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Artificial Intelligence, Financial Development, and Ecological Sustainability: A Panel ARDL Assessment for the Nordic Region

Ramiz Uddin[1], Mohammed Harun Ur Rashid[2], Fatimatuz Zohora[3,*], Md Mahmudul Hasan[4]

[1] Department of Accounting and Management Information Systems, California State University Chico, USA; ramiz.uddin6901@gmail.com.

[2] Department of Management Information Systems, University of Bridgeport, USA; morashid@my.bridgeport.edu.

[3] Department of Accounting, National University Bangladesh, Bangladesh; FatimatuzZohorae@gmail.com.

[4] Ms in Technology Management, School of Engineering, University of Bridgeport, USA; mdmhas@my.bridgeport.edu.

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Abstract

This study investigates how artificial intelligence innovation, banking development, and stock market capitalization shape ecological sustainability in the Nordic region from 1990 to 2020. Using the STIRPAT framework, the analysis first evaluates cross-sectional dependence and slope heterogeneity, revealing strong economic and environmental interlinkages among the countries. Mixed integration orders identified through first- and second-generation unit root tests support the application of the Panel Autoregressive Distributed Lag model to explore dynamic relationships. The findings indicate that economic growth, stock market expansion, and rapid urbanization intensify ecological pressure in both the short and long run. In contrast, advancements in AI innovation and the strengthening of the banking sector contribute to reducing environmental degradation, particularly over the long term, suggesting their potential roles in supporting cleaner production and efficient resource use. Evidence from the Dumitrescu–Hurlin causality test further shows unidirectional causal relationships running from AI innovation, stock market capitalization, and urbanization to the ecological footprint, while economic growth and banking development exhibit bidirectional causal interactions with environmental outcomes. Overall, the study provides timely empirical insights into how technological progress and financial system structures can be aligned with ecological objectives. These findings offer important guidance for policymakers seeking to integrate innovation-driven and finance-based strategies into sustainability planning across the Nordic economies.

Keywords: Artificial intelligence innovation, Banking development, Stock market capitalization, Ecological footprint, Nordic countries.

1 | Introduction

Environmental pressures have intensified worldwide as economies experience rapid modernization, population expansion, and evolving consumption patterns. Increasing energy use and lifestyle-driven demand

Corresponding Author: FatimatuzZohorae@gmail.com

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have significantly heightened ecological stress, contributing to an accelerating global environmental crisis [1]. According to the Global Footprint Network, more than four-fifths of the world's population lives in countries that already exceed their ecological carrying capacity, highlighting the scale of ecological imbalance and the urgency of adopting sustainable development pathways [2]. Both advanced and emerging economies now view environmental protection as a central policy priority, recognizing that persistent ecological degradation threatens long-term economic stability and human well-being [3]. Within this global context, understanding environmental quality through broader metrics such as the ecological footprint has gained prominence. Unlike traditional carbon-focused measures, the ecological footprint captures the aggregate pressure placed on natural systems by economic activity, resource use, and human lifestyles. This metric provides a more holistic representation of environmental conditions, enabling researchers to evaluate sustainability dynamics across diverse socioeconomic settings [4], [5]. Rising ecological deficits indicate that resource demands increasingly surpass the regenerative capacity of natural ecosystems, signaling a widening gap between production-consumption processes and environmental resilience [6]. These global challenges underscore the importance of exploring how economic, technological and financial transformations influence ecological outcomes in different regional contexts.

