negative and the coefficient of its squared term is positive (i.e. $\beta_1 =$

$\frac{\partial ECRS}{\partial BE} < 0$ and $\beta_2 = \frac{\partial ECRS}{\partial BE2} > 0$). These findings will substantiate the U-shaped type nexus between economic expansion and ecological resilience [19,36,38]. The relation between BE and ECRS can also follow N-type pattern as divulged by Ref. [35].

Ecological resilience is holistically assessed by evaluating not only the demand but also the supply of natural assets [38]. In this vein the present study employs the twin indicator of FCLC (ECR and CCR) to uncover the nexus between BE and ecological resilience under the prism of LCC hypothesis. It unriddles the ecological progress via the lens of economic activities in view of the supply (i.e. biocapacity) and demand (i.e. ecological footprint) for ecosystem services. With this in mind, the variety of the studies supports the relevance of FCLC to measure ecological resilience [37,39]. To check the robustness of our baseline findings, the alternative model specifications utilize the CCR to measure FCLC. To ascertain robust and subtle assessment, this analysis is methodologically strengthened by using dual indicators for a response variable: ECR and CCR. This perspective enables us to inspect whether determinants influencing overall ecological resilience (ECR) and its carbon-specific component (CCR) lend greater reliability of the outcomes.

In addition to the growth of the economy, the present study opts for the additional explanatory variables of ecological resilience. To start with, special emphasize is placed on the ecological impact of natural resources as these are among the pillars of the BE. In particular, the economic progress of many countries is closely linked with exploitation and/or processing of natural resources, sparking off subsequent ecological challenges in both resource-abundant and dependent economies [33,38,40]. The other strand of literature, however, evidenced the potential beneficial ecological impacts of CMN and EMN. It is reasoned on the ground that natural resources are used to generate sustainable energy, and as such encourage the abatement of World's reliance on non-renewable energy sources [39,41]. Thus, NTA may either upgrade or downgrade the ecological resilience of our sample of ten EU members (i.e. $\beta_3 = \frac{\partial ECRS}{\partial NTA} > 0$ or < 0).

Pursuing sustainable innovation, a myriad of studies has questioned its ecological impact, mostly evidencing that DET foster ecological resilience [3,40,42]. In particular, sustainable technologies are among the vital drivers of ecological resilience as these support eco-friendly manufacturing sites, encourage utilization of green energy, and mitigate pollutant emission from transport. To continuously improve sustainable production and consumption patterns, economies need to rely on modern technologies, and to implement fresh ideas while developing new products [32]. Worthy to note is sustainable innovation's indirect ecological impact, as these enable countries abundant in natural resources to switch from carbon/energy intensive to carbon/energy efficient production of high-tech goods that will not only accelerate export earnings but also mitigate ecological pressures [4]. The utilization of sustainable technology is expected to accelerate the ecological resilience by heightening the efficiency of MN use and flourishing ecological status of our sample of ten EU members (i.e. $\beta_4 = \frac{\partial ECRS}{\partial DET} > 0$).

As the world is turning out to be more tied and interrelated zone, past studies have evolved to delve into the ecological impact of globalization. Globalization fosters the expansion of social, political, and financial relations, among others, delineating the function of technology and trade in interlinking world economies [13]. As such, globalization is described as the reinforced movement of products, services, people, money, and knowledge on a global basis and has conveyed positive and negative societal and ecological impacts [25]. It is plausible to note the inconclusive findings on the ecological impacts of trade globalization. From one perspective trade globalization may fortify the transfer of modern technology and sustainable ways of production; while from the other perspective it may instigate ecological destruction via the means of intensified energy and carbon intensive production [25,26,28]. From the viewpoint of ecological resilience jeopardizing effect, trade globalization increases market access allowing countries to increase the market share and income streams, with transportation being essential in this process [43]. Herein, the ecological impact of trade globalization is controversial as it is likely to undermine or reinforce the ecological resilience of our sample of ten EU members (i.e. $\beta_7 = \frac{\partial ECRS}{\partial CGB} < 0$ or > 0).

The studies on the sustainable energy - ecological resilience nexus have encountered an upward trend divulging a beneficial ecological impact of STE [19,44,45]. Specifically, sustainable energy that is generated from renewable sources including solar, hydropower, and wind among the others, is harmonized with ecological assets responsible management. The generation process of sustainable energy delivers a substantial reduction of anthropogenic emissions and can achieve the net zero emissions. In particular, IRENA [46] unirddles that the shift to sustainable energy can bring about 90% of needed decrease to carbon dioxide emissions from energy. Herein, sustainable energy is having a central role in ensuring cost-effective and ecologically sustainable energy supply hinging on natural assets that can never run out [47]. Consequently, sustainable energy is inclined to promote the ecological resilience of our sample of ten EU members (i.e. $\beta_5 = \frac{\partial ECRS}{\partial STE} > 0$). Pursuing the ecological impact of PPL, is it instructive to unveil that human activities' ecological impact is directly linked with the number of individuals in a population. To feed the rising population, more natural areas need to be transformed for agricultural purposes. Agricultural production is among the major catalyst of greenhouse gasses emissions, being responsible for more than 25% of total emissions and the world level [48]. The adverse ecological impact of population is also justified on the ground that meeting the demand of rising population magnifies energy consumption and overutilization of resources from nature [23,24]. Herein, our sample of ten EU members are likely to encounter ecological destruction due to PPL as population growth is giving assistance to deforestation, wetlands and grassland destruction (i.e. $\beta_5 = \frac{\partial ECRS}{\partial PPL} < 0$).

A further discourse on the ecological impact of NTA scrutinizes the moderating impact of sustainable innovation on NTA-ecological resilience relation. By the virtue of interaction term, this study questioned whether sustainable innovation facilitates or obstructs the ecological impact of natural resources. Sustainable innovations open the way to improve the efficiency of MN utilization, material efficiency, and energy savings [49]. These innovations are actually changing the way MN are extracted and consumed, focusing on natural capital output efficiency, eco-friendly products, and energy conservation policies to hinder waste generation and ecological destruction [40]. From the demand perspective, sustainable energy hinders the intensity of energy use and bolsters energy-efficiency as STE redefines the way energy is consumed by individuals. Based on the above arguments, sustainable innovations have a pivotal role in tackling the adverse ecological impact of NTA supporting the development of technologies that are less polluting, more energy efficient, and that generate less waste (i.e. $\frac{\partial ECRS}{\partial (DET \times NTA)} > 0$). Herein, to tackle the disadvantageous ecological impact of natural resources, it is essential to foster the productivity of manufacturing sites, energy efficiency, mitigation of pollutant emissions, and the transition to a carbon-free economy via the lens of sustainable innovations. After introducing the joint impact between NTA and DET, Eq. (2), is modified as following (Eq. (3)):

$$LECRS_{it} = \alpha_{it} + \beta_1 LBE_{it} + \beta_2 LBE2_{it} + \beta_3 LNTA_{it} + \beta_4 LMod_{it} + \beta_5 LSTE_{it} + \beta_6 LPPL_{it} + \beta_7 LCGB_{it} + \varepsilon_{it} \tag{3}$$

Such that, Mod = DET × NTA and LMod = L (DET × NTA).

