#ENVECON11



11th ENVECON Conference

31 October – 01 November 2025 | HYBRID

SCOPE

Main issues that concern the Economics of Natural Resources and the Environment.

AIM

Highlight the interdisciplinary nature of environmental research through the exchange of views and experiences of researchers from different scientific fields and the finding of common components of research approaches.

Co-Organized by

Laboratory of Operations Research, UTH

Laboratory of Economics of Strategy, Innovation and Sustainability (LENS), UoP

Conference Organization



Laboratory of Operations Research
Department of Economics | University of Thessaly



Laboratory of Economics of Strategy, Innovation and Sustainability
Department of Economics | University of Patras

Book of Proceedings – 11 ENVECON Conference
Economics Natural Resources & the Environment

Opening Speech for the 11th ENVECON Conference

Dear,
Distinguished guests, esteemed colleagues, and students,

On behalf of the Scientific and Organizing Committee I welcome you to the:
11th Conference on "**Economics of Natural Resources and the Environment**".

It is with immense pride and heartfelt gratitude that I welcome you all to our 11th ENVECON Conference with the scope of "***Sustainability in the Face of Uncertainty***." This year, the conference is co-organised by the ***Laboratory of Operations Research*** (Department of Economics, University of Thessaly) and the ***Laboratory of Economics of Strategy, Innovation and Sustainability (LENS)*** (Department of Economics, University of Patras).

Last year, we celebrated the 10th anniversary of the ENVECON Conference, a testament to the shared efforts of our team, partners, and community, whose dedication has built an organization delivering rigorous science with real policy impact. ENVECON began with a small, determined group committed to disseminating environmental science across diverse fields, and it has grown through resilience and innovation in the face of challenges.

Our journey is marked by four milestones: an initial national phase with four conferences at the University of Thessaly (two on Climate Change in 2014 and two on Environmental Economics in 2015–2016); an international expansion with the 5th ENVECON in 2018; a period of collaboration and openness featuring jointly organized, often online, conferences from 2021 to 2023; and last year's 10th Anniversary ENVECON at the UTH. The conference's core aim is to underscore the relevance of natural resource and environmental economics and to elevate interdisciplinary exchange, drawing on a decade of lessons to spark new ideas, forge partnerships, and shape an even more impactful decade ahead.

I would also like to wholeheartedly thank the keynote speakers of the 11th ENVECON Conference: Prof. ***Ugur Soytas*** (Technical University of Denmark, Denmark, Denmark), Prof. ***Massimiliano Mazzanti*** (University of Ferrara, Italy), Prof. ***Tooraj Jamasb*** (Copenhagen Business School, Denmark), and Prof. ***John Yfantopoulos*** (National and Kapodistrian University of Athens, Greece) who accepted the invitation to present their long-term remarkable research experience on topics relevant to the conference.

Thank you once again for being here to celebrate this special moment with us, as we are here ***93 participants*** from ***58 institutions***. Whether you have been with us since the beginning or joined us along the way, you are part of our story. Together, let us make this conference a memorable one, filled with insight, connection, and inspiration.



ENVECON Conference Scientific Coordinator
Professor George E. Halkos
Laboratory of Operations Research
Department of Economics
School of Economics and Business
University of Thessaly, Volos, Greece

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Scientific & Organizing Committees

Scientific Coordinator of ENVECON Conference

George Halkos, Professor, University of Thessaly

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Tsekouras Kostas, Professor, University of Patras
Chatzistamoulou Nikolaos, Assistant Professor, University of Patras

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- Tsirivis Apostolos, University of Thessaly
- Tzanetatou Evangelia, University of Brighton

Technical Support

- Iatridis Alexandros, University of Thessaly
- Roussos Alexandros, University of Patras

Keynote Speakers

Environmental policies and innovation: theory, methods, empirical evidence

Prof. Massimiliano Mazzanti

Full Professor of Economic Policy

University of Ferrara, Italy



Sustainable societal well-being as an overarching target for energy and climate policies

Prof. Ugur Soytas

Professor & Head of the Climate Economics and Risk Management Section

Technical University of Denmark, Denmark



Green (Energy) Transition and Inequality

Prof. Tooraj Jamasb

Endowed Professor of Energy Economics
Director for Copenhagen School of Energy Infrastructure (CSEI)

Copenhagen Business School, Denmark



Sustainability of Public Social Spending in Greece, 1995-2023

Prof. John Yfantopoulos

Professor of Health Economics & Management

National and Kapodistrian University of Athens, Greece



Concise Conference Programme

Greek Time	Sessions – Topics Day 1 – Friday 31/10/2025
09:30 -10:00	**Opening – Welcome**
10:00-12:00	**Session 1:** Energy: Poverty, Deprivation & Mix in transition *Chairperson: Professor Konstantinos Kounetas*
10:00-12:00	**Session 2:** Climate Change Adaptation: Land Use, Forest & Agriculture *Chairperson: Assoc. Professor Konstantinos Papaspyropoulos*
12:00-12:15	**Coffee Break**
12:15 -13:00	**Keynote Speaker:** Professor Massimiliano Mazzanti
13:00-13:30	**Lunch**
13:30-15:15	**Session 3:** Climate Change: Natural Disasters & Environmental Hazards *Chairperson: Director Dr. Jaime Moll de Alba*
13:30-15:15	**Session 4:** Nature-based Solutions, Innovation & Resilience *Chairperson: Professor Konstantinos Tsekouras*
15:15- 15:30	**Coffee Break**
15:30-17:15	**Session 5:** Circular Economy: Water & Waste Management *Chairperson: Professor George Halkos*
15:30-17:15	**Session 6:** Digitization in Sustainable Tourism *Chairperson: Professor Zacharoula Andreopoulou*
17:15-17:30	**Coffee Break**
17:30-19:30	**Session 7:** Environmental Pollution: Urban, Health & Industrial Dimensions *Chairperson: Professor Christos Kitsos*
19:30-20:15	**Keynote Speaker:** Professor Ugur Soytas
	Day 2 – Saturday 01/11/2025
10:00-11:30	**Session 8:** Novelties in Environmental Valuation under Uncertainty *Chairperson: Asst. Professor Nikolaos Chatzistamoulou*
11:30-11:45	**Coffee Break**
11:45-12:30	**Keynote Speaker:** Professor Tooraj Jamasb
12:30-13:30	**Lunch**
13:30-15:00	**Session 9:** Climate Anxiety & Ecological Awareness *Chairperson: Assoc. Professor Athina Economou*
15:00-16:30	**Session 10:** Sustainable Development: Degrowth & Inclusive Wealth *Chairperson: Professor George Halkos*
16:30-16:45	**Coffee Break**
16:45-17:30	**Keynote Speaker:** Professor John Yfantopoulos
17:30-19:15	**Session 11:** CSR - ESG *Chairperson: Professor Konstantinos Evangelinos*
19:15-19:30	**Closing Remarks of the 11th ENVECON Conference**

Conference Schedule

Friday 31 October

Opening – Welcome – Room 01 **09:30-10:00**

- Prof. *George Halkos*, ENVECON Conference Scientific Coordinator, Department of Economics, UTH
- Prof. *Chrysi Laspidou*, Department of Civil Engineering, Vice Rector of UTH
- Prof. *Ilias Kevork*, Head of Department of Economics, UTH
- Prof. *Ioannis Venetis*, Department of Economics, Vice Rector of UoP
- Prof. *Nikolaos Giannakopoulos*, Head of Department of Economics, UoP
- Prof. *Konstantinos Kounetas*, Department of Economics, Dean of Economics and Business Administration School, UoP
- Prof. *Konstantinos Tsekouras*, Department of Economics, UoP

1st Session – Room 01 **10:00-12:00**

Topic	**Energy: Poverty, Deprivation & Mix in transition**
Chairperson	**Prof. Konstantinos Kounetas**
10:00-10:20	*Rebound effect-A Sisyphean effort or a Chimera? Evidence from transient, persistent and energy efficiency in European Industries* Eirini Stergiou, Nikos Rigas, Giancarlo Ferrara & Konstantinos Kounetas
10:20-10:40	*Energy Developments and Military Expenditure in the Eastern Mediterranean* George E. Halkos & Vasileios Avramopoulos
10:40-11:00	*Energy Poverty, Health, and Child Malnutrition: Panel Evidence from Southeast Asia* Nguyet T.M. Tran & Trung Thanh Nguyen
11:00-11:20	*The Energy Mix in Transition: A Dynamic Approach to the Shift from Non-Renewable to Renewable Sources under Climate Change Constraints* George E. Halkos & Argyro Zisiadou
11:20-11:40	*Uncovering Clean Energy Deprivation in Bhutan: A Multidimensional Analysis of Household Clean Energy Use* Rinzin Dema, Viet-Ngu Hoang & Clevo Wilson

2nd Session – Room 02 **10:00-12:00**

Topic	Climate Change Adaptation: Land Use, Forest & Agriculture
Chairperson	**Assoc. Prof. Konstantinos Papaspyropoulos**
10:00-10:20	*STREMMiAA: A Farm-Level Simulation Model for Assessing Structural Change, Land-Use, and Environmental Dynamics* Stamatis Mantziaris
10:20-10:40	*Economic Valuation and Determinants of Residents' Willingness to Pay for Conservation in the Dadia–Lefkimi–Soufli Forest National Park* Aggelos Symeonidis, Chrysovalantis Malesios, Eleni Zafeiriou, Spyridon Galatsidas, Konstantinos Panytsidis & Garyfallos Arabatzis
10:40-11:00	*How Climate Change is Addressed in the Faustmann Forest Economics Model: A brief review* Sofia Mpekiri & Konstantinos G. Papaspyropoulos
11:00-11:20	*Quantile estimation of CO_2 marginal abatement cost under heterogeneous emission-generating technologies* Haleh Delnava & Sheng Dai
11:20-11:40	*Sustainable Practices and Climate Change Adaptation in Olive Farming: Insights from Producers in Aetolia–Acarnania, Greece* Vassiliki Psilou, Eleni Zafeiriou, Chrysovalantou Antonopoulou, Christos Chatzissavvidis & Garyfallos Arabatzis

Coffee Break **12:00-12:15**

Keynote Speaker – Room 01 **12:15-13:00**

Topic: "Environmental policies and innovation: theory, methods, empirical evidence"

Prof. Massimiliano Mazzanti

Full Professor of Economic Policy
University of Ferrara, Italy

Lunch Break **13:00-13:30**

3rd Session – Room 01 **13:30-15:15**

Topic	**Climate Change: Natural Disasters & Environmental Hazards**
Chairperson	**Director Dr. Jaime Moll de Alba**
13:30-13:50	*Climate Change, Natural Disasters, and Growth Dynamics in Latin America: A Panel Data Analysis* Dimitrios Papadas, Eleni Sardianou, George E. Halkos & Ioannis Kostakis
13:50-14:10	*Sense-Making and Resilience Perspectives of Austrian Micro and Small Enterprises Towards Flooding: A Qualitative Study* Tabea Böhler & Antonis Skouloudis
14:10-14:30	*Extreme weather and individual preferences in rural Thailand and Vietnam* Tri-Anh Duc Nguyen, Gokul P. Paudel & Trung Thanh Nguyen
14:30-14:50	*(C)yber (D)igital (R)isks: Revising the Framework Modern Threats Landscape for Environmental Hazards* Argyro Zisiadou, Apostolos Xenakis & George E. Halkos

4th Session – Room 02 **13:30-15:15**

Topic	**Nature-based Solutions, Innovation & Resilience**
Chairperson	**Prof. Konstantinos Tsekouras**
13:30-13:50	*EUNICoast*
13:50-14:10	*Sustaining Environmental Resilience: A Stackelberg Game* George E. Halkos & George J. Papageorgiou
14:10-14:30	*Eco-process innovation: a "win win" situation or "when you have lemons make lemonade"? The moderating role of marketing innovation* Areti Gkypali, George Koutsouradis & Kostas Tsekouras
14:30-14:50	*Conceptualizing the Symbiosis Maturity for Nature-based Solutions: A SWOT-driven framework across technical, environmental, management and institutional domains* Dimitris Kofinas, Evmorfia Bataka, Nikos Kokosis, Argyro Zisiadou, Panagiotis-Stavros C. Aslanidis, George E. Halkos & Chrysi Laspidou

Coffee Break **15:15-15:30**

5th Session – Room 01 **15:30-17:15**

Topic	**Circular Economy: Water & Waste Management**
Chairperson	**Prof. George Halkos**
15:30-15:50	*Water management practices in Ancient Greece* Emmanouil M.L. Economou & George E. Halkos
15:50-16:10	*Join the dots: A rapid temporal appraisal of the bioeconomy in NUTS II regions in Greece* Georgios Maroulis, Panagiotis Koronaios & Panagiotis Kalimeris
16:10-16:30	*Knowledge, aspects and habits of the residents of Zakynthos, regarding solid waste recycling in the island* Stylianos-Marinos Charalampidis
16:30-16:50	*Toward sustainable Waste for Electrical and Engineering Equipment indicators: Addressing missing values with Coverage mapping, Imputation and Validation* Christos Liotiris & Zacharoula Andreopoulou

6th Session – Room 02 **15:30-17:15**

Topic	**Digitization in Sustainable Tourism**
Chairperson	**Prof. Zacharoula Andreopoulou**
15:30-15:50	*The Digitization of Archaeological Museums as a tool for Sustainable Tourism and Local Development: Evidence from Central Macedonia Greece* Konstadina Bataoula & Zacharoula Andreopoulou
15:50-16:10	*Integrating multi-source data and visualization of heterogeneous time-series for lakes: NDWI surface, ERA5 precipitation, level and fishery production* Lavrentis Konstantinidis, Zacharoula Andreopoulou
16:10-16:30	*Sustainability in Tourism in Greece using e-tourism: the case of Ecohotels and Expedia online platforms in e-Reputation* Ioannis Papathanasiou & Zacharoula Andreopoulou
16:30-16:50	*The Significance of Photography and Video User Generated and Shared Content in Mountainous Sustainable Tourism: The Case of Mount Olympus National Park* Argyrios Georgilas & Zacharoula Andreopoulou

Coffee Break **17:15-17:30**

7th Session – Room 01 **17:30-19:30**

Topic	**Environmental Pollution: Urban, Health & Industrial Dimensions**
Chairperson	**Prof. Christos Kitsos**
17:30-17:50	*Stairways to Heaven for European Industries: Multi-driving paths for CO_2 emissions generation* Eirini Stergiou & Konstantinos Kounetas
17:50-18:10	*Regulation schemes for pollutants. Multiple steady states and pollution traps.* George E. Halkos & George J. Papageorgiou
18:10-18:30	*Urban centers, Traffic, Atmospheric Pollution and Associated Health Risks: Evidence from Africa* Bertrand Tchanche
18:30-18:50	*A Marxist analysis of the Relation Between CO_2 Emissions Growth and Sectoral Profitability* Theofanis Papageorgiou & Yorgos Pisinas
18:50-19:10	*The Pollution levels in Athens and Salonica: An Environmental Analysis Approach* George E. Halkos, Christos Kitsos & Simeon Nisiotis

Keynote Speaker – Room 01 **19:30-20:15**

Topic: "Sustainable societal well-being as an overarching target for energy and climate policies"

Prof. Ugur Soytas

Professor & Head of the Climate Economics and Risk Management Section
Technical University of Denmark, Denmark

Saturday 01 November

8th Session – Room 01 **10:00-11:30**

Topic	**Novelties in Environmental Valuation under Uncertainty**
Chairperson	**Asst. Prof. Nikolaos Chatzistamoulou**
10:00-10:20	*Environmental Uncertainty Effects on Money Investments: Strengthening or Weakening Resilience to Inflation?* Panayiotis Theodossiou, Nikolaos A. Kyriazis & Konstantinos A. Dimitriadis
10:20-10:40	*Reinstatement of Rail Transport Between Strymon and Alexandroupolis – an Environmental, Financial, and Economic Evaluation* Konstantinos Christidis
10:40-11:00	*Digital Self-Assessment of Accommodation Vulnerability to Climate Change Using Artificial Intelligence Tools* Panagiotis Vouros, Akrivi Vagena, Eva Vaiouli, Konstantinos Evangelinos
11:00-11:20	*Impact of Artificial Intelligence Implementation on Sustainability in Colombo's Business Process Outsourcing Sector in Sri Lanka* S.J.Francis & N. Wijesena

Coffee Break **11:30-11:45**

Keynote Speaker – Room 01 **11:45-12:30**

Green (Energy) Transition and Inequality

Prof. Tooraj Jamasb

Endowed Professor of Energy Economics
Director for Copenhagen School of Energy Infrastructure (CSEI)
Copenhagen Business School, Denmark

Lunch **12:30-13:30**

9th Session – Room 01 **13:30-15:00**

Topic	**Climate Anxiety & Ecological Awareness**
Chairperson	**Assoc. Prof. Athina Economou**
13:30-13:50	*The influence of motivational goal frames and coping strategies on climate anxiety* Anastasia Gkargkavouzi & George E. Halkos
13:50-14:10	*The Role of Environmental Education in Promoting Sustainable Development and Ecological Awareness: An Economic & Social Approach* Christos Chatzifotiadis, Efstathios Loupas, Ifigeneia Chatzinikolaou & Konstantinos Mantzios
14:10-14:30	*The Contribution of the Psychology of Religion to the Formation of Ecological Consciousness* Georgios Fountoulakis
14:30-14:50	*Socioeconomic status and pro-environmental behaviours in the EU* Athina Economou & George E. Halkos

10th Session – Room 01 **15:00-16:30**

Topic	**Sustainable Development: Degrowth & Inclusive Wealth**
Chairperson	**Prof. George Halkos**
15:00-15:20	*The role of institutional and socio-economic factors in shaping environmental performance: A cross-country analysis in fluctuating times* Jawahir M. Alshehhi & Panagiotis D. Zervopoulos
15:20-15:40	*The Economic Geography of Inclusive Wealth: Convergence Clubs Across Nations* George E. Halkos, Christina Bampatsou, Panagiotis – Stavros C. Aslanidis & Shunsuke Managi
15:40-16:00	*Degrowth and Planetary Boundaries: Economic Dimensions of an Alternative Paradigm for Sustainable Transition* Angeliki Spyridoula Kalousi & Konstantinos G. Papaspyropoulos
16:00-16:20	*Transitional Dynamics and Policy Spillovers. Are Market-Based Instruments and Technology Autarky Structural Drivers in the European Green Transition?* Nikos Chatzistamoulou, Andriana G. Dimakopoulou & Dimitris Smyrnakis

Coffee Break **16:30-16:45**

Keynote Speaker – Room 01 **16:45-17:30**

Topic: "Sustainability of Public Social Spending in Greece, 1995-2023"

Prof. John Yfantopoulos

Professor of Health Economics & Management
National and Kapodistrian University of Athens, Greece

11th Session – Room 01 **17:30-19:15**

Topic	**Corporate Social Responsibility – Environmental, Social and Corporate Governance**
Chairperson	**Prof. Konstantinos Evangelinos**
17:30-17:50	*The role of internal CSR as driver of sustainable innovation through intrapreneurship* Panayiotis Jacovides, Constantinos Giagkinis & Constantinos Evangelinos
17:50-18:10	*Disability and Social Economy: Corporate Responsibility for Equal Employment Opportunities in NGOs* Kristina Kucheruk & Konstantinos Evangelinos
18:10-18:30	*Embedding ESG in European Small-Medium Enterprises: The Role of Environmental Management Systems and International Standards* Panagiotis – Stavros C. Aslanidis, Jaime Moll de Alba & George E. Halkos
18:30-18:50	*Corporate Social Responsibility as a New Perspective for Tackling the Refugee Problem* Anna Samothraki & Konstantinos I. Evangelinos

Closing Remarks **19:15-19:30**

Book of Abstracts

Summary

The **11th ENVECON Conference** program consisted of ***11*** sessions that included ***47*** presentations by ***93*** participants from ***58*** institutions. The 11th ENVECON was announced and greeted by ***4*** Keynote speakers. The ***11*** thematic sessions presented energy-related issues including poverty, deprivation and energy mix in transition, climate change adaptation including issues in land use, forestry & agriculture, as well as disasters and natural environmental hazards, and moreover, nature-based solutions, innovation and resilience. Additionally, other sessions focused on circular economy and specifically on water, waste and digitization in sustainable tourism. Furthermore, other sessions delved into environmental pollution (e.g., urban, health, and industrial dimensions), novelties in environmental valuation under uncertainty, and climate anxiety and ecological awareness. Finally, several presentations presented interesting results in sustainable development (degrowth and inclusive wealth), as well as corporate social responsibility and environmental, social and corporate governance issues. In total, ***14*** studies were included in the conference proceedings, however, several papers have not been included in the book of proceedings as they have already been submitted to the conference special issues or in respected international journals.

The 1st paper, authored by *G.E. Halkos and G.J. Papageorgiou*, is titled *"Sustaining Environmental Resilience: A Stackelberg Game"*. This study develops a dynamic Stackelberg game between a social planner and a resource-extracting firm to regulate renewable resource use. The findings show that open-loop strategies lead to environmental instability, while feedback strategies, especially with state-dependent taxation, ensure sustainable and stable outcomes.

The 2nd paper, authored by *A. Gkypali, G. Koutsouradis and K. Tsekouras*, is titled *"Eco-process and Marketing Innovation: How to Turn Lemons into Lemonade"*. This study examines the effects of eco-process innovations (EPT and RET) on firms' innovation performance using data from 7,660 European firms. Results indicate that RET enhances performance, while EPT has negative effects unless it is complemented by marketing innovation.

The 3rd paper, authored by *G. Maroulis, P. Koronaios and P. Kalimeris*, is titled *"Join the Dots: A Rapid Temporal Appraisal of the Bioeconomy in NUTS II Regions in Greece"*. This paper provides a temporal assessment of bioeconomy performance across 13 Greek regions (2010–2022) using 26 indicators. The findings highlight regional differences and offer a framework for identifying model regions and guiding EU bioeconomy strategies.

The 4th paper, authored by *C. Liotiris and Z. Andreopoulou*, is titled *"Toward Sustainable Waste for Electrical and Electronic Equipment Indicators: Addressing missing values with Coverage mapping, Imputation and Validation"*. This study develops a reproducible framework for addressing missing WEEE data across EU27 (2005–2023) using mapping, imputation, and validation techniques. The results ensure coherent, gap-aware time series aligned with macroeconomic indicators for reliable policy analysis.

The 5th paper, authored by *K. Bataoula and Z. Andreopoulou*, is titled *"The Digitization of Archaeological Museums as a Tool for Sustainable Tourism and Local Development:*

Evidence from Central Macedonia Greece". This research explores how digital technologies enhance accessibility, visitor experience, and inclusion in museums in Central Macedonia. Findings show digitization supports sustainable tourism and local economic development while strengthening cultural policy tools.

The 6th paper, authored by *L. Konstantinidis and Z. Andreopoulou*, is titled *"Integrating Multi-source Data and Visualization of Heterogeneous Time-Series for Lakes: : NDWI surface, ERA5 precipitation, level and fishery production"*. This study presents a workflow integrating satellite, climate, and socio-economic data for Lake Doirani (2011–2023). Results reveal links between drought conditions and reduced fishery production, offering a transparent method for environmental monitoring and decision-making.

The 7th paper, authored by *I. Papathanasiou and Z. Andreopoulou*, is titled *"Sustainability in Tourism in Greece Using e-Tourism: : the case of Ecohotels and Expedia online platformsin e-Reputation"*. This study analyzes the relationship between sustainability certifications and hotel e-reputation using data from Ecohotels and Expedia. The findings aim to clarify whether certified hotels achieve higher visibility and better consumer ratings online.

The 8th paper, authored by *A. Georgilas and Z. Andreopoulou*, is titled *"The Significance of Photography and Video User-Generated Content in Mountainous Sustainable Tourism: : The Case of Mount Olympus National Park"*. This research investigates how visitor-generated visual content promotes sustainable tourism in Mount Olympus National Park. Results show strong engagement and a positive link between content creation and sharing, supporting its role in low-cost destination promotion.