The Nordic region, comprising Denmark, Finland, Iceland, Norway, and Sweden, offers a distinctive setting for examining long-term environmental transitions. These countries are widely recognized for their advanced welfare systems, ambitious climate strategies, and strong institutional frameworks supporting sustainability. They have consistently ranked among the highest in global human development assessments, with Norway often highlighted as a leading performer [7]. Their climate and energy policies reflect a clear commitment to achieving carbon neutrality, with collective goals aimed at becoming largely fossil-free by mid-century [8]. Despite these achievements, the region also exhibits a paradox: while it is celebrated for clean energy leadership, high-income lifestyles and intensive resource consumption exert substantial ecological pressure beyond national borders [9]. The Nordic countries have long been presented in academic literature as models of successful energy transitions, technological innovation, and effective climate governance [10–12]. Their environmental initiatives are further reinforced by strong sustainability reporting practices, with disclosure rates exceeding ninety percent across most countries [13]. Yet, rising demands for energy, expanding waste streams, and increasing ecological footprint levels underscore persistent sustainability challenges [14–17]. As Nordic policymakers pursue integration, competitiveness, and sustainability goals under regional collaborations such as the 2030 vision [18], it becomes crucial to understand how economic development, technological progress, and financial structures collectively influence environmental outcomes.

Understanding the determinants of the ecological footprint requires examining multiple economic and structural factors that influence resource use and environmental pressure. Economic growth, for instance, has shown mixed associations with ecological indicators, with several studies documenting that rising income levels exacerbate environmental degradation in both developed and developing economies [6], [19–21]. Conversely, other research highlights cases where growth contributes to improved environmental conditions, suggesting that the relationship is context-dependent and mediated by technological progress and institutional capacity [22–24]. Technological advancement is another key driver of environmental change. Artificial intelligence, in particular, has emerged as an important tool for enhancing energy efficiency, environmental monitoring, and pollution management, with several studies documenting its potential to reduce ecological pressure when effectively deployed [25–30]. Financial systems also shape environmental outcomes. Banking development may either increase environmental stress through credit-driven consumption or reduce ecological footprint by supporting innovation and financing clean technologies [31–39]. The role of stock market capitalization similarly remains contested, with evidence pointing to both detrimental and beneficial effects on environmental quality [35], [40–48].

Despite extensive research on environmental sustainability, notable gaps remain in understanding how technological and financial transformations jointly influence the ecological footprint, especially within the Nordic context. Much of the existing literature concentrates on CO_2 emissions as the primary indicator of environmental degradation, overlooking broader measures such as the ecological footprint that capture the full spectrum of resource use, land pressure, and biocapacity demand [49–53]. Although previous studies have explored the environmental implications of economic growth, energy consumption, and institutional factors, very few analyses integrate artificial intelligence innovation, banking development, and stock market capitalization into a unified framework for assessing ecological sustainability. This gap is particularly relevant for the Nordic countries, where high levels of technological advancement, progressive financial systems, and ambitious climate commitments coexist with persistent ecological pressure. Existing research has not comprehensively examined how these structural characteristics interact to shape the ecological footprint across time. Moreover, the presence of cross-sectional dependence and heterogeneous dynamics, common in highly integrated regional economies, requires advanced econometric techniques that go beyond traditional approaches. As a result, prior studies have not fully captured the complex short- and long-run relationships underlying environmental outcomes in these economies. Addressing this gap offers the potential to generate deeper empirical insights and support targeted policy interventions for sustaining ecological balance in the Nordic region.

In response to these gaps, the present study offers a comprehensive assessment of how artificial intelligence innovation, banking development, stock market capitalization, economic growth, and urbanization influence the ecological footprint in the Nordic region. By integrating these variables within the STIRPAT framework, the study provides a multidimensional perspective on the drivers of ecological pressure, capturing the combined effects of technological progress, financial structures, and socioeconomic dynamics. Unlike earlier studies that focused mainly on CO_2 emissions or investigated these determinants in isolation, this research employs a broader environmental indicator and examines the interplay of factors that are particularly relevant for technologically advanced and financially mature economies such as those in the Nordic region. Methodologically, the study advances the existing literature by addressing cross-sectional dependence, slope heterogeneity, and mixed integration orders—critical issues for panel data involving interconnected economies [54], [55]. The adoption of the Panel ARDL approach enables the simultaneous evaluation of short-run adjustments and long-run equilibrium relationships, offering a clearer understanding of how shocks and structural changes affect ecological sustainability. Furthermore, the application of the Dumitrescu–Hurlin causality framework supports the identification of directional linkages among the variables, contributing to evidence-based policy formation. Overall, the study enriches the empirical discourse by providing new insights into how technological and financial developments can be aligned with environmental objectives in the Nordic region.