3.3. Estimation process

The first task of the econometric investigation embodies the assessment of cross-sectional dependence (CSEC). Our sample of ten EU members are bound together by virtue of harmonized macroeconomic policies, uniformity in financial institutions' principles, and coordinated monetary policies heightening the risk of CSEC issue. Testing this issue has a critical role in panel data analysis as neglecting CSEC gives rise to unreliable empirical outcomes. To handle this scenario, the present study proceeds with the assessment of CSEC by utilizing Pesaran [50] test illustrated as (Eq. (4)):

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

Regarding Eq. (4), T expresses the observed time-span that ranges between 1991 and 2021, while the number of cross-sectional units is specified by N. The relationships between variables are signalized by $\widehat{\rho}_{ij}$. The null hypothesis supposes no relationship between our sample of ten EU members unriddling no CSEC in the investigative laboratory, while CSEC is assumed under the alternative hypothesis.

To probe into the status of our sample of ten EU members' dataset, econometric investigation proceeds with the slope heterogeneity test (HRGS). Under the null hypothesis, the parameter of interest is assumed homogeneous suggesting no EU member-specific heterogeneity. By contrast, alternative hypothesis presumes the heterogeneous slopes, and the HRGS test illustrated by Pesaran and Yamagata [51] is expressed as (Eqs. (5) and (6)):

$$\widetilde{\Delta}_{HRGS} = (N)^{1/2}(2k)^{1/2}\left(\frac{1}{N}\widetilde{S} - k\right) \tag{5}$$

$$\widetilde{\Delta}_{AHRGS} = (N)^{1/2}\left(\frac{2k(T-k-1)}{T+1}\right)^{-1/2}\left(\frac{1}{N}\widetilde{S} - 2k\right) \tag{6}$$

Concerning Eq. (5) and Eq. (6), the values of the HRGS test are exhibited as $\widetilde{\Delta}_{HRGS}$, while the values of this test adjusted for bias are signalized by $\widetilde{\Delta}_{AHRGS}$. T-statistic values are demonstrated by $\widetilde{S}$ and the drives of ecological resilience by k.

Succeeding in the investigation of CSEC and HRGS, the econometric framework maintains the assessment of the order of integration. As a way of doing so, the ongoing study capitalizes on the benefits of second-generation Cross-section Im, Pesaran and Shin (URSP) unit root test proposed by Pesaran [52], to mitigate the CSEC and HRGS issues. The URSP equation can be illustrated as (Eq. (7)):

$$\widehat{URSP} = N^{-1}\sum_{i=1}^{N} CADF \tag{7}$$

In Eq. (7), *CADF* signalizes the cross-sectional augmented Dickey-Fuller applied to assess the stationarity properties under the URSP test. The null hypothesis makes explicit that panels contain unit root, while the null hypothesis witness stationary properties of the underlying variables.

Subsequently, this study utilizes the cointegration tests to assess the co-movement between the selected variables in the long run. It precedes the estimation of regression parameters, and serves out for analyzing cointegration between ecological resilience, BE, NTA, DET, STE, PPL, and CGB. The Westerlund [53] cointegration test is likely to be accurate if the panel data is the subject of CSEC and HRGS issues. The H0 hypothesizes no cointegration, whereas the alterative hypothesis clarifies the prevalence of long-run nexus among the selected critical determinants of ecological resilience.

The final stage of econometric investigation establishes on the Method of Moments Quantile Regression (MMQR) to estimate elasticities. In particular, the estimation pattern established by Machado and Silva [54] is used to scrutinize the effects of BE, NTA, DET, STE, PPL, and CGB on fluctuations in ecological resilience as assessed across low, medium, and high quantiles. This method is reliable in conducting panel data analysis as it allows for CSEC and HRGS. Herein, to handle cross-sectional dependence and slope heterogeneity validated in our balanced panel dataset and to assess heterogeneous affects across our sample of ten EU members with different levels of ECR and CCR, the present study hinges on the Method of Moments Quantile Regression. This sophisticated estimation method is a great asset, as it generates unbiased outcomes in the presence of CSEC and HRGS issues, and notably illustrates how the influence of our drives of ecological resilience varies across the entire ECR and CCR conditional distribution of our sample of ten EU members. Worth noting is that MMQR works well in the case of fluctuating trend variables as well as in the case of distributions that diverge from normal. Another unique feature of MMQR is that it exhibits robust findings in the case of extreme values and considers the conditional heterogeneity effects of the independent variables on the general distribution, instead of shifting them to the mean. The illustration of the MMQR is exhibited as (Eq. (8)):

$$Q_{Y_{it}}(\tau|X_{it}) = \alpha(\tau)'X_{it} + \beta_i, i = 1, \ldots, N; t = 1, \ldots, T \tag{8}$$

$\alpha(\tau)$ is the symbol for elasticities and demonstrates the response of dependent variables to the explanatory variables in Eq. (8). In particular, FCLC stands for the twin dependent variables described by Y_{it} and their drivers are outlined by X_{it}. The MMQR specifications used in the present study are written as ($Models$ 1 & 5 – Eq. 9; $Models$ 2 & 6 – Eq. 10; $Models$ 3 & 7 – Eq. 11; $Models$ 4 & 8 – Eq. 12):

$$\begin{aligned} Q_{LECR|LCCR}(\tau|X_{it}) = {} & a_{1\tau}LBE_{it} + a_{2\tau}LBE2_{it} + a_{3\tau}LCMN_{it} + a_{4\tau}LDET_{it} \\ & + a_{5\tau}LSTE_{it} + a_{6\tau}LPPL_{it} + a_{7\tau}LCGB_{it} + \beta_i \end{aligned} \tag{9}$$

$$\begin{aligned} Q_{LECR|LCCR}(\tau|X_{it}) = {} & a_{1\tau}LBE_{it} + a_{2\tau}LBE2_{it} + a_{3\tau}LEMN_{it} + a_{4\tau}LDET_{it} \\ & + a_{5\tau}LSTE_{it} + a_{6\tau}LPPL_{it} + a_{7\tau}LCGB_{it} + \beta_i \end{aligned} \tag{10}$$

$$\begin{aligned} Q_{LECR|LCCR}(\tau|X_{it}) = {} & a_{1\tau}LBE_{it} + a_{2\tau}LBE2_{it} + a_{3\tau}LCMN_{it} + a_{4\tau}LMod1_{it} \\ & + a_{5\tau}LSTE_{it} + a_{6\tau}LPPL_{it} + a_{7\tau}LCGB_{it} + \beta_i \end{aligned} \tag{11}$$

$$\begin{aligned} Q_{LECR|LCCR}(\tau|X_{it}) = {} & a_{1\tau}LBE_{it} + a_{2\tau}LBE2_{it} + a_{3\tau}LEMN_{it} + a_{4\tau}LMod2_{it} \\ & + a_{5\tau}LSTE_{it} + a_{6\tau}LPPL_{it} + a_{7\tau}LCGB_{it} + \beta_i \end{aligned} \tag{12}$$

In order to check the robustness of the analyzed elasticities under the prism of LCC phenomenon, the present study performs the regression estimation technique (ETDK) developed by Driscoll and Kraay (1998). To scrutinize the ecological impact of the selected drivers of ecological resilience, this study opts for the ETDK as it is reliable in the case of CSEC issues.

4. Empirical outcomes

At the beginning of this section, we deployed the Pesaran [50] test to assess the persistence of CSEC issue among the adopted sample of ten EU members, with the outcomes detailed in Table 4. It is quite likely that the selected countries will encounter the CSEC issue, given their institutional, economic, and financial collaboration under the umbrella of EU bodies and agencies. Given these strong ties, the ecological challenges caused by economic expansion in one EU member pose a vigorous risk in the other EU members.

As outlined in Table 4, the null hypothesis of the CSEC is denied at a 1% confidence level for all models, witnessing the persistence of CSEC

Table 4
CSEC and HRGS analysis.