The 9th paper, authored by *G.E. Halkos and G.J. Papageorgiou*, is titled *"Regulating Schemes for Pollutants: Multiple Steady States and Pollution Traps"*. This study develops a differential game between firms and regulators to analyze pollution dynamics under Nash and Stackelberg equilibria. Findings highlight that strong government leadership can eliminate high-pollution traps and ensure stable environmental outcomes.

The 10th paper, authored by *G. Fountoulakis*, is titled *"The Contribution of the Psychology of Religion to the Formation of Ecological Consciousness"*. This paper explores how religious beliefs, emotions, and ethical values shape ecological awareness and behavior. It highlights the role of responsibility, awe, and respect for nature in fostering deeper environmental consciousness.

The 11th paper, authored by *G.E. Halkos, C. Bampatsou, P.S.C. Aslanidis and S. Managi*, is titled *"The Economic Geography of Inclusive Wealth: Convergence Clubs Across Nations"*. This study uses the Inclusive Wealth Index (1990–2020) to assess sustainable development beyond GDP. Results identify convergence clubs, revealing diverse development paths shaped by human and natural capital.

The 12th paper, authored by *A.S. Kalousi and K.G. Papaspyropoulos*, is titled *"Degrowth and Planetary Boundaries: Economic Dimensions of an Alternative Model for a Sustainable Transition"*. This paper reviews the economic implications of degrowth within the planetary

boundaries framework using PRISMA methodology. Findings suggest growing relevance but emphasize the need for institutional reforms and new well-being indicators.

The 13th paper, authored by *P. Jacovides, K. Giagkinis and K. Evangelinos*, is titled *"The Role of Internal CSR as Driver of Sustainable Innovation through Intrapreneurship"*. This conceptual study examines how internal CSR fosters sustainable innovation through intrapreneurship. It highlights employee empowerment as a key mechanism linking responsible practices to innovation outcomes.

The 14th paper, authored by *K. Kucheruk and K. Evangelinos*, is titled *"Disability and Social Economy: Corporate Responsibility for Equal Employment Opportunities in NGOs"*. This study investigates how NGOs promote inclusion and equal employment for people with disabilities. Findings emphasize the role of organizational culture and CSR practices in enhancing accessibility and social equity.

Keynote Speeches

Sustainable societal well-being as an overarching target for energy and climate policies

Ugur Soytas[1]

[1] Professor & Head of the Climate Economics and Risk Management Section, Technical University of Denmark, Denmark

Abstract

Ecological economists propose sustainable societal well-being (SW) as an overarching target for climate policies. A better understanding of how SW is linked to energy consumption is needed to operationalize this proposal. Examining how the Human Development Index (HDI) correlates with per capita energy use, several studies confirm diminishing SW returns for developed countries and saturation at very high energy consumption levels. However, when planetary pressures are considered, PHDI declines with overconsumption, akin to the income threshold hypothesis. Furthermore, the hedonic and eudaimonic well-being show different associations with resource use, indicating that SW can decouple from energy use.

Keywords: *sustainable well-being; HDI/PHDI; energy use*

JEL Codes: I31; Q01; Q43

Environmental policies and innovation: theory, methods, empirical evidence

Massimiliano Mazzanti[1]

[1] Full Professor of Economic Policy, University of Ferrara, Italy

Abstract

When analysing environmental policy effects, it is relevant to understand the drivers of innovation, including policies, and the role of policy in abating emissions, taking into account country heterogeneity, non linearity, common factors. In a series of recent works, it is highlighted (i) that the larger knowledge investments are, the stronger the possible role of environmental policy in inducing green inventions. The higher the combination of any R&D/R&D spillovers, the stronger socio-technical system capacity to absorb the effect of the policy, translating this into inventions. In addition, (ii) carbon pricing effects on CO2 were significant at the level of the entire economy, not only for sectors covered by the EU ETS policy. Despite the strong non linearity the market exhibited, the policy appears to deliver efficiency gains by Innovation spillovers throughout the entire economic system.

Keywords: *carbon pricing & EU ETS spillovers; R&D/knowledge spillovers and absorptive capacity; policy-induced green innovation & economy-wide CO_2 abatement*

JEL Codes: O31; Q55; Q58

Green (Energy) Transition and Inequality

Tooraj Jamasb[1]

[1] Endowed Professor of Energy Economics, Director for Copenhagen School of Energy Infrastructure (CSEI), Copenhagen Business School, Denmark

Abstract

This presentation examines how dimensions of social inequality shape can impact the green energy transition. Contemporary transition strategies are largely framed by market oriented, techno economic models inherited from policy reforms since the 1990s. Those models tend to treat social effects as secondary or distributable externalities. However, procedural, distributional, and recognition based inequalities materially affect the political feasibility and speed of decarbonisation. The absence of an integrated social framework leaves the techno economic approach and prescriptions vulnerable to resistance and uneven uptake. The presentation concludes by proposing principles for an interdisciplinary research agenda and policy design incorporating distributive justice and participation into modelling and policymaking to enable more equitable—and therefore more durable—green transition.

Keywords: *energy justice & social inequality; participatory governance in decarbonisation; limits of techno-economic transition models*

JEL Codes: D63; Q48; Q58

Sustainability of Public Social Spending in Greece, 1995-2023

John Yfantopoulos[1] & Theodoros V. Stamatopoulos[2]

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[2] Professor of Economics, Department of Accounting and Finance, University of West Attica, Greece

Abstract

We investigate the sustainability of the asymmetric public social spending (PSS)–financialization relationship in Greece over the period of 1995q1–2023q4. We follow the theoretical endogenous nexus of PSS with the financial fragility hypothesis (FFH) and finance-led growth regime; the nonlinear autoregressive distributed lag (NARDL) model and cointegration are applied for this purpose. The analysis suggests the following: (1) The selected determinants of the three stages of the FFH affect dependent PSS asymmetrically in the long run (as well as in the short run, sometimes); meanwhile, more often than not, significantly larger effects tended to be negative changes. (2) The asymmetric shocks of explanatories gently increase PSS in many cases but also decrease it strongly in others. (3) The "automatic stabilizer" role of PSS is proven, whereas the contrary is not rejected; that is, PSS was also used as a "counter-automatic stabilizer" tool.

Keywords: *public social spending & financialization; NARDL; Greece*

JEL Codes: H53; E44; C22

Session 1.

Energy: Poverty, Deprivation & Mix in Transition

Rebound effect-A Sisyphean effort or a Chimera? Evidence from transient, persistent and energy efficiency in European Industries

Eirini Stergiou[1,4], Nikos Rigas[2], Giancarlo Ferrara[3] & Konstantinos Kounetas[1,4]

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[3] Department of Economics, Business and Statistics, University of Palermo, Italy
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Abstract

The energy efficiency paradox dictates that the potential reduction in CO_2 emissions by energy-efficient technologies can be offset by behavioral and systemic responses that increase energy use and diminish energy savings. At the same time, European manufacturing industries need to reduce their energy consumption and increase their capability to substitute between their resources. This study employs a stochastic frontier energy demand framework to 11 manufacturing industries from 27 European countries over the period 1995 to 2022, examining substitution elasticities among key production inputs and distinguishing between transient and persistent inefficiencies. The rebound effect of energy efficiency improvements is evaluated to capture if the expected energy savings are offset by increased production or energy use. Our results in efficiency analysis indicate that improvements in industrial energy performance require long-term structural reforms and targeted investments in technological advancement, rather than short-lived policy interventions. Moreover, complementarity and substitutability analysis reveal that energy–labor substitutability is prevalent in most industries, except for the Mining and Chemical industries. The energy–capital relationship presents both substitutability and complementarity depending on industry characteristics, technology intensity, and energy dependence, with energy-intensive industries displaying more elastic substitution patterns. In conclusion, Europe's pathway to energy efficiency, industrial decarbonization and climate neutrality requires a dual approach: addressing long-term structural inefficiencies, while simultaneously mitigating short-term rebound effects.

Keywords: *Energy demand, Stochastic frontier analysis, Rebound effect*

JEL Codes: O13; O14; Q56.

Energy Developments and Military Expenditure in the Eastern Mediterranean

George E. Halkos[1] & Vasileios Avramopoulos[1,2]

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[2] 2nd Attack Helicopter Battalion, Army Aviation, Ministry of Defense, Larissa, 41001, Greece.

Abstract

Energy development and military expenditure are two strategic dimensions that shape the geopolitical and economic landscape of the Eastern Mediterranean. This study explores the patterns and possible associations between these two areas across nine countries over a twenty-year period (2004–2023). Using secondary panel data, the analysis presents temporal and cross-country trends in military spending-both in current U.S. dollars and as a percentage of GDP-alongside selected indicators of energy development. Since there is no single, agreed-upon definition of "energy development," this study operationalizes it through four dimensions: Contracts between States and hydrocarbon companies, hydrocarbon exploration or discovery, participation in international energy fora, declaration or delimitation of Exclusive Economic Zones, along with military crises or conflicts. Visual analyses, including line plots and heatmaps, are employed to illustrate how military and energy trajectories have evolved across countries and time. The findings reveal notable regional heterogeneity: Countries that have been historically exposed to external threats tend to allocate a larger share of their GDP to military expenditures. In addition, certain localized military incidents drive the countries involved to raise their defense spending as a percentage of GDP. This descriptive exploration contributes to the emerging debate on the energy–security nexus in the Eastern Mediterranean by offering an empirically grounded overview of their joint evolution. The study highlights the need for further econometric and policy-oriented research to better understand whether energy developments act as drivers or outcomes of regional militarization.

Keywords: Energy developments; Military expenditures; Eastern Mediterranean; Energy security; Energy policy.

JEL Codes: Q43; H56; Q48; F52; N75.

Energy Poverty, Health, and Child Malnutrition: Panel Evidence from Southeast Asia

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Abstract

Energy poverty poses a significant barrier to human well-being and economic development in rural developing countries. A large segment of the population in these countries relies on cheaper, more polluted fuel sources to meet energy needs, leading to adverse health consequences and hindering children's development. This study aims to examine the factors contributing to energy poverty and its impact on the health outcomes of household members, as well as the number of malnourished children in rural communities. Utilizing a panel dataset spanning 2007 to 2017 and encompassing 1,566 households in Thailand and 1,555 households in Vietnam, we propose various measures of energy poverty. We address the endogeneity concerns by applying both fixed-effects and instrumental variable estimations. Our findings demonstrate that energy poverty has been decreasing over the years, yet 35% of the population continues to rely on firewood to meet their energy needs. The results from factors affecting energy poverty suggest that employment diversification and higher levels of education pave the way out of energy poverty. Better rural infrastructure plays an important role in reducing energy poverty. Furthermore, energy poverty is consistently linked to more serious respiratory health issues and a higher share of respiratory illness. Regarding child malnutrition, suffering energy poverty positively increases the number of children who are stunted, wasted, and underweight within households. These health consequences are stronger in the long term. Our findings necessitate addressing energy poverty as a growing threat to health status, requiring attention and intervention in rural communities.

Keywords: *Energy poverty; health status; children malnutrition; panel regression, instrumental variables; Southeast Asia.*

JEL Codes: Q4; Q49; I15.

The Energy Mix in Transition: A Dynamic Approach to the Shift from Non-Renewable to Renewable Sources under Climate Change Constraints

George E. Halkos[1] & Argyro Zisiadou[1]

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Abstract

This study provides a comprehensive empirical assessment of the structural transition in national energy mixes from non-renewable to renewable sources across 77 OECD and non-OECD economies during the period 2000–2024. Anchored in the evolving architecture of international climate governance, the analysis explicitly incorporates the temporal influence of the Kyoto Protocol (2005) and the Paris Agreement (2015) as institutional turning points in global decarbonization efforts. The empirical framework employs a dynamic panel data approach, using balanced data to capture both short- and long-term adjustments in energy composition under climate change constraints. Key explanatory variables include participation in climate treaties, Climate Change Performance Index (CCPI) scores, economic growth trajectories, and structural indicators of industrial and energy-sector development. The results aim to identify causal linkages between international climate commitments, policy performance, and the pace of energy transition, while differentiating the behavioral responses of OECD versus non-OECD countries. By integrating econometric rigor with policy analysis, this paper contributes novel evidence on the effectiveness of global climate frameworks in reshaping national energy systems and offers insights into the mechanisms that condition the convergence toward a sustainable low-carbon energy equilibrium.

Keywords: *Renewable and non-renewable energy; Climate Change; Energy mix; econometric modelling; Energy policy effectiveness*

JEL Codes: B23; O13; Q54

Uncovering Clean Energy Deprivation in Bhutan: A Multidimensional Analysis of Household Clean Energy Use

Rinzin Dema[1], Viet-Ngu Hoang[1] & Clevo Wilson[1]

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Abstract

Bhutan achieves near-universal electrification and becomes a net exporter of clean electricity by 2022. However, only 32.85% of its total electricity production is used domestically, while over 82% of total firewood consumption happens in residential settings. The literature remains silent about this potential incidence of clean energy deprivation (CED) in Bhutan. Using latent class modelling on the 2022 Living Standard Survey, this study offers the first empirical examination of clean energy deprivation among Bhutanese households. Our analysis shows three distinct levels of deprivation among households: Very Deprived (16.94%), Deprived (36.38%), and Non-Deprived (46.68%). Households in the periphery and rural areas are more likely to be deprived. The degree of deprivation varies across regions, even within rural areas. Deprived households are characterised by low adoption of LPG, low spending on clean energy, and the use of firewood for cooking and heating, despite having near-universal access to electricity. The key drivers of clean energy deprivation include housing structural attributes, appliance ownership, education of the household head, distance from households to the nearest market and gas distribution points. These findings favour a shift in policy towards targeted and more holistic demand-side support.

Keywords: *Clean energy deprivation, latent class, multidimensional, household, policy*

Session 2.

Climate Change Adaptation: Land Use, Forest & Agriculture

STREMMiAA: A Farm-Level Simulation Model for Assessing Structural Change, Land-Use, and Environmental Dynamics

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Abstract

Small farms play a vital role in the rural sector of the European Union, contributing to food production, preserving landscape features, protecting biodiversity, providing public goods, and maintaining social cohesion in rural and remote regions. Nevertheless, the sector has undergone rapid structural transformation in recent decades, accompanied by adverse demographic developments that threaten the long-term sustainability of small-scale agriculture. Understanding how farms respond to evolving economic conditions and policy frameworks is therefore essential for designing effective agricultural policies. This study presents the Stochastic Recursive Model for Multiannual impact Assessment in Agriculture (STREMMiAA). This newly developed simulation model endogenously captures structural, and land-use change dynamics in arable farming systems. The model integrates a farm-level recursive linear programming framework with an ARIMA stochastic process, allowing the dynamic representation of farmers' adaptive behavior under uncertainty. A post-solution module incorporating means-based environmental indicators enables assessment of environmental performance at the farm level. The model is empirically applied to a representative sample of arable farms in Karditsa (NUTS-3 region), Greece, under three alternative scenarios: (i) Business-as-Usual (BAU), (ii) Common Agricultural Policy (CAP) post-2020, and (iii) CAP post-2020 combined with a scenario of Long War of Attrition (LWA). Simulation results reveal a consistent decline in the share of small farms (<30 ha) and a corresponding concentration of land in larger farms (≥50 ha), indicating limited long-term viability for smaller farms. Land-use projections show an expansion of food crop areas and a decline in industrial crops areas. Environmentally, reductions in water and fertilizer use under new CAP-related scenarios (ii and iii) suggest potential benefits for nitrate-polluted areas such as Karditsa.

Keywords: *Structural Change; Land Use Dynamics; Agricultural Policy; Environmental Impact Assessment; Dynamic Simulation.*

JEL Codes: C61: Q12; Q15; Q18; Q51.

Economic Valuation and Determinants of Residents' Willingness to Pay for Conservation in the Dadia–Lefkimi–Soufli Forest National Park

Aggelos Symeonidis[1], Chrysovalantis Malesios[2], Eleni Zafeiriou[3], Spyridon Galatsidas[1], Konstantinos Panytsidis[4] & Garyfallos Arabatzis[1]

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Abstract

Economic valuation of protected areas is a key component in designing effective management strategies and promoting sustainable development. This study investigates residents' Willingness to Pay (WTP) for the conservation and enhancement of natural resources in the Dadia–Lefkimi–Soufli Forest National Park, a biodiversity hotspot of national and European importance. Primary data were collected through a structured questionnaire survey targeting local residents, examining perceptions of forest, grassland and water resources, landscape values and wildlife conservation. Linear regression models were employed to estimate the determinants of WTP, using socio-demographic variables and indicators of environmental awareness as predictors. The findings reveal significant variation in WTP among residents, influenced by socio-economic characteristics such as education level, employment status and place of residence. Environmental sensitivity and positive attitudes toward conservation were also found to be strong predictors of higher WTP. Residents showed the greatest willingness to contribute financially to landscape and wildlife conservation initiatives, while lower WTP values were observed for grassland and water resource management. These results highlight the importance of integrating local communities into decision-making processes and developing targeted awareness programs to strengthen social support for conservation efforts. The study provides valuable insights into the socio-economic drivers of conservation funding and supports the development of sustainable management policies in protected areas.

Keywords: *Willingness to Pay (WTP), Natural resource management, Protected areas, Environmental valuation*

JEL Codes: Q51; Q56; Q57; Q58.

How Climate Change is Addressed in the Faustmann Forest Economics Model: A brief review

Sofia Mpekiri[1] & Konstantinos G. Papaspyropoulos[1]

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Abstract

This paper examines how climate change is addressed within the Faustmann Forest Economics framework to uncover the main takeaways regarding Optimal Rotation and Land Expectation Value (LEV). Three themes emerge. Mechanisms: climate change is mainly addressed through carbon accounting (life-cycle storage and release, direct and indirect emissions, multiple carbon pools), modeling the risk of climate-related disturbances (fire, storms, insects), and through the valuation of productivity changes and species shifts based on LEV. Optimal Rotation: when risk intensifies with stand age, rotations tend to shorten, whereas the availability of financial instruments such as insurance schemes offsets that effect. Carbon payment schemes generally lengthen rotations, but explicitly accounting for the albedo effect leads to shorter rotations relative to policies that rely solely on carbon emissions and accounting. Stochastic price modeling often leads to earlier harvests and higher LEVs than traditional Faustmann modeling. Replacement of tree species to battle the effects of climate change and increase forest resilience is associated with declines in LEV, and extensive-margin adaptation (replanting more suitable species) typically dominates marginal tweaks to rotation length. Policy: since forest valuation hinges on accounting rules, instrument design (taxation, subsidies, carbon penalties, insurance), and the degree of price uncertainty, climate related policies should align carbon incentives while addressing multi-hazard risk to be effective in addressing climate change through the economic management of forests. Overall, the Faustmann model remains the main vehicle for climate-relevant economic forest management, but recommendations are instrument-sensitive: a carbon-only lens tends to delay harvest, whereas adding age-dependent risk can reverse that result.

Keywords: *Faustmann model; climate change; optimal rotation; land expectation value (LEV); carbon accounting.*

JEL Codes: Q23; Q51; Q54; Q56; Q57.

Quantile estimation of CO_2 marginal abatement cost under heterogeneous emission-generating technologies

Haleh Delnava[1] & Sheng Dai[2]

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Abstract

Marginal abatement cost (MAC) is a critical metric for designing efficient climate policies. However, the reliability of MAC estimates is challenged by heterogeneous inefficiencies, the choice of emission-generating technologies, and the presence of extreme data. To address these issues, the first methodological contribution of this paper is to develop three sign-constrained convex nonparametric least squares models to represent by-production, joint disposability, and weak G-disposability technologies. The second contribution is to extend the analysis to quantile frontiers by proposing a convex expectile regression approach that explicitly incorporates inefficiency in characterizing emission-generating technologies. The third contribution is to investigate how alternative technology choices affect MAC estimates, drawing on empirical evidence from U.S. coal-fired power plants in 2022 and complementary Monte Carlo simulations.

Keywords: *Data envelopment analysis, Marginal abatement cost, Quantile estimation, Monte Carlo simulation*

JEL Codes: O44; O47; O52; Q43; Q56.

Sustainable Practices and Climate Change Adaptation in Olive Farming: Insights from Producers in Aetolia–Acarnania, Greece

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Abstract

Olive cultivation remains a cornerstone of the rural economy and cultural heritage in the Regional Unit of Aetolia–Acarnania, western Greece. However, the sector faces growing challenges from climate change, market volatility, and technological transformation. This study investigates how olive farmers perceive and respond to these pressures, focusing on their adaptive behavior, management practices, and readiness to transition toward sustainable production systems. Primary data were collected through 402 structured questionnaires administered in person between November 2024 and February 2025 across multiple towns and villages in Aetolia–Acarnania. The findings reveal significant heterogeneity among producers in their understanding of climate risks and their capacity to respond effectively. Economic uncertainty, limited access to information and training, and the persistence of traditional cultivation practices emerge as major barriers to adaptation. Nevertheless, there is increasing recognition of the need for environmentally responsible and economically viable approaches to olive production. The results highlight the importance of integrated policy measures that strengthen farmers' adaptive capacity through targeted education, innovation diffusion, and institutional support. Promoting the adoption of sustainable farming practices and the use of new technologies can enhance resilience and ensure the long-term viability of olive cultivation as both an economic activity and a driver of sustainable rural development in Mediterranean regions.

Keywords: olive cultivation; sustainable agriculture; climate change; ecosystem resilience; environmental policy; rural sustainability; Greece.

JEL Codes: Q01 ,Q12, Q15, Q54, Q13

Session 3.

Climate Change: Natural Disasters & Environmental Hazards

Climate Change, Natural Disasters, and Growth Dynamics in Latin America: A Panel Data Analysis

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Abstract

The growing occurrence and severity of climate-related natural disasters and climate change have intensified concerns about their long-term implications for economic stability, particularly in developing and middle-income regions such as Latin America. This research explores the dynamic interplay between climate-induced disasters and economic growth, with particular attention to how trade openness and capital formation shape this relationship. Drawing on a balanced panel dataset covering nine Latin American economies over the period 1980–2024, the study integrates short- and long-run econometric techniques to provide a nuanced understanding of how natural shocks affect macroeconomic performance. The empirical approach employs Fixed Effects (FE), Random Effects (RE), and Driscoll–Kraay (DK) estimators to address potential issues of unobserved heterogeneity, serial correlation, and cross-sectional dependence. To examine distributional heterogeneity across income levels, Quantile Regression is applied, while Panel Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimations are used to assess long-term relationships. The dependent variable is real GDP per capita, with explanatory variables including capital formation, trade openness, urbanization, agricultural and service value added, and measures of climate-related disaster frequency and severity. The results consistently indicate that capital formation and trade openness are powerful drivers of growth, reinforcing the importance of domestic investment and international integration for sustained development. In contrast, urbanization and agricultural value added are negatively associated with growth, implying that unregulated urban expansion and overreliance on primary sectors may hinder productivity. Climate-related disasters exert a persistent and significant negative effect, highlighting their disruptive impact on infrastructure, output, and human capital. Meanwhile, the services sector supports short-term recovery and stability, though its contribution appears statistically insignificant in long-term estimations. A central finding is the positive and significant interaction between disasters and trade openness, suggesting that countries more connected to global markets experience smaller economic losses from climate shocks. This moderating effect is robust across models. Results from the Quantile Regressions reveal that the resilience benefits of trade and investment are more substantial among higher-income economies, where institutional and structural capacity is greater. Long-run models (FMOLS and DOLS) reinforce these patterns, yielding exceptionally high explanatory power. In conclusion, the evidence demonstrates that trade integration and capital accumulation not only stimulate economic growth but also enhance resilience to climate-related disruptions. The findings highlight the need for policies that promote regional trade cooperation, investment in climate-resilient infrastructure, and sustainable urban and agricultural management to strengthen long-term development and adaptive capacity in Latin America.