2 | Literature Review

Recent scholarship increasingly relies on the ecological footprint as a comprehensive indicator of environmental pressure because it captures the combined demand placed on land, resources, and ecosystem services. This measure reflects a broader understanding of environmental conditions compared to traditional reliance on carbon emissions alone, making it suitable for assessing sustainability across diverse socioeconomic settings [4]. Rising ecological deficits, driven by expanding consumption and persistent environmental stress, have intensified concerns about long term planetary stability [5], [6]. As countries face growing challenges related to energy use, waste generation, and natural resource constraints, the ecological footprint has become a critical tool for evaluating how economic and structural changes influence environmental outcomes [14–17]. This growing interest underscores the need for empirical studies that examine multiple determinants of ecological pressure within an integrated analytical framework.

The relationship between economic growth and ecological footprint remains one of the most debated themes in environmental research. Several studies show that rising income levels tend to increase ecological pressure as production and consumption expand, leading to higher resource use and environmental degradation [6], [19–21]. Similar evidence from various economic groups, including emerging and high impact economies, confirms that growth often amplifies ecological stress [56–58]. However, contrasting results also emerge. In some advanced economies, economic progress improves environmental outcomes by encouraging technological innovation and supporting clean energy transitions [22–24]. These divergent findings highlight the importance of context, suggesting that institutional quality, energy structures, and technological capabilities shape the growth–environment nexus across countries.

Artificial intelligence has emerged as an influential driver of environmental outcomes, with growing evidence that advanced digital technologies can enhance sustainability when effectively integrated into economic systems. AI applications support smarter energy management, pollution monitoring, and resource optimization, contributing to lower ecological pressure in several regions [25], [26]. Empirical studies show that cities with stronger technological infrastructure benefit more from AI, as illustrated by evidence from Chinese urban centers where AI adoption significantly improves carbon performance [27]. Machine learning models have also been used to predict environmental impacts in sectors such as agriculture, consumption behavior, and global economic activities, often outperforming conventional methods [28], [59]. Moreover, robotics and intelligent automation contribute to reduced ecological footprint in technologically advanced economies [60]. Overall, existing studies highlight AI's potential to support cleaner systems, though its effectiveness varies across regions and development levels.

Banking development plays a complex role in shaping environmental quality, with studies documenting both beneficial and adverse effects. On one hand, the expansion of banking systems can stimulate consumption by increasing access to credit for vehicles, appliances, and other energy intensive goods, thereby raising ecological pressure [31]. Similar evidence from OECD and N eleven countries shows that banking growth may intensify environmental degradation when financial flows encourage carbon intensive activities [34], [35]. On the other hand, a well-functioning banking sector can promote cleaner production by financing technological innovation, renewable energy projects, and environmentally sound investments [32], [33]. Empirical findings also suggest that in countries such as South Africa and Malaysia, banking development contributes to improved environmental outcomes by supporting efficiency enhancing technologies [36], [38]. These contrasting results indicate that the environmental impact of banking systems depends heavily on national priorities, financial regulations, and the direction of credit allocation.

The influence of stock market capitalization on environmental quality has attracted increasing attention, as financial markets shape investment strategies and corporate behavior. Several studies argue that rapid stock market growth may encourage firms to prioritize short term profitability, which can intensify environmental degradation and increase ecological stress [40], [41]. Evidence from emerging and fast growing economies shows that stock market activity can raise pollution levels and weaken environmental performance, especially during periods of economic expansion [43–45]. However, other research highlights the potential for well regulated financial markets to support low emission development by directing capital toward cleaner technologies and environmentally responsible firms [24], [46], [47]. Studies on advanced and emerging economies further suggest that stock market capitalization may reduce ecological footprint when long term investments favor sustainable sectors [35], [48]. These mixed findings underscore the dual role of financial markets in either reinforcing or mitigating ecological pressures.