Test/Model	Model 1	Model 2	Model 5	Model 6
Cross-sectional dependence by Pesaran [50]	7.116a (0.000)	7.286a (0.000)	14.579a (0.000)	14.759a (0.000)
HRGS Δ test	10.028a (0.000)	10.025a (0.000)	11.687a (0.000)	11.742a (0.000)
HRGS Δ adj. test	11.903a (0.000)	11.900a (0.000)	13.873a (0.000)	13.938a (0.000)

a, b, and c - 1%, 5% and 10% statistical significance, respectively; p values in dot-dash underline.

issue. It is pertinent to spotlight from these outcomes that there is a strong dependence across our sample of ten EU members delineating that ecological resilience betterment effect in one of EU members will quickly foster ecological progress in the rest of the region. To diagnose the HRGS, this study establishes on the estimation pattern proposed by Pesaran and Yamagata [51] and specifies its outcomes in Table 4.

Concerning the outcomes of HRGS technique, it is suitable to specify that the null hypothesis is rejected against alternative for base and alternative model specifications. Herein, Table 4 delineates the persistence of HRGS issue suggesting that the relationship between ecological resilience and its drivers varies among our sample of ten EU members. It can be noticeable from Table 4 that the present study should consider CSEC and HRGS while selecting appropriate econometric techniques. In light of this, the second-generation unit root test (Table 5) is apparently viable to examine the stationarity properties.

As per the findings of Table 5, all variables face unit root challenge at levels, considering constant and trend. However, when all variables are tested at their first difference, they become stationary at a 1% significance level. Thereby, all variables have first-order integration ($I(1)$). While the estimation of variables that suffer from unit root is unlikely to furnish unbiased outcomes, the cointegrated data can provide trustworthy empirical outcomes. Accordingly, this study utilizes the cointegration test, as detailed in Table 6.

Regarding the outcomes presented in Table 6, the null hypothesis on no cointegration is dismissed for all models. Herein the assumption of joint co-movement between ecological resilience and its drivers cannot be rejected in the long-run. Based on the outcomes of Table 6, the panel dataset under consideration is qualified to evaluate the regression coefficients in the long-run while tackling the CSEC and HRGS issues. In this sense, the current study decides upon MMQR, and presents the consecutive outcomes for odd quantiles in Table 7 and for even quantiles in Fig. 2. As reported in the Appendix, confidence intervals are outlined in Tables A1 and A2.

It can be noted from Table 7 and Fig. 2 that the growth of the economy is positively related with biocapacity global hectare – gha per person/ecological footprint gha per person which is used as a base proxy for ecological resilience. The findings deduce that an escalation in BE tends to support the ecological resilience across low, middle, and higher quantiles. The positive elasticities of BE are statistically significant across quantiles 0.1-0.8 in our baseline model that uses contribution of materials from nature (MN) to BE to assess the ecological impact of NTA. There is a decreasing trend, outlining a more substantial ecological resilience boosting impact for our sample of ten EU members with poor ecological resilience and weaker impact for our sample of ten EU members with strong ECR. Regarding the ecological impact of its squared term, it is nuanced from Table 7 and Fig. 2 that an increase in BE2 hinders ecological resilience of EU members. In particular, the coefficient of BE2 is statistically significant and negative across multiple quantiles depicting an increasing trend such that BE2 hinders ecological resilience with a sounder effect in more ecologically resilient EU members. A positive coefficient of BE and a negative coefficient pertaining to its quadratic term exerted a concave relationship between growth of the economy and ECR. Herein, BE and ecological resilience nexus do not adhere to the LCC pattern [20]. Specifically, the early stages of growth are attributable to ecological resilience betterment effect (up to a turning point – Table 7), whereas the later stages of growth reduce the ecological resilience contradicting the assumptions of LCC phenomenon. Herein, BE is not effective in tackling the ecological pressure of our sample of ten EU members in the long run. Such a pattern unfolds that the BE positively relates with FCLC and reinforces the ecological resilience in the initial stages as ecological destruction takes some time and cannot be detected automatically [18]. However, at the later stages of economic growth, our sample of ten EU members experienced an escalation of production and consumption pattern coupled with overreliance of fossil fuels bringing about the deterioration of ecological resilience. This clearly underscores that our sample of ten EU member's economy remains intrinsically linked to resource-intensive growth. In a situation like that, the BE does not ultimately advocate the ecological resilience of our sample of ten EU members, necessitating the more responsible use of MN. The non-confirmation of LCC phenomenon is justifiable on the ground that our sample of ten EU members are still dependent on the non-renewable sources and pollution intensive industries. Consequently, BE is not enough to tackle ecological pressures and needs to be supported by sustainable innovations. Although our sample of ten EU members is dedicated to support eco-friendly economic activities, the strong reliance on fossil fuels can harm the biocapacity in favor of ecological footprint. These conclusions are in line with [36,39] that clearly identified the non-authenticity of LCC hypothesis in the long-run in China and Germany, respectively. In the same fashion [35], delineated that BE works for ecological quality of India in early stages of growth, whereas later stages of growth are increasing the ecological pressure.

Table 6
Cointegration analysis.

Model/Stat.	Model 1	Model 2	Model 5	Model 6
Vr. ratio	−1.825b	−1.805b	−1.443c	−1.438c
P value	0.034	0.036	0.074	0.075

a, b, and c - 1%, 5% and 10% statistical significance, respectively.

Regarding the coefficients of CMN and EMN, it can be clarified that overdependence on resources from nature is not a plausible avenue to foster the ecological resilience of our sample of ten EU members, this overdependence rather accomplished ecological pressure. The elasticity of CMN witnesses an increasing trend such that the contribution of materials from nature (MN) to BE led to a drop in ecological resilience with a stronger impact in our sample of ten EU members with strong ecological resilience. Natural resources are among the vital drivers of economic expansion as it requires substantial amount of energy for manufacturing and transportation. Herein, the intensification of energy use demands more natural resources to be extracted [14]. Since traditional extraction process generates waste and emits pollutants in the atmosphere, ecological quality is likely to be jeopardized [22]. The irresponsible use of natural resources may further harm ecological quality via the lens of land erosion, soil devastation, forest loss, and the decline of biological diversity threatening the capacity of ecosystem to produce natural capital and absorb greenhouse gases. Such findings are well established in the literature, delineating that natural resources promote the ecological unsustainability of advanced and emerging economies as posited by Ref. [40]. These adverse ecological consequences are unsurprising as economic emancipation establishes on the magnified use of natural resources, such that their extraction consumes immense amounts of energy and emits dangerous chemicals. Our findings also support the notions of [38] outlining that the overconsumption of natural capital prevents the ecological resilience of Asia Pacific emerging countries, portraying the negative association between FCLC

Table 5
URSP analysis.

Test/Var.	LBE	LBE2	LCMN	LEMN	LDET	LSTE	LPPL	LCGB	LECR	LCCR
Constant and trend (Log-transformed variable)	−1.952	−1.929	−2.397	−2.542	−3.923	−2.700	−2.503	−2.616	−4.161	−3.650
Constant and trend (First difference)	−3.333a	−3.331a	−5.353a	−5.437a	−5.328a	−5.464a	−4.195a	−5.745a	−6.336a	−6.316a

a, b, and c - 1%, 5% and 10% statistical significance, respectively.

Table 7

MMQR analysis (ECR-proxy for ecological resilience).