Keywords: *Climate change; Natural disasters; Economic growth; Trade openness; Capital formation; Latin America; Panel data*

JEL Codes: Q54, F43, O44, C33, O54

Sense-Making and Resilience Perspectives of Austrian Micro and Small Enterprises Towards Flooding: A Qualitative Study

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Abstract
Climate change increases the frequency and intensity of extreme weather events, such as floods. Micro and small enterprises (MSEs) are particularly vulnerable to such events due to limited resources and low preparedness. This study explores the attitudes of Austrian MSE owners toward flood risk and challenges they face in strengthening organizational resilience after the severe flood of September 2024 that occurred in Austria. Twelve semi-structured interviews were conducted with MSE owners from flood-affected areas. Data were analysed through two coding cycles, combining open and deductive coding based on Protection Motivation Theory (threat and coping appraisals). Findings highlight critical barriers to resilience and reveal varying levels of learning from past flood experience, leading to a typology of flood risk attitudes. Findings also suggest that MSEs emphasise physical preparedness over organisational and strategic planning. The study recommends that local authorities and business associations promote peer-learning, experience-sharing, and tailored advisory services to assist enterprises design integrated resilience strategies extending beyond physical protection.

Keywords: *Flooding; Micro- and Small Enterprises; Climate Change Adaptation; Resilience; Qualitative Study; Austria.*

JEL Codes: Q54; Q56; L26; D22; O13.

Extreme weather and individual preferences in rural Thailand and Vietnam

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Abstract

We investigate how cumulative exposure to extreme weather shapes individual preferences. Leveraging longitudinal survey (2016–2024) from rural Vietnam and Thailand, we investigate the experience effects on patience, risk aversion, and non-financial risk attitudes. Exploiting the between- and within-individual variations of disaster experiences with Seemingly Unrelated Regressions, we uncover four findings. First, the cumulative experience of droughts, floods, and landslides can cause significant impacts in risk and time preferences with the direction depending on the country. The landslides leave the strongest effects among all events. Furthermore, a cumulative disaster experience characterized by more frequent sufferings affect individual preferences the most. We reveal a striking frequency-intensity paradox where moderate but more frequent disasters systematically produce larger behavioral changes than severe rare disasters. Third, extreme weather shocks amplify existing gender and ethnic inequalities and highlight how weaker institutions in Vietnam compound vulnerabilities. However, the males' effects are more persistent than those of female samples after controlling for the local market and health shocks. Disaster risk management policies should prioritize building resilience against moderate, frequent shocks while implementing targeted social protection mechanisms, as the behavioral impacts of frequent moderate disasters exceed those of rare severe events and disproportionately affect the most vulnerable communities.

Keywords: *Climate change; risk aversion; patience; seemingly unrelated regression; gender effect.*

JEL Codes: D12; D81; J16; Q54.

(C)yber (D)igital (R)isks: Revising the Framework Modern Threats Landscape for Environmental Hazards

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Abstract
Conventional frameworks for disaster risk reduction have traditionally been structured around four foundational components: hazard, exposure, vulnerability, and capacity. However, the increasing digitalization and interconnectivity of critical infrastructure systems have introduced a novel and systemic category of risk that extends beyond these established dimensions. This paper advances the argument for recognizing *digital risk* as a fifth pillar within the risk assessment paradigm, given the significant implications of cyber threats—particularly those involving remote access attacks—on physical infrastructure and environmental stability. Malicious intrusions into essential systems such as power grids, water treatment plants, and industrial control networks have demonstrated a growing capacity to initiate or amplify environmental crises. Unauthorized digital access can, for example, result in the intentional discharge of hazardous substances, compromise safety mechanisms, or lead to the malfunction of containment systems—thereby generating cascading impacts that surpass the digital domain. This study examines the converging trajectories of cybersecurity vulnerabilities and environmental hazards, positing that digital technologies must be conceptualized not solely as instruments of resilience but also as emergent sources of systemic risk. A revised risk assessment framework is proposed, incorporating digital risk as an integral component alongside the conventional four pillars, thereby providing a more comprehensive model to address the complexities of modern threat landscapes. Furthermore, the paper presents a set of policy and technical strategies for embedding cybersecurity into disaster risk governance, with particular attention to early warning systems, intersectoral coordination, and the development of digital competency. Recognizing digital risk as a distinct and critical pillar is imperative for constructing holistic, adaptive approaches to the protection of critical infrastructure and the advancement of environmental security.

Keywords: *Digital Risks, Technology-pillar, Risk Assessment, Environmental Hazards, Framework*

JEL Codes: D81; O13; O33; P18; Q54

Session 4.

Nature-based Solutions, Innovation & Resilience

Eco-process innovation: a “win win” situation or “when you have lemons make lemonade”? The moderating role of marketing innovation.

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Abstract
This study advances the eco-innovation literature by analysing the distinct effects of eco-process innovation components, specifically end-of-the-pipe (EPT) and resource-efficient technologies (RET), on firms’ innovation performance and whether marketing innovation moderates these effects. We analyse data from 7,660 product innovator firms across eight European countries using a Conditional Mixed Process (CMP) approach. The empirical results suggest that eco-process innovation does not have a uniform impact on innovation outcomes and that marketing innovation can transform compliance-driven environmental efforts into strategic advantages. EPT adoption has a negative impact on innovation performance, whereas RET adoption exerts a positive effect. Marketing innovation emerges as a key moderating factor, positively moderating the relationship between EPT technologies and innovation performance. On the contrary, marketing innovation does not exert a significant moderating impact on firms’ innovation performance in the case of RET.

Keywords: *Eco-innovation; green technology; innovation performance; marketing innovation; CMP*

JEL Codes: O31, Q55, M31

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1. Introduction

In recent years, climate change has become the centre of public concern as its impact become gradually more severe and harmful. In response, European governments have introduced programmes and policies (European Commission, 2020) designed to accelerate the development, diffusion, and adoption of technologies that are assumed to be "greener". Green technologies, such as solar panels and wind turbines, waste heat recovery systems, , zero-waste production processes, and advanced filtration, purification, or treatment systems, have being widely recognized as the vehicle with which firms can significantly reduce greenhouse gas emissions and energy consumption (Nunes Bennett, 2010; Busch et al., 2018). Despite intensive efforts to promote green transition, firms are still hesitant to commit to green transition (Filiou et al., 2023; Dimakopoulou et al., 2023). This is primarily attributed to the significant challenges firms face in capitalising on the positive effects of eco-innovation on firm performance (Barbieri et al., 2020; Vasileiou et al., 2022). In this context, there is an urgent need for sustainable methods and pathways that facilitate the adoption of green technologies without ramifications for firm performance (Koutsouradis et al., 2025).

Aligning eco-innovation with firm performance becomes particularly important in cases where firms face internal and external pressures to "green" their production and internalise the costs of green transition (Testa et al., 2011; Arranz, 2024; Santos et al.,2025). More specifically, firms face internal pressures such as cost-saving imperatives to save energy and/or material and reputational pressures to demonstrate an environmentally responsible profile and maintain legitimacy with stakeholders (Marshal et al., 2010; Wang et al., 2021). In addition, firms respond also to external pressures, such as regulatory schemes to comply with environmental standards, evolving market conditions, including customer preferences, industry norms and competitors' behaviour (DiMaggio and Powell, 1983). While extant literature has explored the antecedents of eco-innovation, focusing particularly on product innovation as a key driver of competitive advantage and long-term profitability, there is scarce evidence linking eco-process innovation with improved innovation performance.

Moreover, eco-process innovation is heterogeneous and can be distinguished in End-of-pipe technologies (EPT) and Resource efficient technologies (RET) (Demirel and Kessidou, 2011). While the direct impact of EPT and RET on firm financial performance has been extensively studied (Sarkis and Cordeiro, 2001; Rennings and Rammer, 2011; Xie et al., 2015; Ramanathan et al., 2018; Boakye et al., 2020; Brahmana and Kontesa, 2021; Aslam et al., 2021), the corresponding impact on firms' innovation performance is neglected. Even scarcer is the examination of the role of complementary assets, or non-technological innovations, such as marketing innovation, which could potentially contribute positively to shaping the relationship between PET and RET with innovation performance. Marketing innovation can enhance the visibility of eco-process innovations and connect environmentally conscious consumers to the green firm, thereby expanding the customer base by better communicating the firm's environmental messages. It can also assist in identifying opportunities to elevate eco-technologies from niche applications to mainstream designs for mass markets. (Pinkse et al., 2024).

To address these profound gaps in the relevant literature, we develop an integrated framework based on internal and external pressures that drive eco-innovation adoption (Wang et al., 2024), and capabilities theory to examine how firms leverage complementary assets to profit from their innovation efforts (Teece, 1986, 2006, 2018). More specifically, we argue that both internal and external pressures, i.e. cost efficiency and reputation, regulation and market demand conditions, differentially drive the adoption of two distinct types of eco-process innovation, namely Environmental Process Technologies (EPT) and Resource Efficiency Technologies (RET). We further *argue that firms are able to extract value realised from these types of eco process innovation based on complementary assets, and in particular marketing innovation, which makes otherwise 'invisible' process changes legible and valuable to the market (D'Attoma and Ieva, 2022; Orjuela-Ramirez et al., 2024).* Using a sample of 7,660 product innovators from eight European countries that are classified as "moderate" or "modest" innovators[1] from the 2014 wave of the Community Innovation Survey (CIS) to estimate a four-equation system. In this context and to address issues of endogeneity and self-selection into eco-innovation, we employ a Conditional Mixed Process (CMP) estimator, which allows for the joint estimation of multiple equations with different dependent variable types and correlated error structures.

Empirical findings suggest that EPT and RET adoption are associated with distinct pressures. Specifically, RET is positively affected by reputation, market demand and cost of energy pressures, while EPT adoption is positively affected by reputation and regulation pressures. Furthermore, RET adoption is directly associated to firms' innovation performance, mainly through cost competitiveness and indicating a win-win situation while EPT adoption may benefit firms' innovation performance only if it is part of a business strategy where marketing innovation supports EPT adoption, In this context, non-technological innovations such as marketing innovation can play a key role in fostering returns from compliance-driven eco-process innovations. Our analysis highlights the strategic importance of combining technological and non-technological innovations, offering new insights into how firms can turn compliance costs into competitive opportunities (Dimakopoulou et al., 2024). Our contribution is three-fold: first, we showcase that internal and external pressures exert a heterogeneous and asymmetric impact on the adoption of eco-process innovation. Such impact depends heavily on whether firms pursue RET and/or EPT adoption. Second, EPT and RET exert differential effects on firms' innovation performance; thus, environmental policies aiming to foster eco-process innovation adoption need to account for such heterogeneity. Third, it does 'pay to be green' in the case of eco-process innovation, which is conditioned on the simultaneous adoption of non-technological innovations, specifically marketing innovations, that can mitigate the negative impact of EPT on firms' innovation performance.

The remainder of the paper is structured as follows: Section 2 reviews relevant literature regarding the effects of EPT and RET on innovation performance and the moderating role of innovation marketing on these relationships, followed by Section 3, which presents the methodological framework. Section 4 describes the sample and the variables employed. Section 5 provides the empirical results and discussion while section 6 concludes the paper.

[1] This classification is presented in the European Innovation Scoreboard and remains consistent during consecutive measurement of key innovation indicators.

2. Theoretical Framework and Hypotheses

1.1. Differential impact of internal and external pressures on eco-process innovation

Global environmental challenges have shifted both policy and research interest in finding ways to develop or substantially improve products, processes, organisational practices, and/or marketing strategies that aim to reduce the consumption of resources and minimise the firm's harmful externalities to the environment" (Eco-Innovation Observatory, 2013). In this line, eco-innovation encapsulates this mandate and is distinguished from traditional innovations through its positive environmental impact, including changes in product portfolio or production processes (Frondel et al., 2007; Demirel and Kesidou, 2011; Triguero et al., 2013). In the eco-process innovation side, EPT refer to "*technologies designed to reduce pollution, externalities and/or recover resources at the end of the production process*" (Garcia-Quevedo et al., 2022; Frondel et al., 2007), while on the other hand RET innovationsinclude "*efficiency-enhancing technologies that optimize processes and reduce energy or input consumption"* (Ozusaglam et al., 2018; Cheng and Shiu, 2012). This distinction is crucial given the considerable heterogeneity in how firms approach, implement, and leverage each type of green technology (Khan et al., 2021). In this line, EPT and RET adoption is driven by both external and internal pressures, (Marshall et al., 2010; Tchórzewska et al., 2022; 2025), with nonetheless, differential impact.

External pressures are aligned with regulatory push and market pull forces. Regulatory pressures require or encourage firms to reduce emissions and comply with environmental standards (Greco et al., 2022; Blind, 2012). For example, Blind, (2012) provides empirical evidence based on a sample of OECD countries that environmental regulation strongly determines green innovation intensity. Under such regulatory and compliance pressures firms often prioritize the adoption of abatement, monitoring, and prevention technologies to directly address the negative environmental externalities, avoid penalties or qualify for tax and/or subsidy incentives. As such, when firms are confronted with regulatory and compliance pressures, they are more inclined to adopt EPTs. Furthermore, market-demand conditions, such as upstream suppliers, and downstream customer requirements, NGOs activism and eco-label expectations drive demand for green investments (Bleda and Valente, 2009; Wei et al., 2023; Zhang et al., 2022; Huang et al., 2025). These demand-pull forces can link eco-process innovation with market share and pricing power, especially in cases where customers' and suppliers' environmental demands focus on firms' production processes (Yenipazarali et al., 2020). Specifically, pressures from supply chain members to adopt greener processes and improve environmental performance incentivise stronger firms to introduce eco-innovations throughout the supply chain, maintaining competitiveness and legitimacy with their stakeholders. Moreover, when external stakeholders explicitly value lower resource intensity, RET adoption becomes strategically important as it simultaneously reduces costs and satisfies buyers' criteria (Khan et al., 2021; Porter and van der Linde, 1995).

At the other end, internal pressures are associated with managerial expectations regarding cost-efficiency and reputational imperatives (Yang and Kang, 2020). For instance, growing public awareness about carbon emissions has led on several occasions firms to introduce and promote carbon-capture technologies in their production processes even if it doesn't directly

reduce costs, because it satisfies external stakeholders and avoids sanctions (Blind, 2012; Petkova et al., 2014; Turken et al., 2020). In this line, gaining or maintaining firms' reputation as ecologically proactive can stimulate both RET and EPT adoption, being particularly salient for EPT adoption where the environmental benefit is externality reduction rather than internal efficiency. Firms that take a proactive environmental stance invest in systems and technologies, like cleaner production or voluntary standards, to preserve their legitimacy and signal their dedication, accepting that the return on this environmental investment may not be immediate cost savings.. For example, many airline companies promote the usage of recycled and diversified fuel that has a reduced CO2 emissions impact (Chiambaretto et al. 2024). Furthermore, adopting Resource Efficient Technologies (RET) yields a dual benefit: the resulting resource and cost savings directly enhance cost-competitiveness (Ambec and Lanoie, 2008; van Leeuwen and Mohnen, 2017), while simultaneously boosting the firm's reputation as ecologically proactive. More specifically, Ghisetti and Rennings (2014) argue that firms develop and introduce technologies in their production processes that reduce energy/materials consumption, to enjoy productivity gains. Moreover, this type of efficiency-oriented eco-innovation often results in complementarities among different technologies (e.g., lean manufacturing plus energy-efficient equipment), thus, generating cumulative productivity effects (Khan et al., 2021). Therefore, firms aiming to improve their financial performance will be more inclined to adopt eco-process innovations that streamline operations and improves productive efficiency (Ying et al., 2022). From this integrative perspective we argue that Resource-efficiency technologies (RET), are primarily driven by internal cost pressures and market demand conditions, and End-of-pipe technologies (EPT), are primarily triggered by external compliance and legitimacy pressures (Frondel et al., 2007; Horbach et al., 2012; Khan et al., 2021) leading to the development of the following hypothesis:

H1: EPT and RET adoption are driven by different internal and external pressures

1.2. EPT, RET and Innovation Performance

While the effects of eco-process innovation on financial and environmental performance have been evaluated (indicatively Stucki, 2019; Casseta et al., 2023; Valero-Gil et al., 2023), evidence on its impact on firm's innovation performance remains scarce. Rennings and Rammer (2011) show that regulation-driven eco-innovations have mixed effects on innovation performance based on the source of innovation. The integration of green technologies into the innovation process mix often prompts firms to adopt novel R&D practices, leading to an enrichment of their innovation capabilities (Bolívar–Ramos, 2023). Additionally, the introduction of new green technology can push firms to move beyond incremental activities and consider breakthrough solutions, thus fostering higher levels of technological advancement (Davis and Tomoda, 2018).

However, eco-process innovation can also introduce complexities (Dimakopoulou et al, 2024) and resource tensions, as investments in green technologies may divert attention and funding from other potentially high-impact innovation projects. Furthermore, due to strict regulations focused on forcing environmentally friendly solutions, firms may prioritise technologies that are not necessarily optimal for

innovation capability exploitation but are aligned with environmental standards (Ayoub and Lhuillery, 2024). For example, firms may be forced to adopt technologies that are "second best" or incompatible with their own organization of production, resulting in disruptions in production and productivity slowdowns (Kounetas and Tsekouras, 2010; Ayoub and Lhuillery, 2024). The underlying heterogeneity requires the distinguishment between the different components of eco-process innovation (Carrillo-Hermosilla et al., 2010; Tchórzewska et al., 2025).

By reducing expenditure on inputs, RET adoption frees up resources that can be redirected in further innovation activities. This increased flexibility, combined with greater cost efficiency, allows firms to price their innovative products more competitively, which can translate into higher sales and improved market performance (Rexhäuser and Rammer, 2014; Xie et al., 2015; Ozusaglam et al., 2018). The effectiveness of RETs is due to their integration into the firm's long-term innovation strategy (Chien and Peng, 2012; Nelson, 2018). In this context, when firms possess the organisational flexibility, technological know-how, and absorptive capacity to align RETs with their existing assets, they can translate the green investments into innovation outputs (Abdulai, 2019; Aarikka-Stenroos and Ritala, 2017). Furthermore, Ozusaglam et al. (2018), argue that firms that adopt RETs tend to do so on a self-selection basis , recognising that investments in efficient use of resources can provide a competitive edge (Orsato, 2006; Llach et al., 2025). Thus, RET adoption exemplifies how the pursuit of sustainability can be compatible with, and even drive, innovation performance, particularly due to it being primarily the outcome of internal strategic choice rather than external regulatory pressure (Rehfeld et al., 2007; Horbach et al., 2012).

In contrast, EPTs are not essential to the production process but serve the primary purpose of meeting environmental compliance (Rennings et al., 2006; Tchórzewska et al., 2025; Horbach, 2008; Horbach et al., 2012;2013; Zhu et al., 2023), often with limited, or even negative, direct benefits for productivity or innovation. In this regard, EPT adoption can introduce significant frictions in firms' innovation strategy. First, the costs associated with EPT assimilation may divert resources away from other innovation activities, creating distortions in resource allocation (Frondel et al., 2007; Shao et al., 2019). This is particularly problematic for strategic objectives targeting cost efficiency, due to the creation of trade-offs between maintaining low costs and absorbing the additional investments required for compliance (França et al., 2023). While regulations can be effective at prompting the adoption of EPTs, such investments are generally incremental, having little effect on the development of more radical or transformative innovations (Horbach et al., 2013; Liu et al., 2023). In this regard EPT may create no benefit in terms of capability development or even hinder the introduction of new technologies into the innovation knowledge base mix. The above lead to the formulation of the following research hypotheses:

H2a: Eco-process innovation captured by RET positively affects firms' innovation performance.
H2b: Eco-process innovation captured by EPT negatively affects firms' innovation performance.

1.3. Marketing Innovation as a complementary asset

Recent research has showcased that marketing innovation (MI) may be an important complementary asset in firms' innovation strategy (Dimakopoulou et al., 2024). Marketing innovation (MI) refers to the implementation of new marketing methods involving improvements in product design, packaging, price, distribution and promotion (OECD/Eurostat, 2005, p. 49). Marketing innovation enables firms to sense changes in the market environment and adapt their strategies accordingly (Zahoor and Lew, 2022), has the potential to influence all types of innovation pursued by the firm (Medase and Barasa, 2019) and can exert a positive effect on innovation-based sustainable strategies (Yu and Ramanathan, 2016). In this line, Pacheco et al. (2018) argue that marketing capabilities are higher-order capabilities which enable firms to benefit from their green strategies More specifically, MI can further boost innovation returns from RET adoption by enhancing market awareness and helping firms to recognise shifts in customer preferences, competitors' activities, and emerging opportunities (Petroni, 1998; Pekovic et al., 2016). In this regard, as RET adoption aims at reducing input costs and operate more efficiently, marketing innovation could ensure these advantages are maintained in the long run (Jedidi et al., 1999) through adaptation, reconfiguration and coordination of RET facets. At the other end, because EPTs are often implemented in response to regulatory pressures and may not directly generate competitive differentiation on their own, the ability to effectively market these environmental improvements can make a significant difference in innovation performance. Firms that invest in new methods of promotion, branding, or customer engagement can highlight the added value and compliance benefits of EPT, translating regulatory-driven changes into opportunities for market growth and improved reputation (Peattie, 2001). In this sense, marketing innovation helps bridge the gap between compliance and commercial success. This leads to the following research hypotheses.

MI can therefore enhance the benefits of EPT and RET by allowing process innovations to manifest as customer-perceived benefits. Indeed, eco-process innovations often remain "behind the scenes" and may not necessarily result in the introduction of new products which are directly visible and appreciated by customers. By leveraging marketing strategies with eco-process innovation, firms can make these hidden green investments visible. In this line, Yenipazarali et al., (2020) argue that it might be more beneficial to differentiate a product on the basis of its environmental impact *during* the manufacturing process rather than during the *usage* stage. For example, firms branding their products as manufactured with sustainable processes or obtaining eco-labels and then highlighting these in promotions can yield higher returns compared to promoting a product with environmental benefits because of its usage. This strategy relies on complementing marketing capabilities with RET and EPT adoption so that firms can differentiate themselves and their offerings in the eyes of their consumers, thereby turning process improvements into market gains (D'Attoma and Ieva, 2022; Chiambaretto et al. 2024). Recent studies also support this complementary role of marketing innovation. Orjuela-Ramirez et al. (2024) provide empirical evidence that marketing innovation allows a firm to capture greater value from its eco-innovation efforts even though they do not distinguish between eco-product and eco-process innovations.

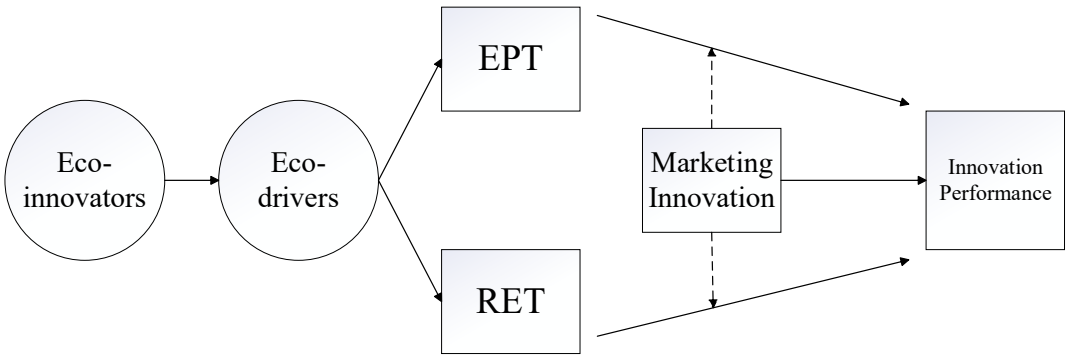
Therefore, we argue that marketing innovation positively moderates the relationship between eco-process innovation—both EPT and RET—and innovation performance. In other words, a firm that excels in promoting its eco-processes can offset the potential adverse effect of EPT and further enhance the positive relationship of RET. Marketing innovation educates customers, allows the firm to build a green corporate image, and generates demand linked to its eco-processes,increasing sales or prices, which translates into higher innovation performance (D'Attoma and Ieva, 2022; Orjuela-Ramirez et al., 2024). This leads to our final hypotheses:

H2a: Marketing innovation positively moderates the relationship between RET adoption and firms' innovation performance

H2b: Marketing innovation positively moderates the relationship between EPT adoption and firms' innovation performance.