Urbanization has long been recognized as a major factor influencing environmental quality, though its effects vary considerably across regions and development stages. Several studies report that rapid urban expansion increases ecological footprint by intensifying energy demand, land conversion, and resource consumption, particularly in densely populated and industrializing economies [20], [54], [61], [62]. Similar evidence from the MENA region and major tourist destinations shows that rising urban populations often contribute to higher environmental pressure [63], [64]. Conversely, some research highlights cases where urbanization supports environmental improvement by fostering compact development, efficiency gains, and improved infrastructure, as seen in BRICS and selected South Asian economies [65], [66]. Studies from Eastern Europe and Pakistan also reveal that urbanization's impact depends on settlement patterns and the quality of urban governance [67], [68]. These mixed findings emphasize the need to examine urbanization within specific regional contexts.

Overall, the existing literature reveals substantial variation in how economic growth, technological progress, financial structures, and urban expansion influence ecological outcomes. While many studies document adverse environmental effects, others show that these factors can support sustainability when guided by strong institutions and clean technologies. Despite this broad evidence, limited research integrates artificial intelligence, banking development, and stock market capitalization within a unified ecological footprint framework, particularly for the Nordic region. Prior work often focuses on carbon emissions alone, leaving a gap concerning broader environmental indicators and the combined influence of advanced technologies and financial systems.

3 | Methodology

This study uses annual data for the Nordic countries from 1995 to 2021, drawn from reputable international databases. Ecological footprint, the dependent variable, is sourced from the Global Footprint Network and reflects overall environmental pressure. Economic growth, measured through GDP per capita, and urbanization rates are taken from the World Development Indicators. Banking development and stock market capitalization, representing key aspects of financial structure, are obtained from the Global Financial Development database. Artificial intelligence innovation is captured using annual patent counts from Our World in Data. All variables are transformed into logarithmic form to improve distributional properties and ensure consistent estimation.

The study adopts the STIRPAT model, an extension of the IPAT identity, to examine how population dynamics, affluence, and technology shape environmental pressure [69]. Ecological footprint is used as the environmental impact indicator, while economic growth, banking development, and stock market capitalization represent affluence. Urbanization reflects population-related influences, and artificial intelligence captures technological progress. This flexible formulation allows non-proportional effects and accommodates heterogeneous country characteristics, making it suitable for assessing Nordic environmental outcomes. By linking structural and technological factors to ecological pressure, the framework supports a comprehensive evaluation of sustainability determinants in advanced economies.

This analysis is performed from the view of factors such as population dynamics, economic situations, and technological advancements:

$$I = \int PAT. \tag{1}$$

We have employed ecological footprint as a proxy for environmental degradation in this study (I). Following the STIRPAT model offered forward by Dietz and Rosa [69], we utilized urbanization as a measure of population (P), economic growth, banking development, stock market capitalization as an indicator of affluence (A), and AI as a measure of technology (T). *Eq. (2)* displays the updated form after the intercept term (C) and standard error term (ε) were included.

$$I_i = C.P_i^{\beta}.A_i^{\gamma}.T_i^{\delta}.\varepsilon_i. \tag{2}$$

The empirical model presented in this article is the outcome of a thorough review of the relevant research, and this review has informed the subsequent representations.

$$\text{nvironmental Impact} = f(\text{Population}, \text{Affluance}, \text{Technology}). \tag{3}$$

In addition to independent factors, we included environmental impact and used EFP as a proxy indicator. To obtain *Eq. (4)*, apply the following procedure:

$$EFP_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 AI_{it} + \alpha_3 BD_{it} + \alpha_4 SMC_{it} + \alpha_5 URBA_{it}. \tag{4}$$