Model	Var.	ETDK		GQ = 0.1		GQ = 0.3		GQ = 0.5		GQ = 0.7		GQ = 0.9	
		EA	p	EA	p	EA	p	EA	p	EA	p	EA	p
1	LBE	1.529a	0.002	1.775b	0.034	1.646a	0.004	1.551a	0.002	1.460b	0.012	1.243	0.252
	LBE2	−0.108a	0.000	−0.113a	0.006	−0.111a	0.000	−0.109a	0.000	−0.107a	0.000	−0.103c	0.057
	LCMN	−0.039a	0.000	−0.042a	0.003	−0.041a	0.000	−0.039a	0.000	−0.038a	0.000	−0.035c	0.057
	LDET	0.063b	0.016	0.076b	0.014	0.069a	0.001	0.064a	0.000	0.060a	0.005	0.049	0.225
	LSTE	0.080a	0.000	0.063a	0.001	0.072a	0.000	0.079a	0.000	0.085a	0.000	0.100a	0.000
	LPPL	−0.084	0.138	−0.190a	0.006	−0.134a	0.004	−0.094b	0.023	−0.055	0.252	0.038	0.672
	LCGB	0.467a	0.001	0.250	0.178	0.363a	0.004	0.447a	0.000	0.527a	0.000	0.719a	0.003
	Turning point	1229.889 in 2015 US$											
2	LBE	1.506a	0.003	1.757b	0.036	1.622a	0.004	1.527a	0.002	1.434b	0.014	1.219	0.255
	LBE2	−0.105a	0.000	−0.110a	0.008	−0.107a	0.000	−0.106a	0.000	−0.104a	0.000	−0.099c	0.061
	LEMN	−0.038a	0.000	−0.042a	0.003	−0.040a	0.000	−0.038a	0.000	−0.036a	0.000	−0.032c	0.075
	LDET	0.064b	0.015	0.077b	0.013	0.070a	0.001	0.065a	0.000	0.061a	0.005	0.049	0.213
	LSTE	0.080a	0.000	0.063a	0.001	0.072a	0.000	0.079a	0.000	0.085a	0.000	0.099a	0.000
	LPPL	−0.086	0.131	−0.191a	0.005	−0.135a	0.004	−0.095b	0.022	−0.057	0.241	0.033	0.707
	LCGB	0.467a	0.001	0.247	0.184	0.365a	0.004	0.449a	0.000	0.529a	0.000	0.718a	0.003
	Turning point	1343.227 in 2015 US$											
3	LBE	1.529a	0.002	1.775b	0.034	1.646a	0.004	1.551a	0.002	1.460b	0.012	1.243	0.252
	LBE2	−0.108a	0.000	−0.113a	0.006	−0.111a	0.000	−0.109a	0.000	−0.107a	0.000	−0.103c	0.057
	LCMN	−0.102a	0.001	−0.118a	0.001	−0.110a	0.000	−0.103a	0.000	−0.098a	0.000	−0.083c	0.074
	LMod1	0.063b	0.016	0.076b	0.014	0.069a	0.001	0.064a	0.000	0.060a	0.005	0.049	0.225
	LSTE	0.080a	0.000	0.063a	0.001	0.072a	0.000	0.079a	0.000	0.085a	0.000	0.100a	0.000
	LPPL	−0.084	0.138	−0.190a	0.006	−0.134a	0.004	−0.094b	0.023	−0.055	0.252	0.038	0.672
	LCGB	0.467a	0.001	0.250	0.178	0.363a	0.004	0.447a	0.000	0.527a	0.000	0.719a	0.003
	Turning point	1229.889 in 2015 US$											
4	LBE	1.506a	0.003	1.757b	0.036	1.622a	0.004	1.527a	0.002	1.434b	0.014	1.219	0.255
	LBE2	−0.105a	0.000	−0.110a	0.008	−0.107a	0.000	−0.106a	0.000	−0.104a	0.000	−0.099c	0.061
	LEMN	−0.102a	0.001	−0.120a	0.001	−0.110a	0.000	−0.103a	0.000	−0.097a	0.000	−0.082c	0.079
	LMod2	0.064b	0.015	0.077b	0.013	0.070a	0.001	0.065a	0.000	0.061a	0.005	0.049	0.213
	LSTE	0.080a	0.000	0.063a	0.001	0.072a	0.000	0.079a	0.000	0.085a	0.000	0.099a	0.000
	LPPL	−0.086	0.131	−0.191a	0.005	−0.135a	0.004	−0.095b	0.022	−0.057	0.241	0.033	0.707
	LCGB	0.467a	0.001	0.247	0.184	0.365a	0.004	0.449a	0.000	0.529a	0.000	0.718a	0.003
	Turning point	1343.227 in 2015 US$											

a, b, and c - 1%, 5% and 10% statistical significance, respectively; p values in dot-dash underline; Mod1 = DET × CMN; Mod2 = DET× EMN; EA = estimated coefficients; GQ = grid of quantiles.

and NTA. Ecological resilience challenges are fostered by NTA, as their exploitation generates waste, reduces forest area, and emits pollutants [33]. These findings also give credence to the outcomes presented in Table 7 and Fig. 2 unfolding that developed economies witness the adverse ecological consequences attributable to natural resources consumption.

Concerning the ecological impact of sustainable innovation as measured by environment-related technologies, the outcomes detailed in Table 7 and Fig. 2 delineate that DET ameliorates the ecological resilience of our sample of ten EU members in models without moderation (models 1 and 2). To be more specific, the coefficient of sustainable innovation is positive and statistically significant for quantiles 0.1-0.8 witnessing a decreasing trend. Thus, sustainable innovation causes an improvement of FCLC such that our sample of ten EU members with poor ecological resilience manifest the strongest effects. Regarding this outcome, it can be suggested that environmental-technology patents may contribute to ecological resilience directly and indirectly. As of the direct ways, sustainable innovations support the development of cleaner industrial procedures, expand renewable energy utilization, and mitigate emissions caused by different transportation methods. Thereby, sustainable innovations may seriously threat the demand for non-renewables fostering the radical transition towards renewable sources. In addition, sustainable innovation is a catalyst of productivity gains as modern technology enables companies to increase the level of output accompanied with minimum environmental pressure. Our outcomes are the same as the results of [40] uncovering that innovations positively relate with environmental quality. Analogously, Padhan and Bhat (2024) note that the demand for materials from nature can be lowered while ecological quality improved by moving away from traditional energy use towards modern eco-friendly and energy efficient machineries via the means of sustainable innovation. The same outcome has been uncovered by Ref. [3] postulating the advantageous environmental impact of sustainable innovation in the case of India. However, these outcomes contradict Caglar et al. [6] underscoring the negative association between green technology and environmental quality. As a possible justification, the authors condemn that green technology may necessitate the installation of large renewable energy generating units which can fragment habitats and degrade ecosystem. As observed in the models without (model 1 and 2) and with moderation (models 3 and 4), there is a positive sign coefficient of CGB, portraying that trade globalization enhances ecological resilience of our sample of ten EU members. The increasing trend and statistically significant coefficients of CGB are reported in Table 7 across middle and high quantiles of ecological resilience. Hence, these findings postulate that trade globalization is fruitful for ecological resilience, especially in our sample of ten EU members with high FCLC. The positive coefficient of CGB unriddles that trade globalization may encourage the movement of eco-friendly machineries that will result in more output and less ecological pressure. In addition, trade globalization may drive the modifications in the manufacturing, investment, and consumption patterns in agriculture to reduce the dependence on chemical-intensive food production. Lu et al. [25] validated the same outcome for emerging countries highlighting that globalization acts for ecological progress via the channel of sustainable innovation. The findings of [26] matched with the outcomes portrayed in this study outlining that CGB may synchronously enhance economic performance of Bangladesh and guarantee the betterment of ecological resilience. Likewise [25], posited that globalization can exacerbate ecological quality of developing countries opening up opportunity for considered countries to enhance its FCLC. Our findings also lent credence to Ref. [28] observing that trade globalization supports the