Figure 1 below summarises our integrated framework and research hypotheses. We argue that firms adopt EPT and RET as response to internal and external pressures. These two types of eco-process innovation do not contribute uniformly to performance: while RET adoption is expected to enhance innovation performance, EPT adoption may entail compliance-driven or cost-increasing adjustments that negatively affect performance, at least in the short run. At the same time, we argue that MI functions as a complementary mechanism that can moderate these effects by enabling firms to communicate and promote more effectively their eco-process innovation efforts.

Figure 1. Graphical presentation of research model



3. Methodological Underpinnings

The research examines firms' impact of the adoption of eco-process innovations on innovation performance of laggard European firms. Eco-process innovation is comprised of EPT and RET. Given the associated costs of implementing eco-process innovation, I aim to examine whether marketing innovation has a mitigating impact on relationship between eco-process innovation and innovation performance. Beyond the basic relationships described in the two hypotheses presented above, our analysis models the decision to become an eco-

innovator, to account for selectivity bias, and the decision to adopt any of the two examined eco-technologies (Abdesselam et al., 2024).

In this regard, I employ the Conditional Mixed Process (CMP) estimator Roodman (2011) proposed to handle multiple endogeneity levels and the left-hand variables' mixed character. Being a multiequation, multilevel methodology, CMP allows for the joint estimation of two or more equations that may feature different types (i.e. continuous, censored, ore ordered) of dependent variables with correlations among their error terms (Roodman, 2011). By jointly modelling the eco-technologies equations, the CMP methodology provides clear benefits in capturing the underlying complexities and offering potential efficiency gains. Additionally, it addressed cases of omitted variables that arise from the joint equation estimation. This approach is particularly useful since common unobserved factors influence variables, and endogenous relationships exist between the eco-technology equations.

In the framework introduced above, innovation performance of the *i-th* (i=1,…, n) firm may be modeled as:

$$IP_i = \lambda_R Ret_i^* + \lambda_{RM}(MIn^* Ret^*)_i + \lambda_P Ept_i^* + \lambda_{PM}(MIn^* Ept^*)_i + \boldsymbol{\beta' X_i} + \varepsilon_{IPi} \quad (1)$$

where the main dependent variables are defined as:

$$Ret_i^* = \begin{cases} 1 & if\ Ret > 0 \\ 0 & otherwise \end{cases} \quad Ept_i^* = \begin{cases} 1 & if\ Ept > 0 \\ 0 & otherwise \end{cases} \quad MIn_i^* = \begin{cases} 1 & if\ MIn > 0 \\ 0 & otherwise \end{cases}$$

where $\boldsymbol{X_i}$ is a matrix including determinants of innovation performance. The parameters to be estimated are λ_R, λ_{RM}, λ_P, λ_{PM}, and $\boldsymbol{\beta}$, while ε_{IPi} corresponds to the error term. For the measurement and construction of the dependent variable IP_i and the exact measurement of the main variables Ret_i^* and Ept_i^* see the following Subsection 4.2. Equations (2) and (3) below correspond to the decisions to engage in RET and EPT eco-innovation activities respectively via probit models

$$Ret_i = \lambda_{PPr}(PP^*)_i + \lambda_{RGr}(RG^*)_i + \lambda_{RPr}(RP^*)_i + \lambda_{ECr}(EC^*)_i + \boldsymbol{\delta' C_i} + \varepsilon_{Reti} \quad (2)$$

$$Ept_i = \lambda_{PPe}(PP^*)_i + \lambda_{RGe}(RG^*)_i + \lambda_{RPe}(RP^*)_i + \lambda_{ECe}(EC^*)_i + \boldsymbol{\varepsilon' C_i} + \varepsilon_{Epti} \quad (3)$$

where the eco-technology drivers are defined as:

$$PP_i^* = \begin{cases} 1 & if\ PP > 0 \\ 0 & otherwise \end{cases} \quad RG_i^* = \begin{cases} 1 & if\ RG > 0 \\ 0 & otherwise \end{cases} \quad RP_i^* = \begin{cases} 1 & if\ RP > 0 \\ 0 & otherwise \end{cases}$$

$$EC_i^* = \begin{cases} 1 & if\ EC > 0 \\ 0 & otherwise \end{cases}$$

The coefficients λ_{PPr} λ_{RGr} λ_{RPr} λ_{ECr} correspond to the estimations of the EPT drivers and λ_{PPe} λ_{RGe} λ_{RPe} λ_{ECe} correspond to the estimations of the RET drivers. The terms ε_{Reti} and ε_{Epti} corresponds to each equation's error terms, respectively. Finally, the realization of the latent variable for the eco-innovation is observed through the binary variables Eco_i modeled via the following probit equation.

$$Eco_i = \boldsymbol{\eta' Z_i} + \varepsilon_{ecoi} \quad (4)$$

where $\boldsymbol{Z_i}$ is a vector of determinants of eco-innovation and ε_{ecoi} denotes the error term in equation (4).

In the preceding multiple equation model (Eq. 1–4), the estimation process involves prediction errors ε_{IPi}, ε_{Reti}, ε_{Epti}, and ε_{ecoi} which are assumed to be correlated, reflecting the interdependence of the multiple outcome variables. However, firm-specific errors are viewed as independent, indicating an absent cross-firm correlation. To capture this pattern, the covariance structure of the prediction errors is modelled to allow for correlations among the

four errors belonging to the same firm, while setting the covariance between errors from different firms to zero. This means that each firm has a distinct covariance pattern among the four prediction errors, but these patterns do not influence each other across firms. The covariance matrix for a single firm's prediction errors is estimated using a partially symmetric structure that assumes a consistent correlation pattern across the different error terms. The off-diagonal elements of this matrix (ρ), represent the pair-wise correlations between the prediction errors. These ρ values need to be non-zero for the joint estimation with CMP to be meaningful.

4. Data and variables definition

Our dataset is drawn from Community Innovation Survey (CIS) 2014 wave, which is the latest available containing information on eco-innovation. It comprises of 7,660 product innovators across eight EU countries, namely Bulgaria, Estonia, Greece, Croatia, Hungary, Latvia, Portugal, and Romania. We have opted to examine firms from these countries for four reasons. First, to avoid mixing innovation systems with quite different structural characteristics and performance, which increases the heterogeneity that bemuses aspects of our analysis. Second European Union acknowledges that to realise full potentials, must go beyond the "usual suspects", the leading innovation countries, and exploit the untapped opportunities in the full spectrum of European space (Amaral-Garcia et al, 2023) Third, due to the pressing need for a deeper investigation regarding innovation strategies that promote eco-innovation in firms from countries that fall below average in terms of environmental innovation performance. Fourth, due to their provision of adequate responses regarding the environmental aspects of the survey (Parrilli et al., 2023), as well as on the innovation aspects essential for the objectives of this research. National Innovation Systems idiosyncrasies of Central and Eastern European countries, including Croatia, Hungary, Bulgaria, Estonia, Latvia and Romania, are examined by Radosevic (2017), where he documented the fragmented character of the corresponding innovation systems. Mediterranean countries included in the sample, Greece and Portugal, share many common characteristics of their National Innovation Systems with CEE countries (Gkypali and Tsekouras, 2015; Dimakopoulou et al, 2024). In the employed dataset. 51% of the firms operate in the manufacturing sector while 49% are active in the service sector.

4.1. Key Variables

As a dependent variable, we used firm's innovative sales which is defined as the percentage of sales from new or significantly improved products or services (Laursen and Salter, 2006; Barbieri et al., 2020; Dimakopoulou et al., 2023). Furthermore, to identify EPT and RET and in line with previous research (Ghisetti et al., 2015; Hottenrott et al., 2016; Ozusaglam et al., 2018) we classified a firm as adopting EPT if it has implemented innovations that result in at least one of the following environmental benefits: (i) reduced air, water, noise, or soil pollution within the enterprise, (ii) recycling of waste, water, or materials for internal use or sale, (iii) replacement of fossil energy with renewable sources, and/or (iv) substitution of materials with less polluting or hazardous alternatives. Similarly, we defined RET adoption as innovations that yield in at least one of the following environmental benefits: (i) reduced material or water use per unit of output within the enterprise and/or (ii) lower energy consumption and a reduced CO_2 footprint through decreased total CO_2 production. In our analysis, marketing innovation (MI) acts as a moderating variable. It is a binary indicator

assigned the value of one if a firm introduced at least one of the following: (i) significant changes to the aesthetic design or packaging of a product, (ii) new media or techniques for product promotion, (iii) new methods for product placement or sales channels, and/or (iv) new methods of pricing goods or services.

To capture internal and external pressures to adopt RET and/or EPT, we relied on information regarding firms' motivations to introduce eco-innovations. To avoid the multicollinearity of the motivation variables we have employed principal component analysis (PCA) to reduce dimensionality and extract components that summarise the common variance[2]. Based on the PCA results, we constructed four (4) composite indicators. Drawing from both the empirical literature and the patterns emerging from the data, we identified the following indicators: (i) regulatory pressure, (ii) market demand, (iii) cost of energy, and (iv) reputation. Table 1 below presents the definitions and basic descriptive statistics of the key variables 2used in our empirical analysis.

Table 1. Definition and descriptive statistics of the key variables

	Variable definition	Average (std.dev)	min (max)
	Dependent Variable		
IS : Innovative Sales (cont.)	% of turnover from product innovations new to the market	0.25 (0.29)	0.00 (1.00)
	Eco-process innovation and Moderator		
EPT: End of Pipe Technologies (0/1)	Encompasses innovations that generate at least one of the following environmental benefits: (i) reduced air, water, noise, or soil pollution within the enterprise, (ii) recycling of waste, water, or materials for internal use or sale, (iii) replacement of fossil energy with renewable sources, or (iv) substitution of materials with less polluting or hazardous alternative	-	0: 55.19% 1: 44.81%
RET: Resources Efficiency Technologies (0/1)	Encompasses innovations that generate at least one of the following environmental benefits: (i) reduced material or water use per unit of output within the enterprise or (ii) lower energy consumption and a reduced CO_2 footprint through decreased total CO_2 emissions	-	0: 62.88% 1: 37.12%
MI: Marketing Innovation (0/1)	Participation in one or more of: Significant changes to the aesthetic design or packaging New media or techniques for product promotion New methods for product placement or sales channels New methods of pricing goods or services	-	0: 48.08% 1: 51.92%

[2] The PCA results are presented in the Appendix

	Internal and External Pressures		
RP: Regulatory Pressure (categ.)	Composite indicator comprising from the following variables: (i) existing environmental regulations (ii) existing environmental taxes, charges or fees (iii) Environmental regulations or taxes expected in the future	1.69 (0.92)	0.00 (3.00)
REP: Reputation (categ.)	Composite indicator comprising from the following variables: (i) Improving the enterprise's reputation (ii) Voluntary actions or initiatives for environmental good practice within the sector	1.31 (0.57)	0.00 (2.00)
MD: Market Demand (categ.)	Composite indicator comprising from the following variables: (i) Government grants, subsidies or other financial incentives for environmental innovations (ii) Current or expected market demand for environmental innovations and, (iii) Need to meet requirements for public procurement contracts	1.21 (0.82)	0.00 (3.00)
CE: Cost of Energy (categ.)	Composite indicator comprising from the following variables: (i) high cost of energy, water or materials	0.65 (0.36)	0.00 (1.00)

4.2. Control Variables

Turning to control variables included in the innovation performance equation, we have included innovation collaboration as an important control variable, as firms involved in collaborative innovation activities are more likely to undertake radical innovations (Tether, 2002; Kobarg et al., 2019), benefit from access to external knowledge not available internally (Belderbos et al., 2018; Christensen et al., 2019) and expand their awareness of market opportunities (Van Beers and Zand, 2014) all of which influence innovation performance[3]. Furthermore, we account for firms' absorptive capacity, commonly proxied by innovation expenditures (Laursen and Salter, 2006; Gkypali et al., 2018), which reflects the firm's ability to identify, assimilate, and utilise external knowledge (Cohen and Levinthal, 1990; Zahra and George, 2002). Export variable is also included as it acts as a channel for learning and knowledge acquisition, thereby enhancing firms' capacity for innovation. (Gkypali et al., 2021). Being part of an enterprise is also considered as it fosters access to geographically dispersed resources, enabling firms to successfully adapt and introduce innovations tailored to varied markets and regulatory environments (Van Beers and Zand, 2014). Employment growth is included as expanding workforce capacity can enhance a firm's ability to generate and implement new ideas (Audretsch et al., 2014). R&D subsidies are utilised to alleviate financial constraints and the uncertainty associated with innovation, which can stimulate the commercialisation of new products and services (Greco et al., 2017). The role of intellectual property rights (IPR) is also examined, as effective IPR protection can enhance the firm's ability

[3] Because innovation collaboration has significant effects for eco-innovation, acting as an enabler for all types of eco-innovation activities (Triguero et al., 2013) it has also been included as a determinant of the decision to introduce an eco-innovation.

to appropriate the benefits of their innovation efforts (Lee et al., 2018). Table 2 below provides basic variables definition along with descriptive statistics of the additional control variables included in the main equation.

Table 2. Definition and descriptive statistics of the control variables

	Variable definition	Average (std.dev)	min (max)
IE: Innovation Expenditures (cont.)	Total expenditures on innovation activities in 2014 as % of turnover	0.13 (2.17)	0.00 (1.56)
EG: Employment Growth (cont.)	Growth of total employment between 2012 and 2014	0.22 (1.28)	-1.00 (2.00)
EXP: Export performance (cont.)	% of the total turnover from sales to clients outside the country in 2014	0.28 (0.35)	0.00 (1.00)
NM: New to the Market (0/1)	Introduction of a product new to the market	-	0: 44.55% 1: 55.45%
IPR: Innovation Property Rights (0/1)	Applied in one or more of: Patent, European utility model, industrial design right, trademark, licensed out or sell a patent, industrial design right, copyright or trademark to another enterprise, university or research institute, licensed in or buy a patent, industrial design right, copyright or trademark owned by another enterprise, university or research institute	-	0: 72.41% 1: 27.59%
COL: Innovation Collaboration (0/1)	Cooperation arrangements on innovation activities	-	0: 62.99% 1: 37.01%
SUB: Innovation subsidies (0/1)	Obtain public funding from one or more of the following sources (i) local or regional authorities (ii) central government (iii) EU	-	0: 65.92% 1: 34.08%
PGE: Part of group Enterprise (0/1)	Firm is part of an enterprise group	-	0: 57.88% 1: 42.12%
Selection: Decision to introduce an eco-innovation			

EI: Eco-innovation (0/1)	Introduction of innovations with environmental benefits obtained: (i) within the enterprise and/or (ii) during the consumption or use of a good or service by the end user	-	0: 44.31% 1: 55.69%
PRI: Process Innovation (0/1)	Introduction of one or more of: a new or significantly improved method of production, a new or significantly improved logistic, delivery or distribution system, a new or significantly improved supporting activities	-	0: 35.46% 1: 64.54%
PDI: Product Innovation (0/1)	Introduction of one or more onto the market of: a new or significantly improved good, a new or significantly improved service	-	0: 6.88% 1: 93.12%
EMS (0/1)	Environmental management systems	-	0: 65.27% 1: 34.73%
	Fixed effects		
SZ: Size (cat.)	Firm size (number of employees)	-	Small: 52.10% Medium: 33.42% Large: 14.48%
Country (cat.)	Bulgaria, Estonia, Greece, Croatia, Hungary, Latvia, Portugal, Romania	-	Bulgaria: 20.31% Estonia: 3.30% Greece: 10.14% Croatia: 8.13% Hungary: 19.82% Latvia: 3.17% Portugal: 31.33% Romania: 3.79 %
Industry (cat.)	(i) Manufacturing, (ii) Electricity, gas, steam and air conditioning supply, (iii) Water supply; sewerage; waste management and remediation activities, (iv) Construction, (v) Wholesale and retail trade; repair of motor vehicles and motorcycles, (vi) Transporting and storage, (vii) Accommodation and food service activities, (viii) Information and communication, (ix) Financial and insurance activities , (x) Real estate activities (xi) Professional, scientific and technical activities, (xii) Administrative and support service activities, (xiii) Human health and social work activities	-	(i): 50.09% (ii): 0.86% (iii): 01.98% (iv): 0.37% (v): 20.56% (vi): 04.55% (vii): 0.38% (viii): 10.81% (ix): 04.80% (x): 0.06% (xi): 05.45% (xii): 0.01% (xiii): 0.09%

Moreover, Table 2 presents right hand variables included in the selection equation, i.e. the decision to introduce an eco-innovation. Because innovation collaboration has significant effects for eco-innovation, acting as an enabler for all types of eco-innovation activities (Triguero et al., 2013) it has also been included as a determinant of the decision to introduce an eco-innovation. In addition we have included a variable capturing whether firms have introduces Environmental Management Systems (EMS), as firms adopting EMS standards tend

to reconfigure their business model and strategies to align with environmentally friendly objectives (Manders et al., 2016). In that manner firms complying with EMS standards are more prominent to eco-innovate compared to their counterparts (Papagiannakis et al., 2019). Binary variables capturing whether firms have intorduced product and/or process innovation have been incorporated to account for the prerequisite role of basic innovation capabilities, as eco-innovation typically build upon existing foundation of product and/or process innovation (Moreno-Mondéjar et al., 2020). Finally, we have accounted for size, industry and country effects introducing the corresponding variables in all equations. The correlation matrix of all the used variables is presented in Table 3.

Table 3. Correlation matrix of the used variables*

	INNS	EPT	RET	RP	REP	MD	CE	IE	EG	EXP	MI	NM	IPR	COL	SUB	PGE	PRC	ENI	SIZE	CNT	IND
INNS	1.00																				
EPT	-0.16	1.00																			
RET	0.02	0.12	1.00																		
RP	-0.02	0.65	0.30	1.00																	
REP	0.00	0.59	0.42	0.45	1.00																
MD	0.12	0.25	0.39	0.50	0.46	1.00															
CE	-0.08	0.39	0.71	0.43	0.35	0.27	1.00														
IE	0.03	-0.03	-0.06	-0.01	-0.04	-0.01	-0.02	1.00													
EG	0.05	0.01	0.04	0.04	0.03	0.05	0.05	0.03	1.00												
EXP	0.05	0.06	0.22	0.07	0.03	0.01	0.10	-0.04	0.02	1.00											
MI	0.07	0.01	0.04	0.03	0.09	0.08	-0.02	-0.01	0.01	-0.09	1.00										
NM	0.17	-0.08	0.07	-0.03	0.08	0.07	-0.04	0.04	-0.02	0.03	0.10	1.00									
IPR	0.02	-0.05	0.08	-0.01	0.03	0.04	-0.02	0.04	-0.02	0.04	0.19	0.14	1.00								
COL	0.07	-0.10	0.20	0.05	0.09	0.12	-0.02	0.03	0.00	0.10	0.07	0.16	0.16	1.00							
SUB	0.02	0.02	0.14	0.06	0.07	0.15	0.08	0.07	0.02	0.15	0.01	0.10	0.16	0.21	1.00						
PGE	-0.08	-0.07	0.26	0.03	0.02	-0.02	0.07	-0.01	0.01	0.19	-0.02	0.05	0.04	0.27	0.04	1.00					
PRC	0.06	0.08	0.09	0.09	0.12	0.07	0.04	0.02	0.01	0.02	0.14	0.06	0.02	0.11	0.13	-0.04	1.00				
ENI	0.00	0.18	0.30	0.27	0.22	0.20	0.15	-0.02	0.00	0.21	-0.01	0.06	0.07	0.16	0.12	0.25	0.07	1.00			
SIZE	-0.08	0.03	0.58	0.15	0.10	0.06	0.13	-0.06	0.01	0.31	0.00	0.04	0.11	0.24	0.11	0.47	0.05	0.39	1.00		
CNT	-0.26	0.41	-0.14	0.03	0.00	-0.19	0.25	0.01	-0.02	-0.06	-0.04	-0.07	-0.02	-0.24	0.00	-0.08	0.02	-0.07	-0.04	1.00	
IND	0.02	-0.43	-0.04	-0.18	-0.05	-0.06	-0.11	0.07	0.04	-0.34	0.08	0.03	0.06	0.08	-0.07	0.09	-0.01	-0.14	-0.04	-0.09	1.00

* For the binary variables, tetrachoric correlations have also been computed. EPT and RET variables represent the predicted CMP values. For space limitations reasons, they are not presented but are available upon request

5. Results

Table 4 presents the empirical results from the CMP estimation. Models 1 through 7 incorporate all relevant control and determinants related to firm characteristics. Model 1 represents the baseline model with only the control and innovation performance determinates. Model 2, Model 3 and Model 4 assess the main effects of eco-process innovation technologies, EPT and RET, on innovative sales. Model 5 examines the moderating impact of innovation marketing on EPT, while Model 6 assesses the moderating effect of marketing innovation on RET. Model 7 includes both interaction terms to evaluate further the robustness of our hypotheses regarding the moderation effects. The bottom part of the estimation's Table 4 presents the correlation between the error terms (ρ) for each estimated equation. Except $\rho_{Insales*EPT}$, the correlation terms are found statistically different from zero indicating that estimating the equations separately could introduce endogeneity concerns due to unobserved confounding factors. In contrast, the joint estimation framework addresses these issues by accounting for the correlation among the disturbances. In that manner, CMP is appropriate in our context.

Table 4. Empirical Results (estimated coefficients)

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Innovation Performance Equation							
EPT			-0.011 (0.012)	-0.026* (0.014)		-0.041*** (0.016)	-0.051*** (0.015)
RET		0.058*** (0.017)		0.061*** (0.016)	0.039** (0.017)		0.044*** (0.016)
MI				0.023*** (0.006)	0.004 (0.014)	-0.012 (0.016)	-0.026** (0.013)
EPT*MI						0.043** (0.017)	0.040** (0.019)
RET*MI					0.027 (0.024)		0.026 (0.025)
NM	0.071*** (0.004)	0.070*** (0.004)	0.071*** (0.004)	0.069*** (0.004)	0.069*** (0.005)	0.069*** (0.004)	0.068*** (0.004)
IE	0.003 (0.003)	0.003 (0.003)	0.003 (0.003)	0.003 (0.003)	0.003 (0.003)	0.002 (0.003)	0.002 (0.003)
IPR	-0.009* (0.005)	-0.009* (0.005)	-0.009* (0.005)	-0.012** (0.006)	-0.012** (0.006)	-0.013** (0.006)	-0.012** (0.006)
EG	0.009*** (0.004)	0.009*** (0.003)	0.009*** (0.003)	0.009** (0.003)	0.009** (0.004)	0.009*** (0.004)	0.009** (0.003)
COL	-0.007 (0.007)	-0.008 (0.007)	-0.008 (0.007)	-0.009 (0.008)	-0.009 (0.007)	-0.008 (0.007)	-0.009 (0.007)
SUB	0.008 (0.005)	0.007 (0.006)	0.008 (0.005)	0.007 (0.006)	0.007 (0.005)	0.009* (0.005)	0.007 (0.006)
EXP	0.043** (0.018)	0.043** (0.018)	0.043** (0.018)	0.044** (0.018)	0.045** (0.018)	0.045** (0.018)	0.046** (0.018)
PGE	-0.029** (0.015)	-0.029* (0.015)	-0.029** (0.015)	-0.028* (0.015)	-0.028* (0.015)	-0.029** (0.015)	-0.028** (0.015)
Constant	0.362*** (0.021)	0.325*** (0.028)	0.373*** (0.020)	0.328*** (0.027)	0.322*** (0.023)	0.380*** (0.027)	0.358*** (0.027)
EPT Equation							
RP			0.193*** (0.025)	0.191*** (0.024)		0.193*** (0.025)	0.191*** (0.024)
REP			0.320*** (0.029)	0.322*** (0.029)		0.320*** (0.029)	0.322*** (0.029)
MD			-0.029 (0.026)	-0.029 (0.025)		-0.029 (0.026)	-0.029 (0.025)
CE			-0.123*** (0.033)	-0.121*** (0.032)		-0.124*** (0.033)	-0.121*** (0.032)

Constant			0.330*** (0.051)	0.331*** (0.056)		0.330*** (0.051)	0.332*** (0.056)
				RET Equation			
RP		-0.073*** (0.010)		-0.073*** (0.010)	-0.073*** (0.010)		-0.073*** (0.010)
REP		0.081*** (0.024)		0.085*** (0.026)	0.081*** (0.025)		0.085*** (0.026)
MD		0.054*** (0.013)		0.054*** (0.013)	0.054*** (0.013)		0.054*** (0.013)
CE		0.845*** (0.062)		0.845*** (0.061)	0.846*** (0.062)		0.844*** (0.061)
Constant		0.204*** (0.034)		0.195*** (0.039)	0.204*** (0.034)		0.195*** (0.038)
				Eco-innovation Selection Equation			
PRC	0.593*** (0.083)	0.601*** (0.083)	0.593*** (0.081)	0.598*** (0.082)	0.601*** (0.083)	0.592*** (0.081)	0.598*** (0.082)
PRD	0.623*** (0.073)	0.621*** (0.074)	0.610*** (0.076)	0.613*** (0.077)	0.621*** (0.074)	0.609*** (0.076)	0.613*** (0.077)
ISO	0.608*** (0.058)	0.628*** (0.060)	0.621*** (0.058)	0.638*** (0.060)	0.628*** (0.060)	0.622*** (0.058)	0.638*** (0.060)
COL	0.254*** (0.048)	0.251*** (0.043)	0.238*** (0.050)	0.240*** (0.044)	0.251*** (0.043)	0.238*** (0.050)	0.240*** (0.044)
Constant	-0.930*** (0.096)	-0.940*** (0.097)	-0.915*** (0.096)	-0.926*** (0.098)	-0.939*** (0.097)	-0.914*** (0.097)	-0.926*** (0.098)
$\rho_{Insales*EP}$			0.019 (0.028)	0.0245 (0.032)		0.021 (0.030)	0.026 (0.034)
$\rho_{Insales*RE}$		-0.105** (0.051)		-0.111** (0.050)	-0.107** (0.053)		-0.114** (0.051)
$\rho_{Insales*ec}$	-0.113*** (0.027)	-0.084** (0.038)	-0.130*** (0.028)	-0.082** (0.038)	-0.074 (0.042)	-0.121*** (0.029)	-0.079** (0.038)
$\rho_{EPT*RET}$				0.222*** (0.018)			0.222*** (0.018)
$\rho_{EPT*eco-i}$			-0.614*** (0.033)	-0.611*** (0.044)		-0.614*** (0.035)	-0.611*** (0.044)
$\rho_{RET*eco-i}$		-0.454*** (0.059)		-0.441*** (0.050)	-0.453*** (0.059)		-0.441*** (0.050)
LL	-3842.73	-6313.02	-5696.73	-8154.15	-6308.40	-5690.68	-8150.94
N	7,515	7,660	7,660	7,660	7,660	7,660	7,660

Robust standard errors clustered by industry are reported in parentheses. One, two, and three asterisks denote significance at 10%, 5% and 1%, respectively. The models include fixed effects for firm size, industry, and country, which are not reported due to space limitations.