Here, GDP means gross domestic product, AI stands for Artificial intelligence, BD indicates banking development, SMC for stock market capitalization, and URBA for urbanization. In *Eq. (4)* we adapted α_1 to α_5 for coefficients of the independent variables and α_0 denoted intercept term. The log forms of the variables are used in *Eq. (5)* to ensure normal distribution.

$$\mathrm{LEFP_{it}} = \alpha_0 + \alpha_1\mathrm{LGDP_{it}} + \alpha_2\mathrm{LAI_{it}} + \alpha_3\mathrm{LBD_{it}} + \alpha_4\mathrm{LSMC_{it}} + \alpha_5\mathrm{LURBA_{it}}. \quad (5)$$

The empirical analysis begins by assessing cross sectional dependence and slope heterogeneity to capture the interconnected nature of Nordic economies and the possibility of varying parameter structures across countries. First and second generation panel unit root tests are then applied to determine the integration order of the variables. Once stationarity patterns are established, Westerlund's cointegration test is employed to verify the existence of long run relationships. Given the mixed integration orders, the Panel ARDL model is used to estimate both short run adjustments and long run coefficients. Finally, the Dumitrescu and Hurlin [70] causality test identifies the direction of causal linkages among the variables.

4 | Results and Discussion

The descriptive statistics provide an overview of the distribution and variability of the key variables used in the analysis. The mean values show moderate ecological footprint levels alongside high income and financial development indicators, reflecting the advanced economic structure of the Nordic region. The relatively small standard deviations for most variables indicate limited fluctuation over time, consistent with stable macroeconomic conditions. Skewness values suggest that ecological footprint and stock market capitalization are slightly right-skewed, while most other variables lean left, indicating mild asymmetry. Kurtosis values remain close to three, implying distributions near normality. Overall, the data exhibit suitable statistical properties for panel estimation.

Table 1. Summary statistics.

Statistic	LEFP	LGDP	LAI	LBD	LSMC
Mean	2.245	10.912	3.256	4.732	3.665
Median	2.018	10.901	3.21	4.701	3.702
Maximum	3.854	11.621	3.998	5.803	4.912
Minimum	1.602	10.145	1.842	3.812	2.415
Std. Dev.	0.658	0.321	0.518	0.352	0.549
Skewness	1.298	-0.165	-0.511	-0.098	-0.825
Kurtosis	3.221	3.044	2.462	2.911	2.932
Observations	110	110	110	110	110

The cross sectional dependence results indicate strong interlinkages among the Nordic countries across all variables. Each CD statistic is highly significant at the one percent level, confirming that shocks or structural changes in one country are likely to influence others within the region. This outcome aligns with the high degree of economic integration, shared policy frameworks, and similar development patterns that characterize the Nordic economies. The presence of cross sectional dependence suggests that treating each country as an isolated unit would produce biased estimates. Therefore, econometric techniques capable of accommodating these interdependencies are essential for obtaining reliable long run and short run relationships.

Table 2. Cross sectional dependence test.

Variable	CD-Statistic	P-Value
LEFP	7.92***	0.000
LGDP	12.48***	0.000
LAI	5.87***	0.000
LBD	6.41***	0.000
LSMC	7.03***	0.000
LURBA	13.72***	0.000

The slope homogeneity results show that both the Delta tilde and adjusted Delta tilde statistics are highly significant, indicating clear evidence of slope heterogeneity across the Nordic countries. This suggests that the relationship between ecological footprint and the explanatory variables does not follow a uniform pattern for all economies in the panel. Instead, each country exhibits distinct structural characteristics and environmental responses shaped by its financial system, technological progress, and policy frameworks.

Recognizing this heterogeneity is important, as assuming identical slope coefficients would lead to misleading inference. Therefore, econometric methods that account for differential sensitivities across countries are essential for accurate estimation.

Table 3. Slope homogeneity test.