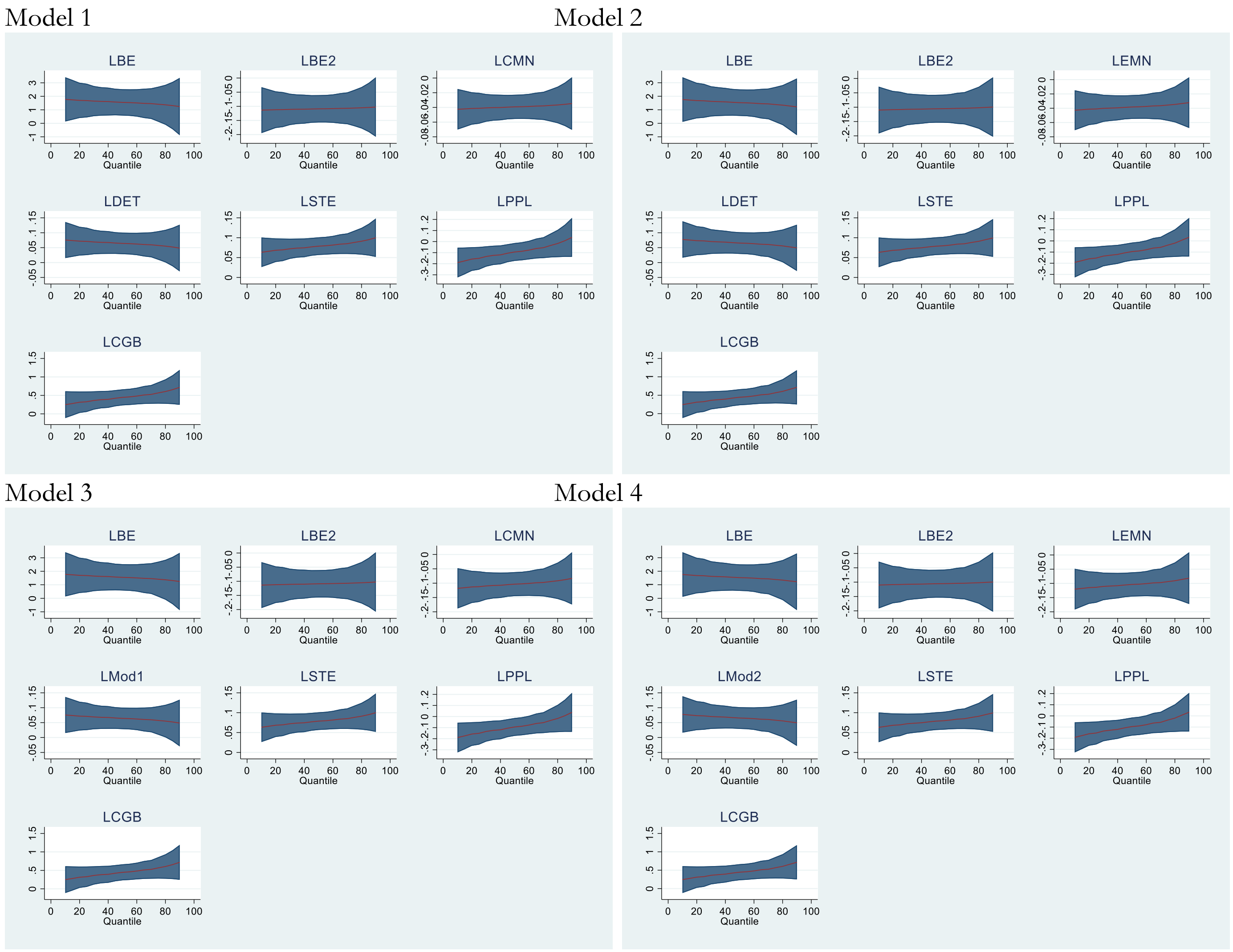

Fig. 2. Plotting elasticities from MMQR analysis (ECR-proxy for ecological resilience).

ecological quality of Japan.

The ecological effect of sustainable energy is meaningful in augmenting the load capacity factor of our sample of ten EU members highlighting that STE is an effective avenue in meeting ecological resilience targets. It can be seen from Table 7 and Fig. 2 that the coefficient of sustainable energy is significant and positive across heterogeneous quantiles of the load capacity factor in all model specifications. The economic connotation of these findings clarifies that the investment in STE is paid off in our sample of ten EU members and thus instigate the reduction of energy volatility via the means of diversified energy mix as supported by Ref. [19,44,45]. Considering the coefficient of PPL it is negative, and statistically significant across low and middle quantiles (models 2 and 4) and low quantiles (models 1 and 3). Our model specifications show an increasing trend, such that population reduces FCLC and ecological resilience of our sample of ten EU members, with a more substantial effect in economies with high ECR values. This unveils that for our sample of ten EU members with inferior ecological outcomes, population growth exerts pronounced pressure, whereas its impact is less intense in high-performing members. It can be attributed to the fact that EU areas with growing population encounter problems or rising energy demand and overconsumption of natural assets. Rising population presses hard on the use of resources from nature and threats our sample of ten EU member's prospect of achieving its ecological resilience. The harmful ecological impact of population pattern in also portrayed by Ref. [23], considering the case study of Russia. Likewise [24], clarified that rising population encourages weaker quality of water and air, as it flourishes anthropogenic emissions and jeopardizes ecological resilience.

Model specifications with moderation (models 3 and 4) further look into the connection between natural resources (both proxies) and ecological footprint by inserting the interaction term. The positive coefficient of the DET-NTA joint impact further clarifies that sustainable innovations assist in alleviating the ecological footprint catalyzed by NTA, indicating a protective role. This implies a desirable moderating effect of higher levels of sustainable innovation on the negative ecological impact per unit of natural resource utilization in the ten EU member states, thereby stimulating remedy for the biocapacity loss in favor of FCLC. This may be due to the fact that sustainable innovation may encourage countries to improve the efficiency of their industrial sites, and to reduce power consumption generated from dirty sources. The transition to modern production techniques may utilize lower level of inputs, reduce the demand for natural assets, and mitigate pollutants associated with their extraction. In addition, sustainable innovation can improve the efficiency of NTA's extraction techniques that will flourish energy conservation. Comprehending these channels [40], delineated that technological advancements help in mitigating the adverse environmental impacts of natural resources. In particular, the combined impact of technological advancements on NTA cuts down the negative environmental externalities of NTA. In the similar fashion [49], postulated that sustainable innovation is a key to solve the irresponsible consumption of natural resources and deplete emissions, provoking ecological resilience.