Concerning the determinants of eco-technology adoption, the average marginal effects for equations (2) and (3) presented Table 5 reveal significant differences between RET and PET. For EPT adoption, model (1) indicates that regulatory pressure and firm reputation are positively associated and highly significant at 1% level. At the same time, energy cost exerts a negative and statistically significant effect on the likelihood of adopting EPT. The market demand factor is found not statistically significant for EPT adoption. In contrast, regarding RET adoption, model (2) firm reputation and market demand factor and energy cost exert significant and positive effects. In contrast, regulatory pressure is negatively associated with the adoption of RET. Model (3) in Table 5 shows that even when both variables are included in the estimation results remain robust.

Focusing on the main effects of EPT and RET on innovation performance, the empirical results from Model 4 in Table 6 indicate that EPT is negatively associated, at the 10% level, with firms' innovation performance (Hypothesis H2a is supported). On the other hand, RET is positively associated with innovation performance at the 1% level (Hypothesis 2b is supported). Additionally, marketing innovation emerges as a positive and highly significant determinant of innovation performance. These findings suggest that eco-process innovation does not have a unidimensional effect on innovation performance and that marketing innovation can leverage changes in production to foster an 'environmentally friendly' innovation strategy.

Table 5. Average Marginal Effects for EPT and RET adoption equations

	Model 1	**Model 2**	**Model 3**
		EPT	
RP	0.065*** (0.008)		0.064*** (0.008)
REP	0.110*** (0.009)		0.108*** (0.009)
MD	-0.01 (0.009)		-0.01 (0.008)
CE	-0.042*** (0.011)		-0.041*** (0.011)
		RET	
RP		-0.027*** (0.004)	-0.027*** (0.004)
REP		0.030*** (0.009)	0.031*** (0.009)
MD		0.020*** (0.005)	0.022*** (0.005)
CE		0.310*** (0.021)	0.311*** (0.02)

Numbers in parentheses are standard errors. One, two, and three asterisks denote significance at 10%, 5% and 1%, respectively.

The role of marketing innovation becomes more prominent when considering its moderating impact on RET and EPT technologies. Reported results from Model 5 in Table 6 indicate that RET association with innovation performance remains positive when marketing innovation is absent from the firm's strategic mix. At the same time, the interaction term RET*MI is not significant for innovation performance, suggesting that marketing innovation is not a significant moderator of firms' innovation performance in the case of RET (H3a is rejected). This finding indicates that the efficiency gains embedded in RET adoption are sufficient on their own to generate innovation returns. In this context, marketing innovation does not appear to strengthen the RET and innovation performance relationship, as these technologies already contribute directly to competitiveness. On the contrary, EPTs' association with innovation performance becomes negative at 1% level when the firms don't engage in marketing innovation. Additionally, the interaction EPT*mkt has a positive impact on innovative sales suggesting that marketing innovation positively moderates the relationship between EPT and innovation performance (H3b is supported). The results of Model 7 in Table 6, which include both interaction terms (EPT*mkt and RET*mkt), demonstrate that the results remain robust across model specifications. The moderating effects of marketing innovation on the relationships of EPT and RET with innovation performance are graphically illustrated in Figure 2 and Figure 3, respectively. The average marginal effects of the CMP 's innovative sales estimation presented in Table 6 further support the robustness of the empirical findings.

Figure 2. Moderating effect of marketing innovation of EPT

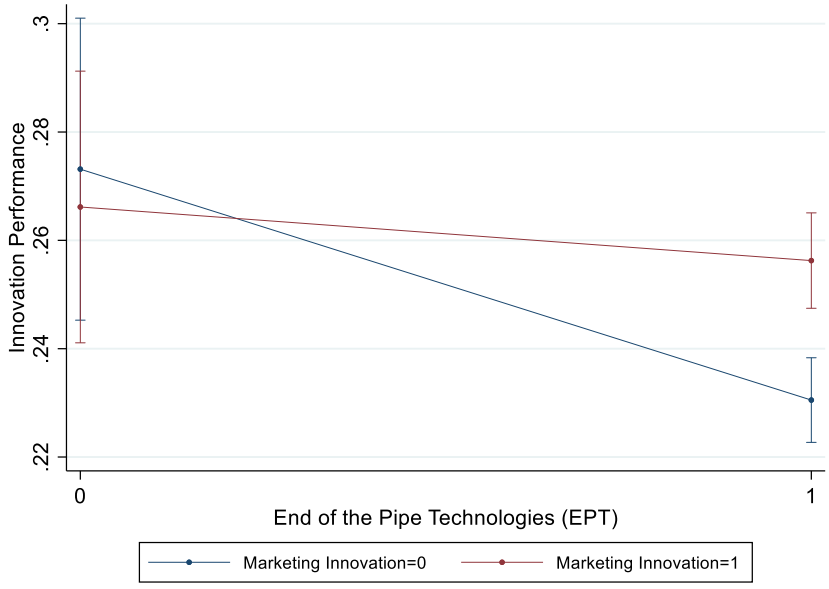


Figure 3. Moderating effect of marketing innovation of RET

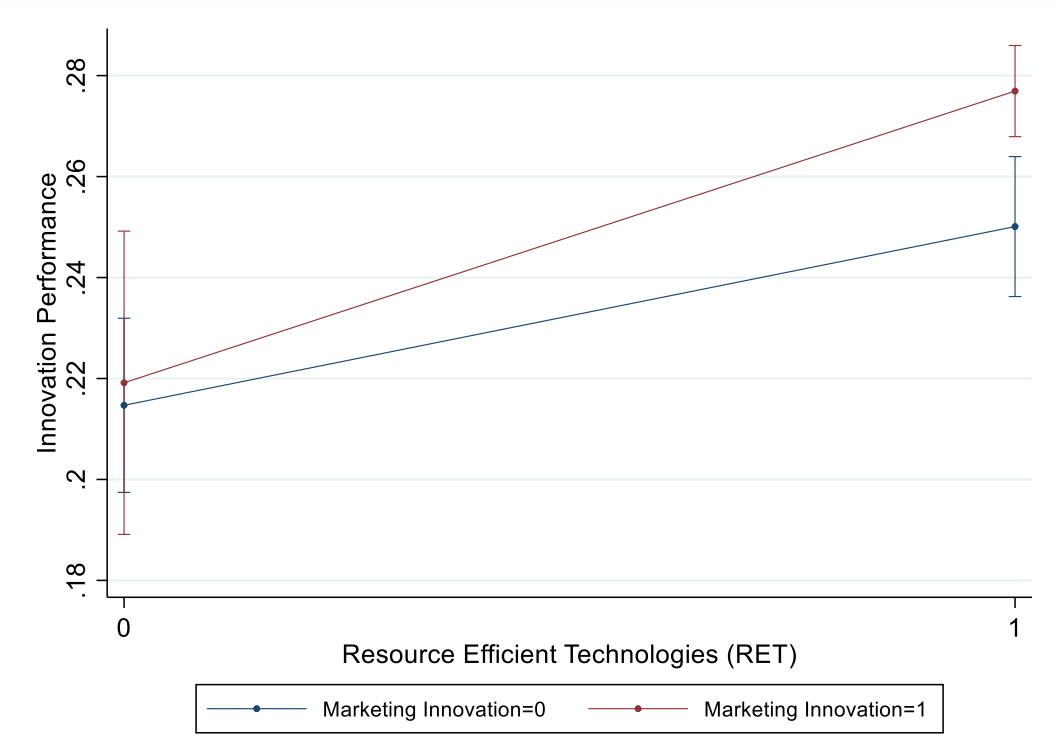


Table 6. Average Marginal Effects for Innovation Performance Equation

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
	Innovation Perfromance						
EPT			-0.010 (0.01)	-0.022* (0.011)		-0.011 (0.01)	-0.021 (0.012)
RET		0.048*** (0.014)		0.050*** (0.013)	0.047*** (0.014)		0.05 (0.014)
MI				0.019*** (0.005)	0.019*** (0.005)	0.019*** (0.004)	0.02 (0.004)
EPT*MI						0.036** (0.014)	0.033** (0.016)
RET*MI					0.023 (0.019)		0.022 (0.02)
NM	0.06*** (0.004)	0.058*** (0.004)	0.060*** (0.004)	0.057*** (0.004)	0.057*** (0.004)	0.058*** (0.003)	0.057*** (0.004)
IE	0.002 (0.002)	0.002 (0.003)	0.002 (0.002)	0.002 (0.003)	0.002 (0.003)	0.002 (0.002)	0.002 (0.003)
IPR	-0.008* (0.004)	-0.007* (0.004)	-0.007* (0.004)	-0.01** (0.005)	-0.010** (0.005)	-0.011** (0.005)	-0.01** (0.005)

EG	0.008*** (0.003)	0.007*** (0.003)	0.008*** (0.003)	0.007*** (0.003)	0.007** (0.003)	0.008*** (0.003)	0.007*** (0.003)
COL	-0.003 (0.006)	-0.005 (0.006)	-0.004 (0.006)	-0.006 (0.006)	-0.006 (0.006)	-0.004 (0.006)	-0.006 (0.006)
SUB	0.007 (0.004)	0.006 (0.005)	0.007 (0.004)	0.006 (0.005)	0.006 (0.005)	0.007* (0.004)	0.006 (0.005)
EXP	0.036** (0.015)	0.035** (0.015)	0.035** (0.015)	0.037** (0.015)	0.037** (0.015)	0.038** (0.015)	0.038** (0.015)
PGE	-0.024** (0.012)	-0.024* (0.012)	-0.024** (0.012)	-0.023* (0.012)	-0.023* (0.012)	-0.024** (0.012)	-0.024** (0.012)

Numbers in parentheses are standard errors. One, two, and three asterisks denote significance at 10%, 5% and 1%, respectively.

5. Discussion and Conclusions

Our research contributes to resolving a critical ambiguity in the eco-innovation literature: the heterogeneity surrounding the relationship between eco-process technologies and firms' innovation performance. Distinguishing eco-process innovation into its core components, Resource-Efficient Technologies (RET) and End-of-Pipe Technologies (EPT) and employing a robust Conditional Mixed Process (CMP) approach on a sample of 7,660 product-innovating firms across eight European countries with fragmented innovation systems, we demonstrate that investments in eco-process technologies yield vastly different strategic innovation outcomes. Although internal and external pressures drive both types of eco-process innovation adoption, the relative effect of each pressure depends on the component of eco-innovation on which it is exerted, which in turn displays different patterns of association with firms' innovation performance.

5.1. Theoretical contribution

Our findings confirm the conventional view that EPT technologies are introduced primarily to comply with regulatory standards (Zhu et al., 2023; Tchórzewska et al., 2025) without any direct benefits for the input side of firms. This argument is further supported by the negative association of the cost of energy with the probability of EPT adoption. On the other hand, regulatory pressures are negatively associated with RET adoption, which suggests that firms are more likely to adopt RET voluntarily, in anticipation of competitive gains, rather than as a response to regulatory coercion. In this line, the cost of energy is positively related to firms' decision to adopt RET as a mechanism to make processes more efficient and counterbalance the increasing energy cost (Frondel et al., 2007; Triguero et al., 2013). On the demand side, incentives for RET adoption are valued for their ability to reduce resource consumption, which in turn, can be appealing to environmentally conscious consumers and shareholders. Firms may therefore adopt them in response to market signals that reward lower energy use, reduced material intensity, or sustainable production practices (Mrkajic et al., 2019). These findings are consistent with prior research. For example, Cainelli et al. (2020) report on the significance of demand-side factors in fostering the adoption of environmental innovations that promote

recycling, reduce waste, and decrease material use. By contrast, EPTs are add-on solutions designed for pollution control, introduced to meet environmental regulations enforced by public authorities rather than to satisfy customer preferences. In this regard, customers generally expect firms to comply with environmental standards and to prevent pollution as a basic responsibility, rather than as a differentiating market attribute (Mantovani et al., 2017). Consequently, demand-are of limited importance for the firms' decisions to adopt EPT. Lastly, the significance of firm's reputation factor for both EPT and RET adoption indicates that firms may pursue either as part of a signalling strategy to demonstrate environmental responsibility to stakeholders (Lee and Rhee, 2005; Seroka-Stolka, 2023) and enhance their "green image" (Xie et al., 2019a).

Moreover, we offer a new, nuanced perspective on the links between eco-process innovation components and innovation performance. Empirical results confirm that RET adoption is a direct enabler of innovation success, positively related to firms' innovation performance. RET, being largely voluntary and mainly driven by internal efficiency pressures, aligns consistently with long-term innovation strategy, establishing a genuine "win-win" hypothesis. In essence, by boosting resource and cost efficiency, RET adoption can free up resources (Klassen and Whybark, 1999; Ozusaglam et al., 2018) that can be reinvested in further innovative activities, which in turn increase innovation performance. On the other hand, consistent with concerns over resource diversion and compliance burdens, EPT adoption is found to be directly negatively related to innovation performance. The negative link between EPT and innovation performance reflects the compliance-driven nature of such technologies, which often involve additional costs (Sun et al., 2024) without directly improving efficiency or product quality. Firms adopting EPTs mainly to meet regulatory standards face a trade-off between environmental compliance and innovation output. EPT represents the "lemons" of environmental regulation.

By extending the Profiting from Innovation framework (Teece, 1986; 2006; 2018), we demonstrate that non-technological innovations, specifically marketing innovations, are crucial for realising returns from EPT adoption. Therefore, empirical findings underscore the strategic complementarity between technological and marketing innovation as a mechanism through which firms can turn "lemons into lemonade" by leveraging Marketing Innovation. These findings emphasise that simply complying with environmental regulations is not a precondition of performance gains unless it is complemented by managerial initiatives aimed at effectively communicating, repositioning, or redesigning products and processes (Macron et al., 2017; Yenipazarali et al., 2020; D'Attoma and Ieva, 2022) in ways that convey firms' environmental responsibility to consumers. In this regard, marketing innovation allows firms to reframe eco-process innovation adoption mandated by government regulations into proactive decisions within the framework of a broader sustainability strategy, therefore strengthening their reputation and positive customer perception. Consequently, this shift in consumer perception increases customer demand for the firm's environmentally friendly products (Xie et al., 2019b). It extends to its current and potential new offerings, generating a brand effect that increases innovation performance.

5.2. Managerial and Policy Implications

Our empirical findings have important implications for both managers and policy makers. In terms of managerial relevance, empirical results suggest that achieving a competitive edge from eco-process technologies is heavily dependent on the type of eco-process innovation. While managers proactively adopt RET technologies to enjoy efficiency and reputational gains and satisfy environmental concerns from stakeholders, they remain averse towards the adoption of EPTs, since the additional adoption and adjustment costs may erode productive efficiency (Frondel et al., 2007; França et al., 2023; Kounetas and Tsekouras, 2010). On this basis, we concur with extant empirical literature that energy/material saving technologies classified as RET, are positively associated with innovation performance (Ambec and Lanoie, 2008) and that EPTs are indeed 'lemons' that firms are forced to adopt due to regulation and to avoid damage in their public profile. However, empirical evidence suggests that firms can turn 'lemons into lemonade' by exploiting complementarities between EPTs and marketing innovation (D'Attoma, I., Ieva, M., 2022; Orjuela-Ramirez et al., 2024). This is particularly important for managers, since a key element of their marketing strategy to boost sales of innovative products is to communicate to stakeholders. These environmental benefits are not apparent at the usage stage but instead materialise during the manufacturing process (Yenipazarli et al., 2020) and would remain invisible without proper promotion and communication. Put differently, by introducing new methods of promotion, branding, and customer engagement, marketing innovation transforms the otherwise "invisible" compliance efforts into a visible and valuable signal of environmental responsibility, translating regulatory-driven changes into commercial opportunities.

In terms of policy design for the green transition, our research highlights the need for policy measures promoting eco-process innovation to differentiate between technologies aimed at improving resource efficiency and those seeking to reduce negative externalities through compliance. In the case of regulatory policies, complementary actions and incentives should be supported to strengthen the marketing and communication capabilities of firms subject to such regulations. For example, official labelling schemes or certification frameworks actions can assist European firms in clearly communicating and enhance the credibility of their compliance with EU environmental standards, such as those set for green technology adoption, emission reduction, and waste management (indicatively, Directive (EU) 2010/75; European Commission, 2021). This visibility would enable environmentally compliant firms to stand out from competitors operating under less strict regulatory frameworks. Such an approach is consistent with recent evidence showing that environmental policy is most effective when coordinated with complementary instruments that reduce informational frictions and make compliance visible to external stakeholders (Greco et al., 2022).

6.3 Limitations and further research

Our work is not without limitations, indicating new avenues for further research. Scholars should employ panel data to examine the causations and the dynamics of the relationships identified in this study, particularly the effects of each type of eco-process innovation on innovation performance and the complementarities observed between eco-technologies and marketing innovation. Moreover, extending the analysis to countries with more advanced

innovation systems would allow for the exploration of additional complementary assets and components of dynamic capabilities. Such an approach would enhance the understanding of how institutional, regulatory, and market conditions shape the relationship between eco-process innovation and firms' innovation performance. Finally, while a significant finding indicates that marketing innovation can effectively serve as a complementary asset to EPT, the specific marketing strategies involved fall beyond the scope of the present analysis. Future research should therefore investigate which marketing strategies, such as eco-branding, digital communication, or green labelling, are most effective in enhancing the performance outcomes of EPT adoption.

Appendix

To address multicollinearity among the eco-innovation driver's, we employ PCA to construct components that summarise the common variance structure and reduce dimensionality. The results of the PCA are presented in tables A.1 and A.2. All the converging retention criteria, including eigenvalues around or above one, cumulative explained variance at or above roughly 70%, and the inflexion point in the scree plot (figure A.1.), point to a four-component structure. In this regard each component is comprised in the following variables: the first component by (i) Existing environmental regulations (enereg), (ii) Existing environmental taxes, charges or fees (enregf) and, (iii) Environmental regulations or taxes expected in the future (enetx); the second component by (i) Improving the enterprise's reputation (enrep), (ii) Voluntary actions or initiatives for environmental good practice within the sector (enagr); The third component by (i) Government grants, subsidies or other financial incentives for environmental innovations (engra), (ii) Current or expected market demand for environmental innovations (endem) and, (iii) Need to meet requirements for public procurement contracts (enrequ); The four component by (i) High cost of energy, water or materials (encost).

Table A.1. PCA factor retention indices

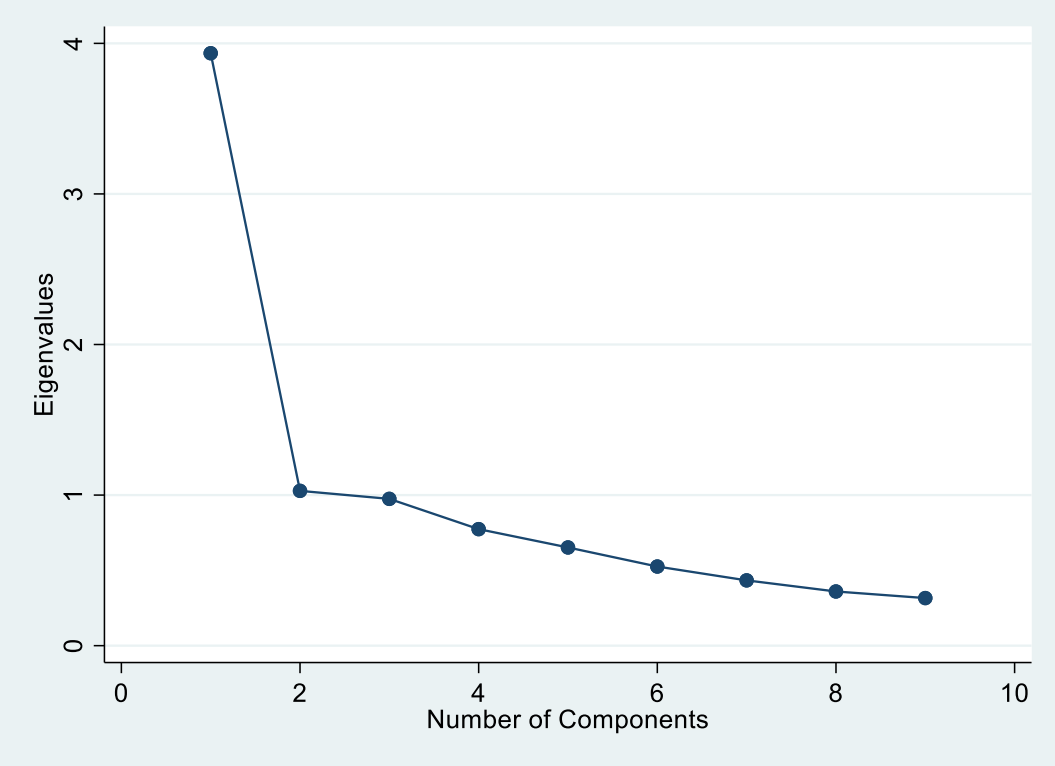
Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	3.990	2.974	0.443	0.443
Comp2	1.017	0.045	0.113	0.556
Comp3	0.972	0.206	0.108	0.664
Comp4	0.766	0.124	0.085	0.750
Comp5	0.643	0.122	0.071	0.821
Comp6	0.521	0.091	0.058	0.879
Comp7	0.429	0.076	0.048	0.927
Comp8	0.353	0.045	0.039	0.966
Comp9	0.309	.	0.034	1.000

Table A.2. PCA factor loadings

Variable	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6	Comp7	Comp8	Comp9
enereg	0.374	-0.391	-0.094	-0.280	-0.047	0.033	0.008	0.779	-0.103
enregf	0.400	-0.324	0.029	-0.133	-0.142	-0.095	0.093	-0.492	-0.661
enetx	0.382	-0.444	0.073	-0.116	0.022	-0.003	-0.024	-0.342	0.721
enrep	0.336	0.365	-0.349	-0.180	-0.067	0.379	-0.665	-0.100	-0.013

enagr	0.297	0.394	-0.435	-0.198	0.274	-0.607	0.276	-0.018	0.087
engra	0.312	0.142	0.484	0.414	-0.154	-0.504	-0.423	0.144	-0.004
endem	0.332	0.374	0.082	0.126	-0.618	0.272	0.503	0.046	0.125
enrequ	0.261	0.282	0.579	-0.234	0.587	0.299	0.156	0.014	-0.065
encost	0.279	-0.132	-0.314	0.759	0.384	0.248	0.125	0.039	-0.063

Figure A.1. PCA Scree Plot



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Sustaining Environmental Resilience: A Stackelberg Game

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Abstract

This paper develops a dynamic Stackelberg game between a social planner and an extracting firm to study the regulation of resource extraction under alternative environmental dynamics. The planner acts as leader by setting extraction quotas, while the firm, as follower, chooses extraction effort in response depending on the allowed quantity. The analysis is conducted under both exponential and logistic regeneration functions, with open-loop and feedback strategies considered. The results show that in the exponential growth case, open-loop equilibria yield unstable steady states, and stability can only be achieved under feedback control with sufficiently strong environmental resources stock-sensitive responses. In the logistic growth case, natural carrying capacity does not guarantee stability; instead, saddle-path equilibria emerge, implying sensitivity to initial conditions and discounting. Across all settings, the planner's quotas discipline extraction effort, but sustainability remains fragile. The findings highlight the limits of regulatory control, the importance of feedback mechanisms, and the necessity of precautionary policy design in achieving long-run resource sustainability.