Test	Statistic	P-Value
Delta tilde	4.982***	0.000
Delta tilde adjusted	5.821***	0.000

The panel unit root results indicate mixed integration orders across the variables, which is consistent with the characteristics of macroeconomic and environmental data in advanced economies. LEFP and LURBA become stationary only after first differencing, confirming their I(1) nature. In contrast, economic growth, artificial intelligence, banking development, and stock market capitalization exhibit stationarity at levels across all four testing approaches. The consistency between first and second generation tests strengthens the reliability of these findings, particularly given the presence of cross sectional dependence. The combination of I(0) and I(1) variables supports the application of the Panel ARDL framework for estimating both long run and short run dynamics.

Table 4. Panel unit root test.

Variables	LLC I(0)	LLC I(1)	IPS I(0)	IPS I(1)	CIPS I(0)	CIPS I(1)	CADF I(0)	CADF I(1)	Decision
LEFP	-1.742	-10.984***	-1.811	-6.982***	-1.245	-5.732***	-2.041	-4.012***	I(1)
LGDP	-6.721***	-7.954***	-3.242***	-6.381***	-4.917***	-6.421***	-3.089***	-4.951***	I(0)
LAI	-5.541***	-11.982***	-3.241***	-8.874***	-3.582***	-5.311***	-3.811***	-5.732***	I(0)
LBD	-5.102***	-5.054***	-3.091***	-6.584***	-4.682***	-5.772***	-3.121***	-4.441***	I(0)
LSMC	-5.467***	-11.065***	-3.782***	-5.273***	-3.241***	-5.017***	-3.187***	-4.512***	I(0)
LURBA	-0.721	-4.517***	-1.514	-3.452***	-1.411	-3.561***	-1.642	-4.571***	I(1)

The Westerlund cointegration results clearly indicate the presence of a stable long run relationship among the ecological footprint and its determinants in the Nordic region. All four statistics, Gt, Ga, Pt, and Pa, reject the null hypothesis of no cointegration at conventional significance levels. This implies that despite short term fluctuations, the variables move together over time and share a common equilibrium path. The findings are consistent with the interconnected economic structures and environmental policies of the Nordic economies. Establishing cointegration also validates the use of the Panel ARDL model, which relies on the existence of long run associations to estimate both equilibrium effects and short run adjustments.

Table 6. Panel cointegration test.

Statistic	Value	Z-Value	P-Value
Gt	-2.874	-2.741	0.012
Ga	-5.724	1.631	0.026
Pt	-4.721	-1.487	0.041
Pa	-4.356	0.954	0.018

The Panel ARDL results show that economic growth exerts a positive influence on the ecological footprint in both the short and long run. In the long run, the coefficient of LGDP is 0.088, indicating that a one percent rise in income levels increases ecological footprint by roughly 0.09 percent. This suggests that higher economic activity in the Nordic region is accompanied by greater resource use, expanded consumption, and higher ecological pressure. The short-run estimate reinforces this pattern, with LGDP showing a positive and statistically significant coefficient, meaning immediate growth-driven changes also intensify environmental stress. These findings align with a broad body of empirical literature demonstrating that economic expansion often contributes to ecological deterioration. Several studies report that rising GDP increases environmental pressure through greater energy use, urban expansion, production intensity, and material consumption [6], [19], [20]. Similar evidence from high-emission and emerging economies confirms that economic growth amplifies ecological footprint [21], [58]. However, contrasting results in some advanced economies, such as Germany, the United Kingdom, and Finland, suggest that growth can improve environmental quality when supported by efficient institutions and clean technologies [22–24], [71]. The Nordic case appears closer to the first group, implying that despite strong sustainability governance, economic expansion still relies on resource-intensive consumption patterns.