Lastly, the present study opts for the alternative indicator of FCLC to scrutinize the authenticity of LCC framework and introduces the alternative econometric technique (ETDK) to verify the robustness of the MMQR. In the view of the alternative dependent variable, biocapacity global hectare – gha per person/carbon footprint component of ecological footprint gha per person as a proxy for ecological resilience is adopted in models (5-8). Given the outcomes presented in Table 8 and Fig. 3 it can be uncovered that the coefficient of BE is positive, whereas the coefficient of its quadratic term is negative disregarding the notion of LCC framework in the sample of the selected EU members. Models 4 and 6 divulge that the contribution of materials from nature (MN) to BE reduces ecological resilience. In the similar fashion, earnings from MN as a second measure of NTA, are exhibiting a devastating ecological impact in models 5 and 7. Contrarily, sustainable innovation, sustainable energy, and trade globalization are positively related with FCLC rendering the ecological progress of our sample of ten EU members. The coefficient of population is negative and statistically significant unriddling that PPL is anticipated to reduce ecological resilience. The coefficient of moderation discovers that sustainable innovation is a trustworthy tool to phase out the adverse ecological impacts of NTA. Considering the alternative econometric technique outlined in Tables 7 and 8, the ETDK findings evidenced that the findings are robust to the alternative explanatory variable (EMN), alternative dependent variable (CCR), and alternative estimation approach (ETDK) and are intuitive enough to provide a vigorous policy framework.

5. Conclusion and policy directions

5.1. Summary

This study demonstrates that economic growth shows an inverted U-shaped association with ecological resilience among ten EU economies that were analyzed. This finding indicates that long-term economic expansion within overdependence on natural resources can trigger ecological degradation. On the other hand, the study also demonstrates that sustainable innovation, sustainable energy consumption, and trade globalization positively impact ecological resilience. Furthermore, the moderating role of sustainable innovation in mitigating the adverse environmental effects of resource exploitation underscores its significance in achieving balanced and sustainable development.

5.2. Policy initiatives

The findings are further suggestive of cogent policy directions. To begin with, EU policymakers need to promote sustainable innovation as a primary strategy to mitigate the negative impact of natural resources on environmental quality in the region. Furthermore, empowering sustainable innovation can also assist the EU in transitioning more smoothly from conventional to green energy consumption. The EU is among the leading blocs at the forefront of the global sustainable innovation drive as evidenced in the European Green Deal that aims to make the bloc carbon-neutral by 2050, and it is highly recommended that the momentum should be sustained. The efforts include implementing green technologies, environmentally friendly manufacturing, and renewable energy. We recommend more investments in leading sustainable innovation projects that prioritize energy transition and

Table 8
MMQR analysis (CCR-proxy for ecological resilience).

Model	Var.	ETDK		GQ = 0.1		GQ = 0.3		GQ = 0.5		GQ = 0.7		GQ = 0.9	
		EA	p	EA	p	EA	p			EA	p	EA	p
5	LBE	2.103a	0.002	2.231b	0.040	2.176a	0.005	2.120a	0.002	2.067b	0.013	1.952	0.220
	LBE2	−0.143a	0.000	−0.141b	0.010	−0.142a	0.000	−0.143a	0.000	−0.143a	0.001	−0.144c	0.073
	LCMN	−0.048b	0.016	−0.050a	0.008	−0.049a	0.000	−0.049a	0.000	−0.048a	0.001	−0.046c	0.099
	LDET	0.058c	0.073	0.030	0.427	0.042	0.117	0.055b	0.019	0.066b	0.023	0.092c	0.097
	LSTE	0.116a	0.000	0.109a	0.000	0.112a	0.000	0.115a	0.000	0.118a	0.000	0.125a	0.002
	LPPL	−0.123	0.119	−0.280a	0.003	−0.212a	0.001	−0.143b	0.014	−0.078	0.290	0.063	0.644
	LCGB	0.598a	0.001	0.379	0.116	0.474a	0.006	0.569a	0.000	0.660a	0.000	0.855b	0.016
	Turning point	1656.707 in 2015 US$											
6	LBE	2.074a	0.003	2.244b	0.038	2.170a	0.005	2.097a	0.002	2.026b	0.015	1.867	0.251
	LBE2	−0.139a	0.000	−0.139b	0.011	−0.139a	0.000	−0.139a	0.000	−0.138a	0.001	−0.138c	0.093
	LEMN	−0.047b	0.019	−0.050a	0.009	−0.049a	0.000	−0.047a	0.000	−0.046a	0.002	−0.042	0.139
	LDET	0.060c	0.068	0.033	0.384	0.044	0.100	0.056b	0.017	0.067b	0.021	0.093	0.102
	LSTE	0.116a	0.000	0.109a	0.000	0.112a	0.000	0.115a	0.000	0.118a	0.000	0.124a	0.002
	LPPL	−0.125	0.114	−0.282a	0.002	−0.214a	0.001	−0.146b	0.012	−0.081	0.268	0.065	0.637
	LCGB	0.598a	0.001	0.374	0.120	0.471a	0.006	0.568a	0.000	0.661a	0.000	0.872b	0.016
	Turning point	1887.796 in 2015 US$											
7	LBE	2.103a	0.002	2.231b	0.040	2.176a	0.005	2.120a	0.002	2.067b	0.013	1.952	0.220
	LBE2	−0.143a	0.000	−0.141b	0.010	−0.142a	0.000	−0.143a	0.000	−0.143a	0.001	−0.144c	0.073
	LCMN	−0.107a	0.008	−0.080c	0.066	−0.092a	0.003	−0.103a	0.000	−0.114a	0.001	−0.138b	0.031
	LMod1	0.058c	0.073	0.030	0.427	0.042	0.117	0.055b	0.019	0.066b	0.023	0.092c	0.097
	LSTE	0.116a	0.000	0.109a	0.000	0.112a	0.000	0.115a	0.000	0.118a	0.000	0.125a	0.002
	LPPL	−0.123	0.119	−0.280a	0.003	−0.212a	0.001	−0.143b	0.014	−0.078	0.290	0.063	0.644
	LCGB	0.598a	0.001	0.379	0.116	0.474a	0.006	0.569a	0.000	0.660a	0.000	0.855b	0.016
	Turning point	1656.707 in 2015 US$											
8	LBE	2.074a	0.003	2.244b	0.038	2.170a	0.005	2.097a	0.002	2.026b	0.015	1.867	0.251
	LBE2	−0.139a	0.000	−0.139b	0.011	−0.139a	0.000	−0.139a	0.000	−0.138a	0.001	−0.138c	0.093
	LEMN	−0.106b	0.010	−0.083c	0.059	−0.093a	0.003	−0.103a	0.000	−0.113a	0.001	−0.135b	0.040
	LMod2	0.060c	0.068	0.033	0.384	0.044	0.100	0.056b	0.017	0.067b	0.021	0.093	0.102
	LSTE	0.116a	0.000	0.109a	0.000	0.112a	0.000	0.115a	0.000	0.118a	0.000	0.124a	0.002
	LPPL	−0.125	0.114	−0.282a	0.002	−0.214a	0.001	−0.146b	0.012	−0.081	0.268	0.065	0.637
	LCGB	0.598a	0.001	0.374	0.120	0.471a	0.006	0.568a	0.000	0.661a	0.000	0.872b	0.016
	Turning point	1887.796 in 2015 US$											

a, b, and c - 1%, 5% and 10% statistical significance, respectively; p values in dot-dash underline; Mod1 = DET × CMN; Mod2 = DET× EMN; EA = estimated coefficients; GQ = grid of quantiles.