Keywords: *Differential games, Environmental degradation, Exponential growth, Logistic growth, Sustainable growth, Stackelberg game.*

JEL Codes: C61, C72, Q58, Q52

1. Introduction

This paper addresses a fundamental problem in environmental economics: how to sustain environmental resilience in the presence of natural resource extraction. We care about how the social planner can control the exploitation of natural capital internalizing environmental and economic sustainability. For that purpose, we develop a Stackelberg differential game to study the conflicting case between social planner and the representative extracting firm. We employ the exponential environmental growth functions and under the well–known informational game structures, i.e., open and closed loop.

The sustainable management of natural resources in the presence of environmental degradation remains a central issue in both environmental economics and policy design. Resource extraction activities, while contributing to economic output and private profitability, simultaneously impose negative externalities on the environment. These externalities manifest through the depletion of natural stocks and the deterioration of ecological quality, thereby undermining long-term welfare. Reconciling the tension between private incentives for resource exploitation and the social objective of environmental preservation requires the design of effective regulatory mechanisms that account for strategic interactions among agents.

A well-established framework to analyze such interactions is the Stackelberg differential game, in which a regulator assumes the role of a *leader* who designs policy instruments to maximize intertemporal social welfare, while an extracting firm acts as a *follower* that chooses extraction rates to maximize discounted profits. This hierarchical structure captures the asymmetry of commitment and informational advantage typically present in real-world regulatory settings, where policymakers anticipate and internalize the behavioral responses of private agents.

This study develops a Stackelberg differential game of resource extraction with a specific environmental dynamic. In this specification, the natural environment evolves according to an exponential growth process, in which regeneration is proportional to the current stock. This regeneration function is a special case of the more general logistic growth functionspecifically when the stock is far below carrying capacity, which incorporate carrying capacity and more accurately capture ecological processes. Within the above specification, two equilibrium concepts are examined: the open-loop Stackelberg equilibrium, where strategies are pre-committed functions of time, and the feedback (closed-loop) Stackelberg equilibrium, where strategies are contingent on the current state of the system.

The comparative analysis of these equilibria yields several insights. Under exponential growth, the equilibrium dynamics are tractable and highlight the role of regulatory commitment in mitigating over-extraction. Moreover, the comparison between open-loop and feedback strategies underscores the importance of commitment and adaptability in shaping both environmental outcomes and welfare trajectories.

This paper contributes to a growing body of research on dynamic resource games and environmental regulationby rigorously demonstrating that:

- The form of regulation matters deeply. Adaptive, state-dependent feedback rules are superior to rigid, open-loop policies.
- Ecological dynamics dictate regulatory design. The optimal policy for an exponentially growing resource is fundamentally different from that for a logistically growing one.
- Sustainability is an active achievement, not a passive outcome. It requires continuous, informed intervention and a design that accounts for both economic rationality and ecological fragility.

The foundation for the analysis of renewable resource dynamics was laid by the seminal work of Clark (1976) on bioeconomic models, while Levhari and Mirman (1980) introduced game-theoretic perspectives on resource exploitation. Subsequent studies have employed differential games to examine conflicts between regulators and firms, including Dockner et al. (2000), who provide a comprehensive treatment of dynamic oligopoly and environmental games, and van der Ploeg and de Zeeuw (1992), who study open-loop versus feedback equilibria in resource management. More recent contributions, such as Mäler et al. (2003), have emphasized the importance of ecological dynamics in shaping regulatory outcomes. By extending this literature to compare exponential and logistic growth processes within both open-loop and feedback Stackelberg equilibria, this paper bridges ecological modeling and strategic regulation, thereby offering both methodological and policy-relevant insights.

More recent research has extended these approaches to contemporary policy contexts. Chen et al. (2021) analyze transboundary pollution control through differential games of ecological compensation, while Ya et al. (2024) investigate the interaction between government carbon trading policies and firm production strategies in a Stackelberg framework. Relatedly, Zhou and Xu (2024) apply game-theoretic models to greenhouse gas regulation, highlighting the role of strategic behavior in climate policy. Advances in methodology have also been made: Zhang and Yong (2022) address the time-consistency problem in open-loop Stackelberg equilibria, and Huang and Shi (2024) extend the framework to stochastic differential games with feedback strategies. Groot et al (2003), in an excellent paper a*ddresses time-consistency in Stackelberg games for resource extraction.*

Benchekroun & Withagen (2012), *extends Stackelberg leadership concepts to non-renewable resources with Markovian strategies*. Petrosian et al. (2023) develop a dynamically updating extraction game, which underscores the importance of adaptability in resource use. Grafton et al (2007) makes a modern review that uses empirical evidence to argue that securing resource tenureis the most effective way to prevent biological and economic overexploitation, notably in fisheries. In the differential game framework, Long, N. V. (2010) in his textbook covers the technical machinery of dynamic games, including renewable resource games. Polasky et al. (2011) moves beyond smooth growth functions to model resources with tipping points (e.g., a fishery that can collapse irreversibly). It shows that optimal management becomes vastly more precautionary when such thresholds exist.

Brock and Xepapadeas (2003) introduce concepts of deep uncertainty ("Knightian uncertainty") and robustness into environmental regulation. When the exact model of the ecosystem is unknown, policymakers should choose rules that perform well across a range of

plausible models. In environmental resilience field, Folke et al (2010), argues that management should focus on maintaining the resilience of social-ecological systems—their ability to absorb shocks and continue functioning—rather than just optimizing the output of a single resource. Walker & Salt (2006), in their book they apply resilience theory to practical resource management, emphasizing the importance of managing feedback loops, diversity, and modularity within systems. Halkos et al. (2024), propose a differential game between firms that extract natural resources and the social planner, that concerns about environmental sustainability.

Linearization, Jacobians, and eigenvalue analysis have long been central tools for studying stability in dynamic economic models. The seminal contribution of Ramsey (1928) introduced the analysis of steady states of capital and consumption, laying the groundwork for modern dynamic optimization. Later, Brock and Mirman (1972) extended this framework to stochastic growth, where eigenvalues characterize local stability under uncertainty. The role of eigenvalues in distinguishing determinacy from indeterminacy was formalized by Benhabib and Farmer (1994), showing how stability properties shape equilibrium uniqueness and the possibility of expectation-driven fluctuations. More recently, Ajevskis (2019) advanced the literature by employing the stable manifold method, starting from Jacobian eigen-decomposition to construct global (nonlocal) solutions. Applications remain diverse: for instance, Halkos et al. (2019) compute the Jacobian and eigenvalues of a dynamic environmental regulation model to study cyclical strategies.

The stable manifold itself has been explicitly applied in various contexts. In a two-sector endogenous growth model, Eicher and Turnovsky (2001) demonstrate that transitional dynamics are governed by a two-dimensional stable manifold, with off-manifold trajectories diverging from the balanced growth path. In a variant of the Ramsey model with logistic population growth, Bundău et al. (2009) show the existence of a saddle-point steady state with a two-dimensional stable manifold describing the set of convergent trajectories. The mathematical underpinnings of this approach trace back to the classical work of Hirsch et al. (1976) on invariant manifolds, which formalizes how local linearization via Jacobians extends to nonlinear global dynamics.

By extending this literature and in order to compare exponential and logistic growth processes within both open-loop and feedback Stackelberg equilibria, this paper bridges ecological modeling and strategic regulation, offering methodological advances as well as policy-relevant insights.

The rest of the paper is organized as follows: Section 2 examines the game with the social planner as a follower; while section 3 considers the extracting firm a follower (social planner is the leader). Section 4 discuss on the value functions of the follower. Section 5 examines the leader's problem, and section 6 considers the environmental state–dependent taxation adapted to the model. Section 7 provides discussion and the contribution of the paper and Section 8 concludes.

2. The social planner as a follower

The case in which the social planner reacts as a follower in a Stackelberg has been examined in Halkos et al (2024). They propose a dynamic leader–follower game between the extracting firms (leader of the game) and the social planner (the follower). The follower maximizes his own functional which is

$$J_2 = \int_0^{\infty} e^{-\rho_2 t} [W_1(E) + W_2(Q)]dt$$

E is the environmental capital, Q is the allowed extracting quantity, ρ_2 is the discount rate of the leader, while $W_1(E)$ is the utility that the society enjoy from a good environmental quality is assumed in a linear form as well, i.e. $W_1(E) = W_1 E$, $W_2(Q) = AQ$ is the utility of extraction (it is assumed that the optimality is ensured). The representative firm that exploits environmental resources maximizes the following functional

$$J_1 = \int_0^{\infty} e^{-\rho_1 t} [h(U,Q) - C(U) - D(E) - \Psi(Q)]dt$$

$h(U,Q)$ is the harvesting function, $C(U) = CU$ is the cost of harvesting, $D(E) = DE$ are compliance costs (e.g., subsidy withdrawals or environmental fees), which depend on the extraction quantity. Moreover, $\Psi(Q) = \Psi Q$ is the opportunity cost from which the firm suffers due to the follower's control policy Q . The constraint under which the maximization takes place is

$$\frac{dE}{dt} = \dot{E} = G\big(E(t)\big) - h(U,Q)$$

$G\big(E(t)\big) = \omega E$ is the environmental growth rate, $h(U,Q) = U^{\pi}Q^{\varepsilon}$, $\varepsilon > 1 > \pi > 0$ is the harvesting function.

2.1. On the exponential growth $G\big(E(t)\big) = \omega E$

Exponential growth function is a partial case of the logistic growth function, i.e. in the early stages of a growing population when the sample is very low.
An example at which the exponential growth is a reasonable modeling choice is for sardine and anchovy fisheries during short-term or early population expansion phases, particularly following periods of low stock abundance.

Sardines and anchovies are small pelagic species characterized by high intrinsic growth rates, short generation times, and rapid recruitment variability. After years of poor recruitment, environmental shocks (e.g., unfavorable oceanographic conditions), or intense fishing pressure,

stock sizes can fall well below the ecosystem's carrying capacity. Under these low-density conditions, density-dependent constraints such as competition for plankton and spawning habitat are weak, allowing population growth to be approximated by the exponential model: $\dot{E} = \omega E$.

We prefer the exponential growth function to model fisheries because it provides a simple and analytically tractable first approximation of fish population dynamics under certain conditions:

(a) Early-stage or low-density approximation

When fish stock levels are far below the environmental carrying capacity (e.g., after overfishing, stock collapse, or at the beginning of a recovery period), density-dependent effects such as competition for food and habitat are weak. In this regime, the population is very small compared with the carrying capacity K, i.e. $\dot{E} = \omega E\left(1 - \frac{E}{K}\right), E \ll K$ implying $\dot{E} = \omega E$, so population grow this approximately exponential.

(b) Short-term modeling horizon

Regulatory decisions in fisheries, forestry, and other renewable resource sectors are frequently made over short time intervals (annual or seasonal). Over such horizons, the influence of carrying capacity is limited, and exponential growth provides a sufficiently accurate representation of biological dynamics. This makes it a practical choice for analyzing policy responses and strategic interactions in differential games.

(c) Limited data availability

Estimating the carrying capacity K requires long-term, high-quality ecological data, which is often unavailable or unreliable. In contrast, the intrinsic growth rate ω is typically easier to estimate from short-run observations. Using the exponential model therefore reduces parameter uncertainty and avoids over-fitting ecological dynamics that are poorly understood.

(d) Analytical simplicity and transparency

The exponential model offers closed-form solutions and simplifies the analysis of dynamic strategic behavior. This is particularly valuable in Stackelberg differential games, where:

- the leader anticipates the follower's reaction,
- the follower solves an intertemporal optimization problem, and
- the resulting system must be analyzed for stability.

Exponential growth allows the focus to remain on strategic interactions rather than on complex ecological nonlinearities. It also facilitates linearization, Jacobian analysis, and explicit characterization of steady states and stable manifolds.

(e) Benchmark or null model

Exponential growth serves as a natural benchmark against which more complex ecological models—such as logistic, age-structured, or threshold-based dynamics—can be compared. Deviations from exponential behavior may signal the onset of density dependence, environmental stress, or overexploitation. As such, it provides a clean baseline for understanding how ecological assumptions influence optimal policy design.

As a case of exponential growth usage is the case of modeling choice for the Northern Atlantic cod population during the initial recovery period following a fishing moratorium.
After the collapse of the cod stock and the subsequent closure of the fishery, the population size was far below its historical carrying capacity. Under these conditions, density-dependent effects such as competition for food, habitat limitation, and intraspecific competition were minimal. Therefore, the population dynamics during the early recovery phase can be approximated by the exponential growth model:

$$\dot{E} = \omega E$$

In this context, the exponential model captures the intrinsic biological recovery potential of the cod population without requiring estimation of the carrying capacity, which is highly uncertain due to long-term ecosystem changes. Because management assessments were focused on short-term stock rebuilding rather than long-term equilibrium levels, the simplicity of the exponential model made it useful for estimating early recovery rates and comparing rebuilding scenarios.
While exponential growth is preferable for the reasons above, it is important to acknowledge that it difficult describe long-term fishery dynamics because it ignores carrying capacity and sustained harvesting. Therefore, it should be viewed as a simplified, short-term or low-density approximation, not a comprehensive management model.

2.2. On the harvesting function $h(U, Q) = U^{\pi} Q^{\varepsilon}$

(a) Each input increases harvest

In the model it is assumed $\varepsilon > 1, 0 < \pi < 1$ and because $\pi > 0$ and $\varepsilon > 0$, increases in either intensity or quota raise total harvest.
This represents technological or biological constraints, as higher quotas encounter environmental limits (e.g., scarcity, reduced stock availability).

(b) Joint complementarity between intensity and quota

Since U and Q enter multiplicatively, each increases the effectiveness of the other:

$$\frac{\partial^2 h}{\partial U \partial Q} = \pi \varepsilon U^{\pi-1} Q^{\varepsilon-1} > 0$$

Interpretation:

- A higher quota increases the productivity of additional effort.
- Higher effort increases the productive impact of a larger quota.
  This reflects real-world fisheries and natural resource exploitation:
- If regulation grants more quota, the marginal value of effort rises.
- If effort increases, the marginal utility of greater allowable catch rises.

Thus, the two instruments are complements in production.

(c) Intensity and quota represent different economic constraints

Economically, U and Q represent two different margins of decision or regulation:

- Intensity U is chosen by harvesters and involves real resource costs (labor, fuel, vessels).
- Quota Q is typically policy-determined, affecting legal limits or access to the resource.

The harvest function shows that:

- Effort and technology determine the *capacity* to extract.
- Regulation determines the *legal limit* to extraction.
- Actual harvest is the interaction of biological, economic, and policy factors.

This allows the model to analyze regulation effectiveness and strategic responses.

(d) The functional form is useful in dynamic games

For the theoretical analysis:

- It is smooth and strictly increasing in both variables.
- It produces simple elasticities that ease dynamic optimization.
- It supports clear comparative statics: increasing quota or intensity scales harvest by known elasticities.

Thus, it is widely used in resource economics because it is both realistic and analytically tractable.

(a) Elasticities & Marginal Products

- Elasticity of harvest w.r.t. effort (π):

In the model it is assumed: $0 < \pi < 1$, harvest increases with effort but at a diminishing rate.

- Economic interpretation: Effort has decreasing marginal productivity. Doubling effort less than doubles harvest. This reflects real-world constraints: congestion, scarcity of easily accessible resources, or capacity limits.
-
- Elasticity of harvest w.r.t. quota (ε):

The assumption $\varepsilon > 1$, means harvest is more than proportionally responsive to quota changes.

- Economic interpretation: A 1% increase in the allowed quota leads to a *more than* 1% increase in actual harvest. This captures "accelerated extraction" when limits are relaxed—firms exploit the additional quota aggressively.

(a) Strategic Implications in the Stackelberg Game

When the planner sets Q (leader):
a. Knowing $\varepsilon > 1$, the planner anticipates that a quota change will be amplified in actual harvest.
b. This makes quotas a potent but risky tool: slight over-generosity can lead to severe over-extraction.

When the firm chooses U (follower):
c. The firm's optimal effort depends on Q, but with diminishing returns to effort.
d. The firm will increase effort when Q rises, but not proportionally (since $\pi < 1$).

(b) $\varepsilon > 1$ is realistic assumption

- Technological/behavioral response: When quotas are relaxed, firms may:

(a) Deploy more efficient technology.

(b) Focus on richer, easier-to-extract resources first.

(c) Work more intensively (longer hours, extra shifts).
- Example: In fisheries, a higher quota may lead to:
  - Fishing in previously avoided areas (higher catch per unit effort initially).
  - Using more efficient gear (e.g., larger nets).
  - Concentrating effort in peak seasons.
- Result: Harvest increases more than proportionally to the quota.

(c) $0 < \pi < 1$ is realistic

- Resource scarcity: As effort increases, the remaining resource becomes harder to extract (lower density, deeper, more remote).
- Congestion & competition: More effort leads to interference among extractors (e.g., boats competing for fishing grounds).
- Capacity constraints: Limited processing/storage capacity reduces marginal gains from added effort.

(d) Summary Table

Parameter	Range	Economic Meaning
π	$0 < \pi < 1$	Diminishing returns to effort. Effort increases harvest but at a decreasing rate.
ε	$\varepsilon > 1$	Increasing returns to quota. Quota changes have amplified effects on harvest.
Interaction	$\frac{\partial^2 h}{\partial U \partial Q} > 0$	Effort and quota are complements. More of one increases the productivity of the other.

Policy implications

- Quotas (Q) determine the legal upper bound of extraction.
- Intensity or effort (U) determines how strongly harvesters try to exploit that boundary.
- Elasticities (π, ε) tell whether quotas or effort regulations have the larger effect.
- The function predicts substitution, compliance behavior, and the effectiveness of policies across fisheries, forestry, and pollution control.

2.3. Stability of the system

In the case the social planner, is the follower of the Stackelberg game his reaction is given by the $Q^*(U) = \left(\frac{W_2}{\varepsilon\mu}\right)^{\frac{1}{\varepsilon-1}} U^{\frac{\pi}{1-\varepsilon}}$, $\varepsilon > 1 > \pi > 0$, μ is the shadow price of environmental quality (Halkos et al, 2024).

Economic implications of reaction strategy

(i) Reaction to the leader's decision U: the exponent on U is $\frac{\pi}{1-\varepsilon}$, since $\varepsilon > 1$ and $\pi > 0 \frac{\pi}{1-\varepsilon} < 0$. This means: if the leader increases U (intensity of extraction), then the optimal allowed quantity $Q^*(U)$ decreases. This implies that, a more aggressive leader strategy makes future extraction costlier in terms of environmental damage.

(ii) Role of resource harvesting elasticity ε: $\varepsilon > 1$ ensures convexity of harvesting, i.e., as Q rises, depletion accelerates disproportionately. Moreover, a higher ε makes the negative effect of the intensity of extraction of U on Q^* stronger, which means the more "resource – hungry" the system is, the less social planner will want to preserve for the future in response to higher leader activity.

(iii) Role of π. Since π measures how strongly the leader's action U contributes to resource depletion, the larger π, the more sensitive Q^* is to changes in U. If π is close to zero, the social planner hardly adjusts its strategy when the leader changes the extraction intensity U, and if π is closer to 1, the adjustment is much sharper.

In short, the policy reaction $Q^*(U)$ says that the social planner reacts defensively to the leader's extraction intensity. The stronger the leader pushes on the environment, the less social planner finds it worthwhile to conserve stock of environmental resources for the future.

Stability check

The constraints of the Stackelberg game is: $\dot{E} = \omega E^* - h(U, Q^*(U))$ and the shadow price $\dot{\mu} = \mu^*(\rho_2 - \omega) - W_1$

Therefore, the steady state values are: $E^* = \frac{1}{\omega} h(U, Q^*(U))$ and $\mu^* = \frac{W_1}{\rho_2 - \omega}$. The harvesting function $h(U, Q)$it is supposed as $h(U, Q) = U^{\pi} Q^{\varepsilon}$, and substituting the reaction policy the steady state value of environment becomes $E^* = \frac{1}{\omega}\left(\frac{W_2}{\varepsilon\mu^*}\right)^{\frac{\varepsilon}{\varepsilon-1}} U^{\frac{\pi}{1-\varepsilon}}$. The linearized system around (E^*, μ^*) has the following Jacobian

$$J = \begin{pmatrix} \frac{\partial \dot{E}}{\partial E} & \frac{\partial \dot{E}}{\partial \mu} \\ \frac{\partial \dot{\mu}}{\partial E} & \frac{\partial \dot{\mu}}{\partial \mu} \end{pmatrix} = \begin{pmatrix} \omega & -h_{\mu} \\ 0 & \rho_2 - \omega \end{pmatrix}$$

And the eigenvalues are:

$$\eta_1 = \omega, \qquad \eta_2 = \rho_2 - \omega$$

The stability check reveals the next proposition.

Proposition 1

The social planner's reaction given by the $Q^*(U) = \left(\frac{W_2}{\varepsilon\mu}\right)^{\frac{1}{\varepsilon-1}} U^{\frac{\pi}{1-\varepsilon}}$, results in a saddle path stability, only if $\rho_2 < \omega$. The more economic restriction imposed is: $0 < \rho_2 < \omega$

Proof

Stability of the steady state depends entirely on the signs of the eigenvalues η_1, η_2. (a) If both eigenvalues are negative, i.e., $\omega < 0$ and $\rho_2 - \omega < 0$, the steady state is asymptotically stable (node). The latter is impossible, because, even $\omega < 0$, could be $\rho_2 < \omega$, i.e., $\rho_2 < 0$, which is economically impossible. (b) If both eigenvalues are positive ($\omega > 0$ and $\rho_2 - \omega > 0$), both directions are unstable and the interior steady state is a repeller, i.e., unstable node, which means that small deviations grow exponentially in both variables. (c) If the eigenvalues have opposite signs, the equilibrium is a saddle node. The latter case has two subcases, (i) $\omega < 0$, and $\rho_2 > \omega$, which means negative environmental growth ($\omega < 0$) yet biologically impossible and (ii) $\omega > 0$, and $\rho_2 < \omega$ which is economically and biologically acceptable, together with $\rho_2 > 0$.