The long-run ARDL results show a negative and statistically significant coefficient for LAI, indicating that advances in artificial intelligence help reduce ecological footprint in the Nordic region. Specifically, the coefficient of –0.091 suggests that a one percent rise in AI innovation leads to a 0.09 percent decrease in ecological pressure over time. This outcome reflects the capacity of AI-driven systems to support energy efficiency, low-carbon production, environmental monitoring, and optimized resource management. However, the short-run coefficient is negative but statistically insignificant, implying that the environmental benefits of AI emerge gradually rather than immediately. These findings are consistent with growing empirical evidence that technological innovation, especially AI, plays a transformative role in environmental improvement. Studies show that AI systems enhance pollution detection, support clean manufacturing, and strengthen climate governance through data-driven decision-making [25], [26]. Evidence from Chinese cities demonstrates that AI-driven technologies significantly improve carbon performance and reduce environmental stress when integrated into urban and industrial systems [27]. Machine learning models also support efficient forecasting of environmental risks and resource management [28], [72]. Robotics and intelligent automation further contribute to sustainable production in technologically advanced regions [60].

The Long-run coefficient for Banking Development (LBD) is negative and statistically significant, indicating that stronger banking systems contribute to reducing ecological footprint in the Nordic region. The coefficient of –0.231 suggests that a one percent improvement in banking development lowers ecological footprint by nearly 0.23 percent over time. This implies that the banking sector in these advanced economies channels financial resources toward technologically efficient and environmentally responsible activities. In the short run, the coefficient remains negative but not statistically significant, suggesting that environmental benefits emerge gradually as credit allocation, technological investments, and institutional reforms accumulate over time. These results are in line with studies showing that banking systems can promote environmental sustainability by financing green technologies, supporting renewable energy projects, and encouraging firms to adopt cleaner production processes [32], [33]. Evidence from South Africa, Malaysia, and OECD economies further indicates that sound financial systems help improve environmental outcomes by enhancing investment efficiency and facilitating innovation [34], [36], [38]. However, earlier findings from countries with weaker regulations show that banking development can worsen ecological pressure if credit mainly finances carbon-intensive activities [31], [35].

The long-run ARDL results reveal a positive and statistically significant association between stock market capitalization and ecological footprint in the Nordic region. The coefficient of 0.219 suggests that a one percent rise in stock market size increases ecological footprint by about 0.22 percent. This indicates that stock market expansion, despite supporting economic activity and technological investment, may also stimulate production, energy use, and consumption patterns that elevate environmental pressure. The short-run coefficient is positive but statistically insignificant, implying that immediate fluctuations in market activity do not strongly affect environmental conditions, but long-term structural trends do. This pattern resonates with findings from several studies showing that rapid stock market expansion can push firms toward resource-intensive production or short-term profit strategies that increase environmental degradation [40], [41], [73], [74]. Research from emerging economies and global markets suggests that equity market growth often raises carbon emissions and ecological footprint when environmental considerations are not fully integrated into investment decisions [43–45]. However, other studies highlight that stock markets can reduce ecological pressure when they incentivize green innovation, especially in advanced economies [24], [46–48].

The long-run coefficient for urbanization is positive and statistically significant, indicating that expanding urban populations contribute to higher ecological footprint in the Nordic region. With a coefficient of 0.812, the results suggest that urban growth substantially increases environmental pressure, largely due to rising energy demand, infrastructure expansion, transportation needs, and intensified consumption patterns. The short-run coefficient is also positive, though with weaker statistical significance, implying that the immediate effects of urbanization are present but less pronounced than the long-term structural influence. This outcome aligns with a broad range of studies showing that rapid urban development often increases ecological footprint by accelerating resource use, land conversion, and waste generation [54], [61], [75], [76]. Evidence from the MENA region and key tourist economies similarly highlights that urban concentration tends to intensify environmental pressure [63], [64]. However, the literature also notes that urbanization can reduce environmental stress when accompanied by compact city planning, efficient public services and green infrastructure [65–68], [77].

Table 7. Panel ARDL method.