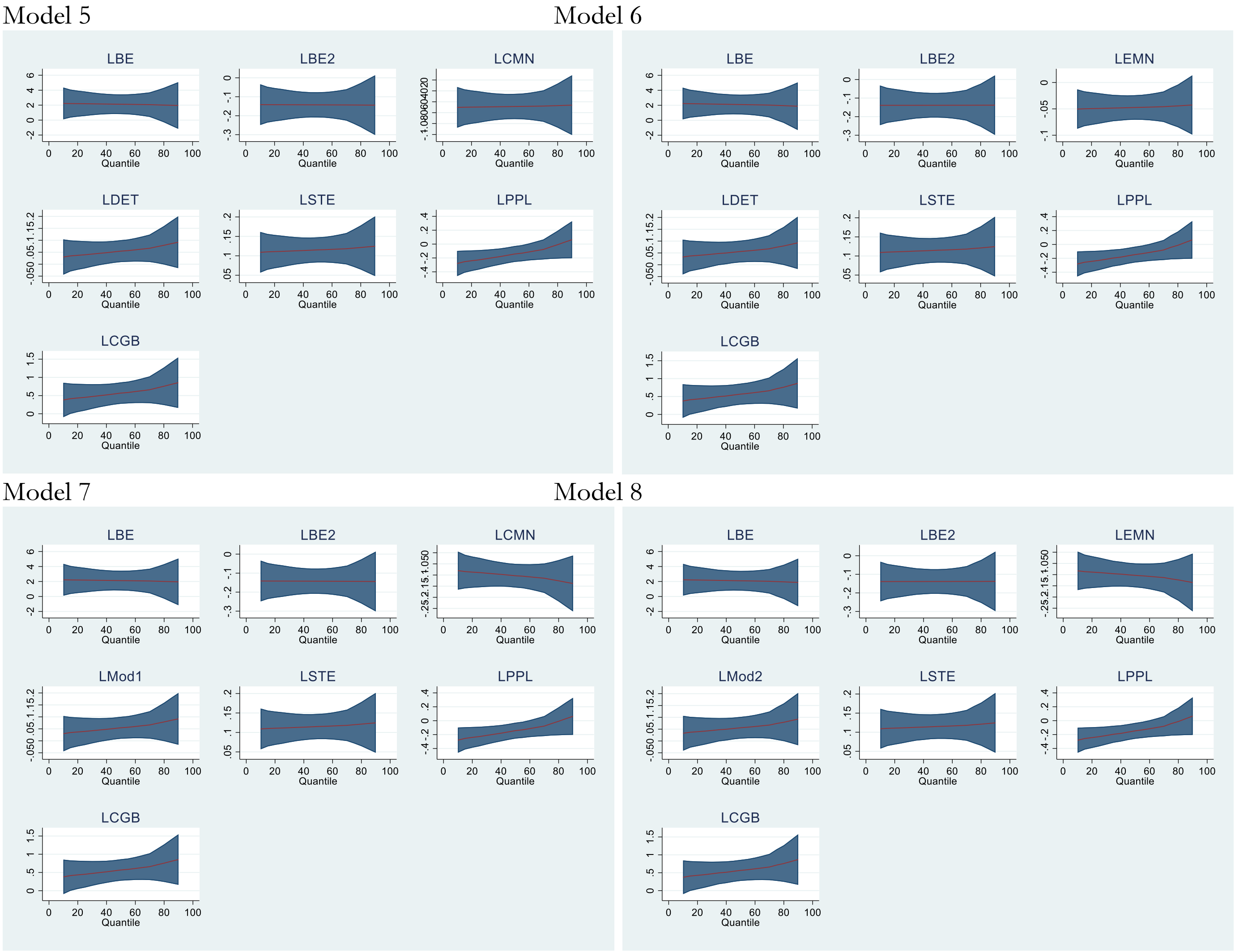

Fig. 3. Plotting elasticities from MMQR analysis (CCR-proxy for ecological resilience).

clean technologies. For instance, more funds should be provided for projects aiming at the development and sustainable utilization of resources and most especially the critical raw materials which are necessary for the desired green transition. Other areas to galvanize priority in sustainable innovation should include transport and green urban environment development. For instance, more support should be given to sustainable innovation for carbon-intensive sectors such as in the energy sector, manufacturing sector, and the transport sector to include the aviation and maritime industries among others.

Furthermore, aside from empowering sustainable innovation and energy, our sample of ten EU members must implement strict regulations to manage its environmental quality and impose substantial penalties on those violating the rules. These policies may become handier in the aspect of improving resource efficiency and reinvesting natural capital earnings into sustainable initiatives. In this regard, the EU government also needs to adopt effective economic growth strategies that specifically target enhancing environmental taxes, investing in green infrastructure, and using nature-based instruments to utilize natural resources more efficiently, given the inverted U-shape relationship between economic growth and ecological resilience. Additionally, since our findings postulate that trade globalization is fruitful for ecological resilience, especially in our sample of ten EU members with high FCLC, it is recommended that these countries should shift their attention from deglobalization policy to green globalization. The current findings allude to the fact that broader trade would promote greater environmental benefits. Since open trade aligned with environmental standards in these EU states, trade globalization can be leveraged to bolster ecological resilience possibly through technology diffusion mechanisms.

Lastly, given that environmental quality can also be influenced by population dynamics, the EU government needs to optimize its regulation related to integrated urban planning, energy efficiency and sustainable consumption to ensure a manageable ecological footprint, which means natural resources are accommodative towards the total need of consumption.

5.3. Limitations and direction for future studies

The current study has provided useful insights on the ecological resilience aspects of sustainable energy, natural resources, and sustainable innovation within the LCC framework using the EU member states context. However, there are some limitations especially in the aspects of sample selection and generalizability of the finding. The extent of data availability imposes a restriction of the sample to only ten EU member states. Although these are mainly innovation leaders, however, their selection is non-random and does not completely represent the entire EU. Hence, there is potential limitation in the extent of generalizability of the results due to differences in economic structures. Future study can therefore look at a broader sample and even extend the analysis to other advanced or emerging economies.

Authors contributions

All authors contributed to the study. Elma Satrovic: Conceptualization, Writing - original draft, Methodology, Formal analysis, Stephen Taiwo Onifade: Conceptualization, Writing - original draft, Editing, and Correspondence, Ilham Haouas: Writing - original draft.

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Declaration of competing interest

The authors wish to disclose here that there are no potential conflicts of interest at any level of this study.

APPENDIX

Table A1
Confidence intervals (ECR-proxy for ecological resilience)