Economic intuition

The biologically natural parameter is $\omega > 0$, while the discount rate ρ_2 is typically positive. Two possibilities:

- If $\rho_2 < \omega$ eigenvalues have opposite sign implying saddle path stability. Economically this means, the social planner costate variable μ must start on the special path (determined by the transversality conditions and optimality) to generate convergence. A saddle is typical in optimal control problems: the steady state is not globally attractive but there is a unique feasible path consistent with optimality.

- $\rho_2 > \omega$, both eigenvalues positive ($\omega > 0,\ \rho_2 - \omega > 0$) is out of interest, since implies instability

Eigenvalue $\eta_1 = \omega$ (how environmental quality responds to its own level). If the natural growth is positive, any perturbation in environmental quality Ewill tend to grow (if above the steady state value) of fall away (if below) – i.e., the environment is self–reinforcing unless the depletion term reacts dynamically to restore it. But here depletion doesn't depend on E, so it cannot stabilize E linearly. The other eigenvalue $\eta_2 = \rho_2 - \omega$ shows how the shadow price μ evolves relative to natural growth. If the social planner discounts the future a lot (ρ_2 large relative to ω), the costate dynamic tends to push μ away from the steady state value, therefore producing instability absent an economic mechanism to pin the path. Concluding, stability hinges on the relative size of natural environmental growth ω and the social planner's discount rate ρ_2.

The next result concerns the stable manifold in the economically acceptable case.

Proposition 2.
In the economically interesting saddle path stability ($\rho_2 < \omega$), the linear stable manifold is the line:
$\mu - \mu^* = \frac{2\omega - \rho_2}{h_\mu(\mu^*)}(E - E^*)$ with $h_\mu(\mu^*)$ evaluated at μ^*. Trajectories that converge to the steady state must lie on this line near (E^*, μ^*), where: $\mu^* = \frac{W_1}{\rho_2 - \omega}$ and $\omega E^* = h\big(U, Q^*(U, \mu^*)\big)$.

Proof

Let λ_s denote the stable eigenvalue (the one that is negative). We examine the economically interesting case at which $\omega > 0$.
If $\rho_2 < \omega$ then $\lambda_s = \rho_2 - \omega < 0$.
From $(J - \lambda_s I)v = 0$ the first row gives

$$(\omega - \lambda_s)v_1 - h_\mu v_2 = 0$$

so, the eigenvector may be chosen as

$$v = \begin{pmatrix} 1 \\ \frac{\omega - \lambda_2}{h_\mu} \end{pmatrix} = \begin{pmatrix} 1 \\ \frac{2\omega - \rho_2}{h_\mu} \end{pmatrix}$$

Thus, the linear stable manifold (tangent at the steady state) is:

$$\mu - \mu^* = \frac{2\omega - \rho_2}{h_\mu(\mu^*)}(E - E^*)$$

with $h_\mu(\mu^*)$ evaluated at μ^*. Trajectories that converge to the steady state must lie on this line near (E^*, μ^*)

Economic interpretation of the stable manifold

The linear stable manifold gives the first–order trade–off between the social planner's shadow price $\mu$and environmental quality$E$ that must hold on convergence. If $k = \frac{2\omega - \rho_2}{h_\mu(\mu^*)} > 0$, then a higher environmental level E must be accompanied by a proportionately higher μ along the saddle path; if $k < 0$ the relationship is inverse. The sign and magnitude of k are determined by natural growth ω, discounting ρ_2, and how strongly the shadow price μ affects depletion via h_μ. Numerically speaking, with $\rho_2 < \omega$ and $\omega > 0$, the numerator $2\omega - \rho_2 > 0$ and the slope magnitude is inversely related to $|h_\mu|$.

In the same setting, i.e., the social planner is the follower, the optimal strategy $U^*$of the firm that extracts natural resources is the following:

$$U^* = \left[\frac{W_2 C(\varepsilon - 1)}{\pi(\Psi\varepsilon\mu + W_2(\lambda - 1))}\right]^{\frac{1-\varepsilon}{\pi+\varepsilon-1}} \left(\frac{W_2}{\varepsilon\mu}\right)^{\frac{\varepsilon}{\pi+\varepsilon-1}}$$

and the feasibility condition for the interior solution to be economically meaningful is:

$$\Psi\varepsilon\mu > W_2(1 - \lambda).$$

λ is the costate variable corresponding to environmental quality E.

The stability analysis (available on request) reveals that, in the economically acceptable case $\omega > 0$, the saddle path condition is:

$$\rho_1 < \omega, \qquad \rho_2 < \omega \text{ and } \rho_1 + \rho_2 > \omega$$

One economic interpretation of that condition would be the following (for the eigenvalues $\eta_i, i = 1, \ldots, 4$):

- $\eta_1 = \omega > 0$: environment's own feedback: the environmental state direction is locally repelling (positive eigenvalue) unless other dynamic forces depend directly on E to stabilize it. In the present setup the harvesting (depletion) term $h(\lambda, \mu)$ doesn't depend on E directly, so the intrinsic growth rateω appears directly as an eigenvalue.

- $\eta_2 = \rho_2 - \omega$ the follower's (social planner) discounting relative to environmental growth. If $\rho_2 < \omega$ this direction is stable, reflecting that the follower values the future sufficiently relative to natural growth so the costate variable μpulled back to its steady state.
- $\eta_3 = \rho_1 - \omega$ the extracting firm's discount rate relative to growth. Similar economic role for the firm's shadow λ.
- $\eta_4 = \rho_1 + \rho_2 - \omega$: a composite direction that mixes the two discount rates. If the sum of discount rates exceeds the natural growth, this direction is destabilizing.

3. The extracting firm as follower

We consider the problem of the follower, i.e. the extracting firm, which takes the decision of the leader as given.

3.1. Open loop strategy

The extracting firm, has to maximize the following functional

$$J_1 = \int_0^{\infty} e^{-\rho_1 t} [h(U,Q) - C(U) - D(E) - \Psi(Q)]dt$$

Assuming linearity for the cost functions, i.e. $C(U) = CU$, $D(E) = DE$, $\Psi(Q) = AQ$ the functional becomes:

$$\max_{U>0} \int_0^{\infty} e^{-\rho_1 t} [U^{\pi} Q^{\varepsilon} - CU - DE - AQ]dt \quad (1)$$

subject to:
$$\frac{dE}{dt} = \dot{E} = \omega E - U^{\pi} Q^{\varepsilon} \quad (2)$$

the Hamiltonian is:

$$H_1 = U^{\pi} Q^{\varepsilon} - CU - DE - AQ + \lambda(\omega E - U^{\pi} Q^{\varepsilon})$$

The first order condition (FOC) for an interior maximum is

$$\frac{\partial H_1}{\partial U} = (1-\lambda)\pi U^{\pi-1} Q^{\varepsilon} - C = 0 \Rightarrow U^*(Q) = \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{1}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}}$$

(Regularity requires $(1-\lambda) > 0$ so the RHS of the FOC has positive value)

The adjoint variable has to follow the differential equation

$$\dot{\lambda} = \rho_1 \lambda - \frac{\partial H_1}{\partial E} = \lambda(\rho_1 - \omega) + D$$

With the optimal control of the follower the depletion function $h(U,Q)$becomes:

$$h(U^*(Q), Q) = \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}} \qquad (3)$$

Social planner as leader
The social planner has to solve the following problem

$$max_Q \int_0^{\infty} e^{-\rho_2 t} [W_1(E) + W_2(Q)]dt \qquad (4)$$

Subject to

$$\dot{E} = \omega E - \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}}$$
$$\dot{\lambda} = \lambda(\rho_1 - \omega) + D$$

and the Hamiltonian is

$$H_2 = W_1 E + W_2 Q + \mu\left(\omega E - \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}}\right) + \xi(\lambda(\rho_1 - \omega) + D)$$

With first order condition

$$\frac{\partial H_2}{\partial Q} = W_2 - \mu\left(\frac{\varepsilon}{1-\pi}\left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}-1}\right) = 0 \Rightarrow$$

$$Q^* = \left[\frac{1}{\mu}\frac{W_2}{\frac{\varepsilon}{1-\pi}\left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi-1}}}\right]^{\frac{\pi+\varepsilon-1}{1-\pi}} = \left[\frac{(1-\pi)W_2}{\mu\varepsilon}\right]^{\frac{1-\pi}{\pi+\varepsilon-1}} \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi+\varepsilon-1}{\pi}} \qquad (5)$$

The costate variables μ and ξ have to follow the differential equations

$$\dot{\mu} = \rho_2\mu - \frac{\partial H_2}{\partial E} \Rightarrow \dot{\mu} = \rho_2\mu - \mu\omega - W_1 = \mu(\rho_2 - \omega) - W_1$$
$$\dot{\xi} = \rho_2\xi - \frac{\partial H_2}{\partial \lambda} \Rightarrow \dot{\xi} = \xi(\rho_2 - \rho_1 + \omega) + \mu\frac{\pi}{\pi-1}\frac{H(Q,\lambda)}{1-\lambda}$$

Where:

$$H(Q,\lambda) = \left(\frac{C}{(\pi(1-\lambda))}\right)^{\frac{\pi}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}} \qquad (6)$$

The next proposition records the optimal open loop strategies of both players.

Proposition 3.

In the Stackelberg game with the social planner as leader and the extracting firm as follower the optimal open loop strategies are given by:

For the extracting firm (the follower of the game) the optimal open loop policy is

$$U^*(Q) = \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{1}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}}$$

and for the social planner the optimal open loop policy is

$$Q^* = \left[\frac{(1-\pi)W_2}{\mu\varepsilon}\right]^{\frac{1-\pi}{\pi+\varepsilon-1}} \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi+\varepsilon-1}}$$

which leads to the depletion and the steady state value of the environmental quality (state variable)

$$h(U,Q) = \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi+\varepsilon-1}} \left(\frac{W_2(1-\pi)}{\varepsilon\mu}\right)^{\frac{\varepsilon}{\pi+\varepsilon-1}}$$

$$E_\infty = \frac{1}{\omega}\left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi+\varepsilon-1}} \left(\frac{W_2(1-\pi)}{\varepsilon\mu}\right)^{\frac{\varepsilon}{\pi+\varepsilon-1}}$$

Proof

The optimal strategy for the social planner follows from the maximization of his Hamiltonian

$$\frac{\partial H_2}{\partial Q} = W_2 - \mu\left(\frac{\varepsilon}{1-\pi}\left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}-1}\right) = 0 \Rightarrow Q^{\frac{\pi+\varepsilon-1}{1-\pi}}$$

$$= \frac{W_2}{\mu}.\frac{1-\pi}{\varepsilon}\left(\frac{C}{(1-\lambda)\pi}\right)^{-\frac{\pi}{\pi-1}}$$

Raise both sides to the power $\frac{1-\pi}{\pi+\varepsilon-1}$, we have:

$$Q^* = \left(\frac{W_2}{\mu}\frac{1-\pi}{\varepsilon}\right)^{\frac{1-\pi}{\pi+\varepsilon-1}} \left(\frac{C}{(1-\lambda)\pi}\right)^{-\frac{\pi}{\pi-1}\cdot\frac{1-\pi}{\pi+\varepsilon-1}} \Rightarrow$$

$$Q^* = \left(\frac{W_2(1-\pi)}{\mu\varepsilon}\right)^{\frac{1-\pi}{\pi+\varepsilon-1}} \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi+\varepsilon-1}}$$

And the optimal strategy for the firm implied from his Hamiltonian, i.e.,

$$\frac{\partial H_1}{\partial U} = (1-\lambda)\pi U^{\pi-1}Q^{\varepsilon} - C = 0 \Rightarrow U^*(Q) = \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{1}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}}$$

Using (6) the depletion function becomes (after substitution Q^* in (6)):

$$h(U^*(Q), Q) = H(Q, \lambda)$$

Because $$H(Q,\lambda) = \left(\frac{C}{(\pi(1-\lambda))}\right)^{\frac{\pi}{\pi-1}} Q^{\frac{\varepsilon}{1-\pi}}$$

Plugging Q^*yields the expression $h(U^*, Q^*) = \left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi+\varepsilon-1}} \left(\frac{W_2(1-\pi)}{\varepsilon\mu}\right)^{\frac{\varepsilon}{\pi+\varepsilon-1}}$

At steady state $\dot{E} = 0$, and $\omega E_\infty = h(U^*, Q^*)$ which implies

$$E_\infty = \frac{1}{\omega}\left(\frac{C}{(1-\lambda)\pi}\right)^{\frac{\pi}{\pi+\varepsilon-1}} \left(\frac{W_2(1-\pi)}{\varepsilon\mu}\right)^{\frac{\varepsilon}{\pi+\varepsilon-1}} \text{q.e.d.}$$

Economic implications of Proposition 3

The firm's effort depends positively on the allowance Q set by the social planner, but the elasticity is governed by the extraction technology parameters (π, ε). Moreover, higher extraction costs reduce the firm's effort. Concerning the shadow price λ, when the environment becomes more valuable (higher λ) effort decreases because the effective cost of extraction is higher. Therefore, the firm's effort is not chosen freely—it reacts passively to the social planner's policy. This illustrates the Stackelberg hierarchy: the planner can indirectly discipline the firm's extraction activity via the allowance of Q.

On the other side the social planner increases extraction allowance when the marginal benefit from extraction W_2 is high. Moreover, the planner's strategy is highly dependent on the environment's shadow price μ, i.e., as the environment becomes more valuable, the planner sets a lower quota Q^*. Concerning the dependence on costs C, from the planner's analytical expression of the strategy it is implied thathigher extraction costs actually increase the allowance Q^*, because firms will in turn exert less effort U^*, so the planner can afford to allow a larger quantity Q. As a result, the planner balances two competing goals: (a) encouraging extraction to generate output/welfare (W_2) (b) preserving the environment (λ, μ). This mirrors the trade-off between short-run resource rents and long-run sustainability.

Inspecting depletion function and the steady state of environmental quality, E_∞, a few key drivers arise:

(a) Discounting: a higher planner discount rate ρ_2 typically lowers μreducing the weight on the future environment and allowing higher extraction—leading to lower steady state environmental quality E_∞
(b) Cost of extraction C: higher costs reduce firms' extraction effort, so the environment stabilizes at a higher E_∞

(c) Technology parameters (π, ε): determine how sensitive depletion is to effort U and allowance Q. If $\pi + \varepsilon > 1$ depletion reacts strongly to extraction intensity, making sustainability harder.
(d) Environmental regenerationω: faster regeneration allows higher steady state environmental quality E_∞.

An important implication can be drawn as: the system settles at an environmental level E_∞ determined jointly by planner's quotas and firm's responses. This level embodies the trade-off between current welfare from extraction and preservation of the environment.

Broader Economic Insights

(a) Leader–follower structure: If the firm acted alone, it would over-extract since it ignores the environmental shadow costs. With the planner leading, extraction is disciplined, improving long-run environmental outcomes.
(b) Planner's policy lever: The planner doesn't control effort directly (firm does), but by restricting Q it indirectly shapes effort and depletion. This is analogous to a regulator setting extraction quotas or emission permits.
(c) Comparative statics: Stronger valuation of the environment (W_1 or μ) implies lower extraction quota, higher steady-state environment. Conversely, higher benefit from extraction W_2 implies higher quota, lower environmental quality and finally, higher extraction cost C results in lower effort therefore, higher steady-state environment.

Proposition 4

With the current dynamics, the steady state value of the environmental quality E_∞, is not asymptotically stable, under the acceptable assumption of positive natural growth rate, $\omega > 0$.

Proof

We linearize the system of (E, λ, μ)

$$\dot{E} = \omega E - H(Q^*(\mu, \lambda), \lambda) = \omega E - K(\mu, \lambda)$$
$$\dot{\lambda} = \lambda(\rho_1 - \omega) + D$$
$$\dot{\mu} = \mu(\rho_2 - \omega) - W_1$$

At the steady state(E^*, λ^*, μ^*) we have

$$\omega E^* = K(\mu, \lambda)$$
$$\lambda^* = \frac{-D}{\rho_1 - \omega} \qquad if\, \rho_1 \neq \omega$$
$$\mu^* = \frac{W_1}{\rho_2 - \omega} \text{if} \rho_2 \neq \omega$$

Linearize around (E^*, λ^*, μ^*). Writing deviations $e = E - E^*, \hat{\lambda} = \lambda - \lambda^*, \hat{\mu} = \mu - \mu^*$, the Jacobian is upper triangular:

$$J = \begin{pmatrix} \omega & -K_\lambda & -K_\mu \\ 0 & \rho_1 - \omega & 0 \\ 0 & 0 & \rho_2 - \omega \end{pmatrix}_{(E^*, \lambda^*, \mu^*)}$$

So, the eigenvalues are $\omega,\ \rho_1 - \omega,\ \rho_2 - \omega$

Local asymptotic stability requires all the eigenvalues are negative, this atypical because $\omega > 0$. The E-block alone gives eigenvalue $\omega > 0$. Holding (λ, μ) fixed at their steady state value, deviations evolve as $\dot{e} = \omega e \Rightarrow e(t) = e(0)e^{\omega t}$. Therefore, E_∞ is locally unstable.

The λ-block is stable if and only if $\rho_1 < \omega$ otherwise is unstable
The μ-block is stable if and only if $\rho_2 < \omega$ otherwise is unstable

With $\omega > 0$ we have at least one positive eigenvalue, the steady state is not asymptotically stable; at best the overall system is saddle – path stable (one or more unstable directions, with the optimal path selected by boundary conditions).

Remarks on instability of environmental quality

I. What means the instability of E_∞,

We saw that with the state dynamics $\dot{E} = \omega E - h(U, Q)$ and with the follower's and leader's policies substituted, the Jacobian eigenvalue in the E - direction is $\omega > 0$. That means:

(a) If environmental quality (E) is slightly above its steady state value E_∞, it will keep growing away from the steady state
(b) If E is slightly below E_∞, it will keep falling away from the steady state

So, the steady state value E_∞ is not a "self–correcting" equilibrium, i.e., it doesn't pull the system back to balance.

II. Economic interpretation

(a) Fragile environmental balance. That means the economy/environment system cannot maintain a stable quality level. Any disturbance (policy shock, intensive exploitation, random fluctuation) drives the environment away from the steady state, leading either to:
   i) Excessive regeneration $(E \to \infty)$: an unrealistic prediction, but it reflects that the model assumes linear unlimited regeneration ωE which makes high E
   ii) Collapse $(E \to 0)$: if depletion dominates, the environment deteriorates irreversibly

(b) Policy ineffectiveness of the social planner
   The social planner chooses quota Q^*optimally, but because the environmental quality$E$ is unstable, the chosen $Q^*$is not enough to recover the system. This could be meant:
   i) Even optimal regulation cannot guarantee environmental sustainability under the given dynamics

ii) The social planner can only hope to enforce a path through transversality conditions (saddle path stability), but it requires perfect foresight and no shocks.

III. Dependence on initial conditions

Because the equilibrium is not attracting, the long–run outcome depends critically on the initial state.

(i) If the initial state $E(0)$ is not exactly on the equilibrium path, the system diverges.

(ii) Economically, this means that small policy mistakes or unexpected shocks can lead to very different environmental and welfare outcomes.

3.2. The Feedback solution

Since we derive the open loop policies which results an unstable steady state for the environmental quality, hence not economically desirable, let's employ the feedback policies in the case at which the social planner is the leader and the extracting firm is the follower of the game.

The follower's maximization problem.

Let $V(E)$ be the follower's value function (depends on state E and on the leader's control variable Q). The stationary Hamilton Jacobi Bellman (HJB) is:

$$\rho_1 V(E) = \max_{U\geq 0}\{U^{\pi}Q^{\varepsilon} - CU - DE - AQ + V'(E)(\omega E - U^{\pi}Q^{\varepsilon})\} \quad (7)$$

So FOC is: $\pi U^{\pi-1}Q^{\varepsilon} - C - \pi V'(E)U^{\pi-1}Q^{\varepsilon} = 0 \Rightarrow (1 - V'(E))\pi U^{\pi-1}Q^{\varepsilon} = C$

If $\left(1 - V'(E)\right) > 0$ (interior), this gives the feedback law, which is recorded in the next proposition.

Proposition 5

The feedback law of the extracting firm, acting as a follower in the Stackelberg game and the social planner as leader is given by:

$$U(E;Q) = \left[\frac{C}{(1 - V'(E))\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}}$$

Proof

Solving the FOC:

$$(1 - V'(E))\pi U^{\pi-1}Q^{\varepsilon} = C \Rightarrow$$

$$U(E;Q) = \left[\frac{C}{\left(1 - V'(E)\right)\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}}$$

4. The Value function of the follower

Since the value functions plays the crucial role for the environmental stability of the Stackelberg game it is reasonable to try with specific forms of that function. We begin with the simplest linear form.

4.1.Linear Value Function of the follower

We provide the next Lemma 1 that establish the linearity of the followers' value function.

Lemma 1

Consider the infinite – horizon problem of the follower$(1)-(2)$, i.e. the problem:

$$\max_{U>0} \int_0^{\infty} e^{-\rho_1 t}\,[U^{\pi}Q^{\varepsilon} - CU - DE - AQ]dt$$

subject to: $$\frac{dE}{dt} = \dot{E} = \omega E - U^{\pi}Q^{\varepsilon}, \qquad E(0) = E$$

Assume the parameters are such that $\rho_1 \neq \omega$ and the interior maximizer $U > 0$ exists for every relevant E. Then the value function $V(E)$ is affine in E, i.e.

$$V(E) = \alpha + \beta E$$

For constants $\alpha,\ \beta$ given by

$$\beta = -\frac{D}{\rho_1 - \omega}, \qquad a = \frac{(1-\beta)Q^{\varepsilon}(U^*)^{\pi} - CU^* - AQ}{\rho_1}$$

Where $U^* > 0$ is the stationary feedback control solving the first-order condition:

$$\pi Q^{\varepsilon}(1-\beta)(U^*)^{\pi-1} = C,$$

Equivalently

$$U^* = \left(\frac{C}{\pi Q^{\varepsilon}(1-\beta)}\right)^{\frac{1}{\pi-1}}$$

Proof
In the Appendix

Remarks on Lemma 1.

- The derivation requires $\rho_1 \neq \omega$. For economic stability it is common to assume $\rho_1 > \omega$

- An interior solution requires $1-\beta>0$, so the critical $U^{*}$is well – defined and positive. Using $\beta=-\frac{D}{\rho_1-\omega}$ this condition is $\rho_1-\omega+D>0$.
- If the interior condition fails, a boundary control (e.g. $U\to 0$, or a corner solution) must be analyzed separately.

Next, we set the linear value function

$$V(E)=\alpha+\beta E \tag{8}$$

and the feedback control becomes constant in E, i.e.,

$$U(E;Q)=\left[\frac{C}{(1-\beta)\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}} \tag{9}$$

Substituting (8) in (7) the left side of (7) becomes: $\rho_1(\alpha+\beta E)$
and the right side: $U^{\pi}Q^{\varepsilon}-CU-DE-AQ+\beta(\omega E-U^{\pi}Q^{\varepsilon})$

Collect coefficients on E:

$$\rho_1\beta=-D+\beta\omega\Rightarrow\beta=-\frac{D}{\rho_1-\omega},\quad \rho_1\neq\omega$$

Constant (terms independent of E):

$$\rho_1\alpha=(1-\beta)U^{\pi}Q^{\varepsilon}-CU-AQ\Rightarrow\alpha=\frac{(1-\beta)U^{\pi}Q^{\varepsilon}-CU-AQ}{\rho_1}$$

Therefore, we get a self-consistent solution:

$$U^{*}(Q)=\left[\frac{C}{(1-\beta)\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}},\beta=\frac{D}{\rho_1-\omega}$$

The resulting policy is recorded as proposition 6.

Proposition 6

The feedback strategy of the extracting firm, acting as follower in a Stackelberg game at which the social planner leads, is given by

$$U^{*}(Q)=\left[\frac{C}{(1-\beta)\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}},\qquad \beta=\frac{D}{\rho_1-\omega} \tag{10}$$

The analytical expression of the followers' value function is as in the next proposition.