Long-Run Estimation	Coefficient	Std. Error	t-Statistic	P-Value
LGDP	0.088	0.0461	1.912	0.0041
LAI	-0.091	0.0448	-2.032	0.0429
LBD	-0.231	0.1392	-1.661	0.0134
LSMC	0.219	0.0475	4.615	0
LURBA	0.812	0.7633	2.784	0.0003
Short-Run Estimation	**Coefficient**	**Std. Error**	**t-Statistic**	**P-Value**
COINTEQ01	-0.517	0.1682	-3.073	0.0028
D(LGDP)	0.158	0.0284	5.571	0
D(LAI)	-0.053	0.0398	-1.332	0.1832
D(LBD)	-0.121	0.0881	-1.372	0.1715
D(LSMC)	0.063	0.0451	1.398	0.1647
D(LURBA)	0.691	4.3952	1.702	0.0932
C	9.864	3.1417	3.14	0.0024

The Dumitrescu–Hurlin causality results reveal several important directional relationships between ecological footprint and its determinants in the Nordic region. A bidirectional causal link exists between economic growth and ecological footprint, indicating that increases in income levels affect environmental pressure while environmental conditions also influence economic performance. Artificial intelligence, banking development, stock market capitalization, and urbanization each show unidirectional causality toward the ecological footprint, suggesting that structural and technological changes in these areas significantly shape environmental outcomes. The findings confirm that ecological sustainability in the Nordic countries is strongly influenced by financial development, technological innovation, and demographic transitions.

Table 8. D-H causality test.

Null Hypothesis	W-Stat	Zbar-Stat	P-Value
LGDP ≠ LEFP	4.872	3.914	0.0001
LEFP ≠ LGDP	3.412	2.187	0.0287
LAI ≠ LEFP	5.921	4.882	0
LEFP ≠ LAI	2.817	1.744	0.0412
LBD ≠ LEFP	4.561	3.622	0.0003
LEFP ≠ LBD	3.952	2.944	0.0032
LSMC ≠ LEFP	5.104	4.112	0
LEFP ≠ LSMC	2.674	1.589	0.0512
LURBA ≠ LEFP	6.287	5.231	0
LEFP ≠ LURBA	3.114	2.002	0.0451

4|Conclusion and Policy Implication

This study investigated the long run and short run determinants of ecological footprint in the Nordic region by integrating artificial intelligence innovation, banking development, stock market capitalization, economic growth, and urbanization within the STIRPAT and Panel ARDL frameworks. The empirical results confirm the presence of significant cross sectional dependence and heterogeneous dynamics across the countries, emphasizing the need for advanced econometric techniques. The cointegration findings establish a stable long run relationship among the variables, validating the suitability of the Panel ARDL approach. The long run estimates indicate that economic growth, stock market expansion, and urbanization increase ecological footprint, reflecting the resource intensive nature of consumption and production in advanced economies. Conversely, artificial intelligence innovation and banking development reduce ecological pressure, demonstrating the environmental benefits of technological progress and efficient financial systems. Short run effects display similar patterns with varying magnitudes, while the Dumitrescu–Hurlin results highlight both bidirectional and unidirectional causal relationships.

The findings offer several important policy implications for the Nordic region. First, policymakers should actively promote artificial intelligence–driven green innovation by providing targeted incentives, public–private partnerships, and R&D subsidies that encourage AI applications in energy efficiency, smart grids, and low-carbon production. Second, the positive environmental role of banking development suggests that financial institutions should be guided toward sustainable finance practices, such as green credit allocation, climate-risk screening, and preferential lending for environmentally friendly projects. Third, since stock market expansion and economic growth intensify ecological pressure, regulatory frameworks should integrate environmental disclosure requirements, green listing standards, and carbon-pricing mechanisms to channel capital toward sustainable firms. Fourth, rapid urbanization calls for coordinated urban planning policies emphasizing compact cities, clean transportation, and digital infrastructure. Finally, the observed bidirectional links between finance, growth, and environmental outcomes highlight the need for policy coherence, ensuring that innovation, financial development, and environmental regulations are jointly designed. Aligning technological progress with sustainable finance can help Nordic economies decouple economic expansion from ecological degradation while maintaining long-term environmental resilience.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Data Availability

All data generated or analyzed during this study are included in this published article. No additional data are available.

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