Model	Var.	ETDK		GQ = 0.1		GQ = 0.3		GQ = 0.5		GQ = 0.7		GQ = 0.9	
		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]	
1	LBE	0.583	2.475	0.137	3.414	0.531	2.762	0.576	2.526	0.327	2.594	−0.883	3.369
	LBE2	−0.156	−0.061	−0.195	−0.032	−0.166	−0.056	−0.157	−0.060	−0.163	−0.051	−0.208	0.003
	LCMN	−0.058	−0.020	−0.070	−0.015	−0.059	−0.022	−0.056	−0.023	−0.057	−0.019	−0.071	0.001
	LDET	0.013	0.113	0.015	0.136	0.028	0.110	0.028	0.100	0.018	0.101	−0.030	0.127
	LSTE	0.054	0.106	0.026	0.101	0.047	0.098	0.057	0.101	0.059	0.111	0.052	0.149
	LPPL	−0.197	0.029	−0.324	−0.055	−0.226	−0.043	−0.174	−0.013	−0.149	0.039	−0.138	0.214
	LCGB	0.210	0.724	−0.114	0.613	0.116	0.611	0.230	0.665	0.274	0.780	0.245	1.193
2	LBE	0.554	2.457	0.111	3.403	0.511	2.732	0.546	2.507	0.294	2.575	−0.879	3.318
	LBE2	−0.153	−0.058	−0.192	−0.029	−0.162	−0.052	−0.154	−0.057	−0.160	−0.047	−0.203	0.004
	LEMN	−0.057	−0.018	−0.070	−0.014	−0.059	−0.021	−0.055	−0.021	−0.056	−0.017	−0.068	0.003
	LDET	0.014	0.115	0.016	0.138	0.029	0.111	0.029	0.102	0.018	0.103	−0.028	0.127
	LSTE	0.054	0.106	0.026	0.101	0.047	0.098	0.057	0.101	0.059	0.111	0.052	0.147
	LPPL	−0.200	0.027	−0.326	−0.057	−0.226	−0.044	−0.176	−0.014	−0.151	0.038	−0.140	0.207
	LCGB	0.209	0.725	−0.118	0.612	0.119	0.612	0.230	0.667	0.275	0.784	0.250	1.185
3	LBE	0.583	2.475	0.137	3.414	0.531	2.762	0.576	2.526	0.327	2.594	−0.883	3.369
	LBE2	−0.156	−0.061	−0.195	−0.032	−0.166	−0.056	−0.157	−0.060	−0.163	−0.051	−0.208	0.003
	LCMN	−0.158	−0.046	−0.188	−0.048	−0.158	−0.062	−0.145	−0.062	−0.146	−0.049	−0.175	0.008
	LMod1	0.013	0.113	0.015	0.136	0.028	0.110	0.028	0.100	0.018	0.101	−0.030	0.127
	LSTE	0.054	0.106	0.026	0.101	0.047	0.098	0.057	0.101	0.059	0.111	0.052	0.149
	LPPL	−0.197	0.029	−0.324	−0.055	−0.226	−0.043	−0.174	−0.013	−0.149	0.039	−0.138	0.214
	LCGB	0.210	0.724	−0.114	0.613	0.116	0.611	0.230	0.665	0.274	0.780	0.245	1.193
4	LBE	0.554	2.457	0.111	3.403	0.511	2.732	0.546	2.507	0.294	2.575	−0.879	3.318
	LBE2	−0.153	−0.058	−0.192	−0.029	−0.162	−0.052	−0.154	−0.057	−0.160	−0.047	−0.203	0.004
	LEMN	−0.159	−0.044	−0.191	−0.048	−0.158	−0.062	−0.146	−0.061	−0.146	−0.047	−0.173	0.010
	LMod2	0.014	0.115	0.016	0.138	0.029	0.111	0.029	0.102	0.018	0.103	−0.028	0.127
	LSTE	0.054	0.106	0.026	0.101	0.047	0.098	0.057	0.101	0.059	0.111	0.052	0.147
	LPPL	−0.200	0.027	−0.326	−0.057	−0.226	−0.044	−0.176	−0.014	−0.151	0.038	−0.140	0.207
	LCGB	0.209	0.725	−0.118	0.612	0.119	0.612	0.230	0.667	0.275	0.784	0.250	1.185

Table A2
Confidence intervals (CCR-proxy for ecological resilience)

Model	Var.	ETDK		GQ = 0.1		GQ = 0.3		GQ = 0.5		GQ = 0.7		GQ = 0.9	
		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]	
5	LBE	0.821	3.385	0.104	4.359	0.654	3.697	0.805	3.435	0.429	3.704	−1.170	5.074
	LBE2	−0.211	−0.075	−0.249	−0.034	−0.219	−0.065	−0.209	−0.076	−0.226	−0.060	−0.302	0.014
	LCMN	−0.087	−0.010	−0.088	−0.013	−0.076	−0.023	−0.072	−0.026	−0.077	−0.019	−0.101	0.009
	LDET	−0.006	0.123	−0.044	0.104	−0.011	0.095	0.009	0.100	0.009	0.124	−0.017	0.200
	LSTE	0.075	0.157	0.057	0.161	0.075	0.150	0.083	0.148	0.078	0.159	0.048	0.202
	LPPL	−0.278	0.033	−0.462	−0.098	−0.342	−0.081	−0.258	−0.029	−0.222	0.066	−0.204	0.330
	LCGB	0.259	0.936	−0.094	0.853	0.135	0.813	0.275	0.863	0.293	1.027	0.160	1.549
6	LBE	0.781	3.367	0.125	4.363	0.650	3.691	0.779	3.414	0.392	3.661	−1.319	5.054
	LBE2	−0.207	−0.070	−0.246	−0.032	−0.216	−0.062	−0.205	−0.072	−0.221	−0.056	−0.299	0.023
	LEMN	−0.085	−0.008	−0.087	−0.013	−0.075	−0.022	−0.070	−0.024	−0.075	−0.017	−0.099	0.014
	LDET	−0.005	0.124	−0.041	0.106	−0.008	0.097	0.010	0.102	0.010	0.124	−0.018	0.203
	LSTE	0.075	0.157	0.057	0.161	0.075	0.150	0.083	0.148	0.078	0.158	0.046	0.203
	LPPL	−0.281	0.032	−0.462	−0.101	−0.344	−0.083	−0.260	−0.031	−0.225	0.063	−0.206	0.337
	LCGB	0.258	0.939	−0.097	0.845	0.133	0.810	0.274	0.863	0.295	1.028	0.164	1.580
7	LBE	0.821	3.385	0.104	4.359	0.654	3.697	0.805	3.435	0.429	3.704	−1.170	5.074

(*continued on next page*)

Table A2 (*continued*)

Model	Var.	ETDK		GQ = 0.1		GQ = 0.3		GQ = 0.5		GQ = 0.7		GQ = 0.9	
		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]	
	LBE2	−0.211	−0.075	−0.249	−0.034	−0.219	−0.065	−0.209	−0.076	−0.226	−0.060	−0.302	0.014
	LCMN	−0.184	−0.030	−0.166	0.005	−0.153	−0.030	−0.156	−0.050	−0.180	−0.048	−0.264	−0.012
	LMod1	−0.006	0.123	−0.044	0.104	−0.011	0.095	0.009	0.100	0.009	0.124	−0.017	0.200
	LSTE	0.075	0.157	0.057	0.161	0.075	0.150	0.083	0.148	0.078	0.159	0.048	0.202
	LPPL	−0.278	0.033	−0.462	−0.098	−0.342	−0.081	−0.258	−0.029	−0.222	0.066	−0.204	0.330
	LCGB	0.259	0.936	−0.094	0.853	0.135	0.813	0.275	0.863	0.293	1.027	0.160	1.549
8	LBE	0.781	3.367	0.125	4.363	0.650	3.691	0.779	3.414	0.392	3.661	−1.319	5.054
	LBE2	−0.207	−0.070	−0.246	−0.032	−0.216	−0.062	−0.205	−0.072	−0.221	−0.056	−0.299	0.023
	LEMN	−0.186	−0.027	−0.169	0.003	−0.155	−0.031	−0.157	−0.050	−0.179	−0.047	−0.264	−0.006
	LMod2	−0.005	0.124	−0.041	0.106	−0.008	0.097	0.010	0.102	0.010	0.124	−0.018	0.203
	LSTE	0.075	0.157	0.057	0.161	0.075	0.150	0.083	0.148	0.078	0.158	0.046	0.203
	LPPL	−0.281	0.032	−0.462	−0.101	−0.344	−0.083	−0.260	−0.031	−0.225	0.063	−0.206	0.337
	LCGB	0.258	0.939	−0.097	0.845	0.133	0.810	0.274	0.863	0.295	1.028	0.164	1.580

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2026.102145.

Data availability

The data for this present study are sourced from the Global Footprint Network- GFN, (http://www.footprintnetwork.org/), the Organization for Economic Co-operation and Development – OECD, (https://www.oecd.org/), and the database of the World Development Indicators (https://data.worldbank.org).

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