Proposition 7

In the case the value function of the extracting firm is linear the analytical expression is given by

$$V(E) = \alpha + \beta E \qquad (11)$$

Where: $= \frac{(1-\beta)(U^*)^{\pi}Q^{\varepsilon} - CU^* - AQ}{\rho_1}$, $\beta = \frac{D}{\rho_1 - \omega}$

Existence and parameter conditions

The requirement $\rho_1 \neq \omega$ is vital for the feedback solution of the game
The interior FOC requires $1 - \beta > 0$, i.e.,

$$1 - \frac{D}{\omega - \rho_1} > 0 \Rightarrow D < \omega - \rho_1$$

If the above condition fails, the interior is invalid and the optimal control is a corner solution.

Checking for Stability

Linearize $\dot{E} = f(E) = \omega E - h(E)$,where $h(E) = U(E;Q)^{\pi}Q^{\varepsilon}$

A steady state E^* satisfies $\omega E^* = h(E^*)$

We want to know whether small perturbations $e(t) = E(t) - E^*$ decay or grow.

Now linearize $\dot{E} = f(E)$ at E^*.The linearized dynamics are

$$\dot{e} = f'(E^*)e, \quad f'(E^*) = \omega - h'(E^*)$$

Therefore, the local stability eigenvalue is

$$\eta_{lin} = \omega - h'(E^*)$$

The stability criterion:

i) If $\eta_{lin} < 0$ then E^* is (locally) asymptotically stable
ii) If $\eta_{lin} > 0$ then E^* is unstable
iii) If $\eta_{lin} = 0$ the test is inconclusive (higher order terms matter)

So, the key object is $h'(E^*)$, the sensitivity of the extraction flow $U^{\pi}Q^{\varepsilon}$ to the environmental stock E. Since $h'(E^*) = \pi U^*(E^*)^{\pi-1}Q^{\varepsilon}U'(E^*)$, where $U'(E^*) = \frac{dU}{dE}$ at E=E^*. Thus, the sign of $\omega - h'(E^*)$ depends on both the intrinsic growth rate ω and on how the feedback strategy reacts to change in the stock of natural resources.

In the HJB solution we used $(E) = \alpha + \beta E$, so $V'(E) = \beta$ a constant, therefore the feedback law of Proposition 5, i.e., the strategy:

$$U(E) = \left[\frac{C}{(1 - V'(E))\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}}$$

And substituting the constant marginal value function the above strategy becomes:

$$U = \left[\frac{C}{(1 - \beta)\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}}$$

which is constant in E. Call that constant U^*. Hence $U'(E) = 0$, therefore $h'(E^*) = \pi U^*(E^*)^{\pi-1} Q^{\varepsilon} U'(E^*) = 0$ and the linearization eigenvalue becomes $\eta_{lin} = \omega - h'(E^*) = \omega$, which results at the same instability (as in the open loop case) since the intrinsic growth rate of environment ω has positive values. The above reasoning boils down into the next proposition.
Proposition 8.

The Stackelberg model with a linear value function of the follower, results in an unstable steady state, even in the feedback solution.

Intuition about the sign of $h'(E^*)$ and stability

Stability needs the eigenvalue $\eta_{lin} < 0$ and therefore $h'(E^*) > \omega$. So, the feedback must make the extraction flow *sufficiently sensitive and positively sloped* with respect to the natural resources stock, i.e., $h' > 0$ and large. Concerning the sign direction: because $h'(E^*) = \pi U^{\pi-1} Q^{\varepsilon} U'$, a positive $U'(E^*)$(extraction *increasing* with the stock) gives $h' > 0$ and can potentially stabilize, a negative $U'(E^*)$ gives $h' < 0$, and therefore results in a more unstable environment. So, counter-intuitively, a feedback that *reduces* extraction when the stock falls $U' < 0$ does not help local linear stability - it makes the linear eigenvalue more positive. The reason is structural: the growth term ωE is proportional to E and if extraction reacts negatively to E it reduces the damping effect in the linearization. Concluding, if $U' > 0$ and large enough so that $h'(E^*) > \omega$, the steady state becomes locally asymptotically stable.

4.2.Quadratic Value Function of the follower

The next Lemma 2 obtains the condition under which the quadratic value function is a solver of the HJB equation, i.e. the condition: if and only if $\pi = \frac{1}{2}$.

Lemma 2

Consider the infinite – horizon problem of the follower$(1) - (2)$, i.e. the problem:

$$\max_{U>0} \int_0^{\infty} e^{-\rho_1 t} [U^{\pi} Q^{\varepsilon} - CU - DE - AQ] dt$$

subject to: $\frac{dE}{dt} = \dot{E} = \omega E - U^{\pi} Q^{\varepsilon}, \qquad E(0) = E$

and assume an interior optimal control exists for relevant states. Let the value function $V(E)$ is a quadratic polynomial in E

$$V(E) = \alpha + \beta E + \gamma E^2, \qquad \gamma \neq 0$$

Then this ansatz is compatible with the Hamilton–Jacobi–Bellman (HJB) equation if and only if $\pi = \frac{1}{2}$.

Proof
In the Appendix

Now we recall the linear value function, we set the model parameter $\pi = \frac{1}{2}$, and according to Lemma 2 a quadratic value function for the extracting firm $V(E) = \alpha + \beta E + \gamma E^2, \gamma>0$, it is a solver for the followers' maximization problem. This function is convex ($V''(E) = 2\gamma > 0$). A value function would be convex since some ecosystem services are worth disproportionately more when the stock is high (biodiversity, carbon sinks, resilience). That convexity means the marginal value of extra stock is higher at high stock levels. A convex value function can stand in for policy goals that reward high environmental stock levels (e.g. sustainability thresholds, environmental protection targets).
The next Lemma 3 gives the exact expression of the local linearization eigenvalue for the environmental state at a steady state E^* for $\pi = \frac{1}{2}$ and a quadratic follower value function.

Remark on Lemma 2

Substituting $\pi = \frac{1}{2}$ and the quadratic value function $V(E) = \alpha + \beta E + \gamma E^2,\ \gamma>0$ into the follower's feedback rule of Proposition 5, the resulting follower's strategy becomes:

$$U(E;Q) = \left[\frac{2C}{(1 - V'(E))Q^{\varepsilon}}\right]^{-2} = \left[\frac{2C}{(1 - \beta - 2\gamma E)Q^{\varepsilon}}\right]^{-2} \Rightarrow U(E;Q) = \left[\frac{(1 - \beta - 2\gamma E)Q^{\varepsilon}}{2C}\right]^{2}$$

the associated harvesting (depletion) flow under the follower's feedback is:

$$h(U,Q) = U^{\frac{1}{2}}Q^{\varepsilon} = \frac{1 - \beta - 2\gamma E}{2C}Q^{2\varepsilon}$$

The next Lemma 3 gives the local linearization eigenvalue for the environmental state at the steady state E^*.

Lemma 3

Let the quadratic value function of the follower $V(E) = \alpha + \beta E + \gamma E^2, \gamma>0$, and consider the feedback structure of the model with $\pi = \frac{1}{2}$ and the state dynamics: $\frac{dE}{dt} = \dot{E} = \omega E - h(U,Q),\ E(0) = E$, with $h(U,Q) = U^{\frac{1}{2}}Q^{\varepsilon}$. Then, the local linearization eigenvalue for the environmental state at the steady state E^* is given by:

$$\eta_{lin}(E^*) = \omega \frac{1-\beta}{1-\beta-2\gamma E^*}$$

Proof
In the Appendix

Moreover, with the quadratic value function of Lemma 2, we have the following stability result.

Proposition 9

Let the quadratic value function of the follower $V(E) = \alpha + \beta E + \gamma E^2, \gamma > 0$, and let the follower use the feedback policy implied by the HJB equation. Suppose (E^*, Q^*) is a stationary equilibrium satisfying the steady state condition

$$\omega E^* = h(E^*, Q^*)$$

Then the equilibrium is locally asymptotically stable if and only if:

$$\omega \frac{1-\beta}{1-\beta-2\gamma E^*} < 0$$

Or equivalently:

- If $\beta < 1$ stability requires $E^* > \frac{1-\beta}{2\gamma}$
- If $\beta > 1$ stability requires $E^* < \frac{1-\beta}{2\gamma}$
- If $\beta = 1$ the linearization degenerates

Proof

Using Lemma 3 the linearized eigenvalue is

$$\eta_{lin}(E^*) = \omega \frac{1-\beta}{1-\beta-2\gamma E^*}$$

Local asymptotic stability requires

$$\eta_{lin}(E^*) = \omega \frac{1-\beta}{1-\beta-2\gamma E^*} < 0$$

The condition reduces to a sign test on the ratio $\frac{1-\beta}{1-\beta-2\gamma E^*}$, that means:

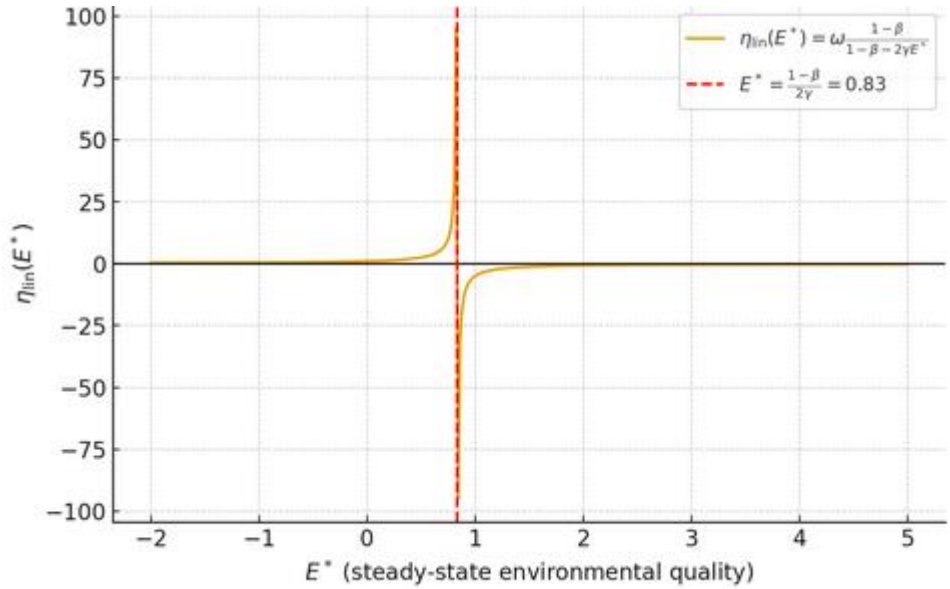
- If $\beta < 1$ the numerator $1-\beta$ is positive, then the denominator must be negative, hence $1-\beta-2\gamma E^* < 0$, and therefore $E^* > \frac{1-\beta}{2\gamma}$

- If $\beta > 1$ the numerator $1-\beta$ is negative, then the denominator must be positive, hence $1-\beta-2\gamma E^* > 0$, and therefore $E^* < \frac{1-\beta}{2\gamma}$, but this is a rejected case.

Remarks on Proposition 9

To ensure the local stability in the case $\beta < 1$, it is required the steady state stock E^* lie above the threshold $\frac{1-\beta}{2\gamma}$, because the larger stock raises the marginal value enough that the followers' response dampens deviations. In the opposite case $\beta < 1$ stability requires the steady state stock E^* lie below the (negative) threshold $\frac{1-\beta}{2\gamma} < 0$, therefore is an economically unacceptable case.

Figure 1. Local stability condition



Here's a plot of the local stability eigenvalue

$$\eta_{lin}(E^*) = \omega \frac{1-\beta}{1-\beta-2\gamma E^*}$$

For the parameter values: $\omega = 1, \beta = 0.5, \gamma = 0.3$

- The dashed red line marks the threshold $E^* = \frac{1-\beta}{2\gamma}$
- The stabilizing region is where $\eta_{lin}(E^*) < 0$, i.e. to the right of the red line when $\beta < 1$

Thus, for $E^* > \frac{1-\beta}{2\gamma}$, deviations from equilibrium decay over time, and the system is locally stable.

Returning back to the original stability condition, i.e. $\eta_{lin} = \omega - h'(E^*) < 0$, it is worth noting that in the special case of non–renewable resources the growth rate ω collapses to zero, and therefore the linearization eigenvalue equals to the negative marginal extraction $h'(E)(\eta_{lin} = -h'(E^*))$, a case at which a further analysis required, that is left for future research.

Stability of the general feedback case (U depends on E)

If the extracting firm's effort, U, is not constant in environmental stock E (i.e., if $V''(E) \neq 0$, (so the HJB yields a non-constant feedback), then $U'(E)^* \neq 0$ in general and $h'(E^*) \neq 0$. We distinguish two cases:

(a) If the feedback is counter–cyclical in the stock ($U'(E^*) < 0$, which means that higher stock implies lower intensity of extraction), then $h'(E^*) < 0$ and $\omega - h'(E^*) > \omega$, making the steady state more likely

(b) If the feedback is pro–cyclical in the stock ($U'(E^*) > 0$, i.e., higher stock implies more intensity of extraction, then the steady state is unstable even if $\omega < 0$ because $\omega - h'(E^*)$ could become positive

So, for the general feedback case, the stability condition is:

$$\omega < h'(E^*) \text{ stable}$$
$$\omega > h'(E^*) \text{ unstable}$$

5. The leader's problem

The transition to the leader's (social planner's) feedback problem has the following steps:
Given the follower's feedback law $U(E;Q)$, the leader maximizes:

$$J_2 = \int_0^{\infty} e^{-\rho_2 t}\,[W_1 E + W_2 Q]dt$$

subject to the state dynamics $\dot{E} = \omega E - h(U(E;Q),Q)$

where:

$$h(U(E;Q),Q) = U(E;Q)^{\pi} Q^{\varepsilon}$$

and knowing that the follower's optimal strategy $U(E;Q)$ depends implicitly on the state E and the leader's control through the follower's evaluation of environmental quality $V'(E)$.
The leader's HJB equation becomes:

$$\rho_2 W(E) = \max_{Q \geq 0}\{W_1 E + W_2 Q + W'(E)\big(\omega E - h(U(E;Q),Q)\big)\}$$

Where $W(E)$ is the social planner's value function, and the FOC is:

$$W_2 - W'(E)\frac{\partial h(U(E;Q),Q)}{\partial Q} = 0$$

With the expansion of the partial derivative term as:

$$\frac{\partial h(U(E;Q),Q)}{\partial Q} = \frac{\partial}{\partial Q}[U(E;Q)^{\pi}Q^{\varepsilon}] = \pi U(E;Q)^{\pi-1}Q^{\varepsilon}\frac{\partial U(E;Q)}{\partial Q} + \varepsilon U(E;Q)^{\pi}Q^{\varepsilon-1}$$

And since $U(E;Q)$ depends on Q, this makes the reaction function nonlinear but fully derivable.

We continue to work with the leader's optimal feedback allowed quantity $Q^*(E)$ under the certain conditions as in the previous case examined, i.e.

- $\pi = \frac{1}{2}$, follower value function $V(E) = \alpha + \beta E + \gamma E^2, \gamma > 0$
- Follower feedback used to obtain the depletion function $(A.13)$ of the Appendix, i.e. the function $h(E,Q) = \frac{(1-\beta-2\gamma)Q^{2\varepsilon}}{2C}$
- Leader's stationary HJB with value $W(E)$ with derivative W_E

The social planner (leader of the game) chooses a state–contingent quantity $Q(.)$ to maximize discounted welfare, taking the follower's feedback $U(E;Q)$ as anticipating how the firm reacts at each state E

The primal problem of the leader:

$$W(E) = \sup_{Q(.)} \int_0^{\infty} e^{-\rho_2 t}[W_1 E(t) + W_2 Q(t)]dt \qquad (12)$$

subject to the state equation

$$\dot{E}(t) = \omega E(t) - h\Big(U\big(E(t);Q(t)\big),Q(t)\Big), \quad E(0) = E \qquad (13)$$

where the follower's feedback $U(E;Q)$ is given by the solution of the follower's HJB (taken as known by the leader). The depletion flow is $h(U,Q) = U^{\pi}Q^{\varepsilon}$.

The admissible controls are feedback maps $Q: E \to Q(E)$ that keep the dynamics and the follower'sFOC feasible and satisfy transversality conditions ensuring the objective is well–defined.

In the general case at which the parameter π is not restricted to take the certain value $\pi = \frac{1}{2}$, let $W(E)$ be the leader's value function, the stationary HJB equation reads:

$$\rho_2 W(E) = \max_{Q \geq 0}\{W_1 E + W_2 Q + W'(E)(\omega E - h(U(E;Q),Q))\} \quad (14)$$

Remarks on the leader's HJB

- The maximization is pointwise in the state E (the leader chooses Q at each E to maximize the HJB integrand).
- The function $U(E;Q)$ is the follower's feedback, and substitute in the depletion function h we obtain the maximum purely in terms of E, Q and primitives
- The transversality condition is: $\lim_{t\to\infty} e^{-\rho t} W(E(t)) = 0$

The following Lemma 4 provides the conditions guaranteeing that the leader's value function is quadratic.

Lemma 4

Consider the feedback Stackelberg game with:

- $\pi = \frac{1}{2}$
- Follower value function $V(E) = \alpha + \beta E + \gamma E^2$, given β and givenγ>0
- Depletion under the follower feedback (equation $(A.13)$ in the Appendix)
- $$h(E,Q) = \frac{(1-\beta-2\gamma E)Q^{2\varepsilon}}{2C}$$
- Leader instantaneous payoff $W_1 E + W_2 Q$, discount factor $\rho_2 > 0$ and state dynamics $\dot{E} = \omega E - h(U,E)$.

Assume an interior feedback equilibrium exists and $2\varepsilon - 1 > 0$. Suppose the leader's marginal value function has the proportionality form

$$W_E(E) = M(1-\beta-2\gamma E) \quad (15)$$

For some constant $M \neq 0$ on the admissible domain of E. Then:

1. The leader's value function is quadratic, specifically:
   $W(E) = a + bE + cE^2$ with $b = M(1-\beta),\ c = -M\gamma$
   for some constant a

2. The interior optimal feedback quota is given in closed form by
   $$Q^*(E) = \left(\frac{W_2 C}{\varepsilon M}\right)^{1/(2\varepsilon-1)} (1-\beta-2\gamma E)^{-1/(2\varepsilon-1)} \quad (16)$$

3. Substituting W, Q^* and h into the stationary HJB yields a linear equation for a. Therefore, there exists a (unique) constant a that makes the HJB hold identically in E provided the

given below algebraic consistency condition 4 is satisfied. Under that consistency condition the leader's stationary value is exactly the quadratic $W(E)$ above.

4. The interior solution is feasible if the sign condition for $Q^*(E) > 0$ holds

$$M(1 - B - 2\gamma E) > 0 \text{ for admissible } E$$

and the second order condition for a maximum in Q is satisfied.

Proof
In the Appendix

Intuition for the leader's *feedback strategy* $Q^*(E)$

The leader's feedback strategy $Q^*(E)$ tells how the social planner (leader of the game) adjusts the extraction quota Q in real time as the environmental stock$E$ changes.

Its formula (16) is a state-dependent control: extraction levels are adjusted depending on how degraded or healthy the environment currently is.

The term$1 - \beta - 2\gamma E$ reflects the *marginal valuation of the resource by the extracting firm (the follower).* When environmental quality E is high the term decreases, and when E is low (degraded environment), it increases.

The exponent: $-1/(2\varepsilon - 1)$ (which has a negative value, since $2\varepsilon - 1 > 0$) makes the quantity $Q^*(E)$ decrease as E increases, i.e. the social planner (the leader) enforces *tighter extraction* when the environment is better.

The economic meaning is that the leader *restrains extraction when the stock is healthy* to preserve long-term sustainability, while *loosening restrictions when the stock is low*, since the marginal productivity of extraction diminishes and the environment itself self-recovers more slowly.
$Q^*(E)$ depends on M, which measures the leader's marginal valuation of environmental quality, therefore:

- If M is large, the leader values the environment highly, making the denominator larger and thus $Q^*(E)$ smaller implies stricter regulation
- If M is small, the leader tolerates higher extraction.

Dynamically, because the leader's control is feedback–based, it adapts endogenously to environmental conditions. Thus, feedback control provides stabilization, i.e. the social planner corrects deviations of E
Away from steady state by tightening or loosening retraction quotas. Moreover, the equilibrium condition $E^* > \frac{1-\beta}{2\gamma}$ (the stabilizing region) shows that the leader's feedback rule helps keep the system in a region where environmental recovery outweighs extraction, preventing divergence or collapse.

Intuition for the leader's quadratic value function $W(E)$

The value function $W(E)$ measures the maximum discounted welfare the leader can achieve starting from a given environmental state E, specifically:

- The linear term bE reflects the direct benefit from environmental quality, i.e. a healthier environment increases welfare.
- The quadratic term cE^2 (with $c < 0$) represents diminishing marginal returns to environmental quality precisely: the leader benefits from a better environment but less do at higher levels) due to opportunity costs or resource use trade-offs).

A quadratic value function $W(E)$ naturally arises because:

- The state equation and extraction rule are linear–quadratic in E and Q.
- The leader faces a dynamic trade–off that is linear in environmental services E but quadratic in E through its effect on costs and extraction.

This mirrors the structure of Linear– Quadratic (LQ) dynamic control problems, where both the control and the value function are quadratic. In such problems:

- The value function's curvature encodes the sensitivity of optimal policy to deviations of E from steady state.
- A more concave value function $W(E)$ (larger $|c|$) implies the leader reacts more aggressively to environmental changes.

An economic interpretation of the curvature is:

- The slope $b = M(1-\beta)$ reflects how much marginal welfare rises with better environmental quality.
- The curvature $c = -M\gamma$, how strongly marginal welfare decreases as environmental quality E increases.

Therefore, a higher follower's sensitivity to environment, γ, makes the curvature c more negative, that means the leader's value becomes more concave, showing higher concern for avoiding environmental extremes like degradation or conservation costs.

Concluding, the leader's feedback strategy $Q^*(E)$ embodies a self–correcting environmental policy, i.e. tighter quotas when the ecosystem is strong, and looser when weak, derived from an underlying quadratic welfare function $W(E)$ that captures diminishing returns to environmental quality and ensures dynamic stability of the ecological–economic system.

5.1.Stability with quadratic value functions

The following Lemma 5 provides the conditions under which the environmental stability in ensured, with the assumptions of quadratic value functions for both players.

Lemma 5

Consider the closed–loop feedback Stackelberg game with state $E(t)$ evolving as

$$\dot{E} = \omega E - h(E, Q^*(E))$$

And assume $\pi = \frac{1}{2}$. Suppose the follower's value function is quadratic $V(E) = \alpha + \beta E + \gamma E^2$ with $\gamma > 0$ and the follower uses the feedback law

$$U^*(E; Q) = \left(\frac{(1 - \beta - 2\gamma E)Q^{\varepsilon}}{2C}\right)^2$$

So, the depletion flow is:

$$h(E, Q) = \frac{(1 - \beta - 2\gamma E)Q^{2\varepsilon}}{2C}$$

assume the leader's value function is quadratic $W(E) = a + bE + cE^2$ and the leader's optimal feedback quota takes the form

$$Q^*(E) = K(1 - \beta - 2\gamma E)^{-1/(2\varepsilon - 1)}, \qquad K := \left(\frac{W_2 C}{\varepsilon M}\right)^{1/(2\varepsilon - 1)}$$

With the parameter restriction $2\varepsilon - 1 > 0$, $1 - \beta - 2\gamma E > 0$ on the admissible domain.
Let E^* be an interior steady state with $Q^* = Q^*(E)$ satisfying

$$\omega E^* = h(E^*, Q^*) = \frac{(1 - \beta - 2\gamma E^*)(Q^*)^{2\varepsilon}}{2C}$$

Then the linearization of the scalar dynamics at E^* has the eigenvalue

$$\lambda = \omega - \frac{(Q^*)^{2\varepsilon}}{2C}\frac{2\gamma}{2\varepsilon - 1}$$

Equivalently, substituting the closed – form quota,

$$\lambda = \omega - \frac{K^{2\varepsilon}}{2C}(1 - \beta - 2\gamma E^*)^{-2\varepsilon/(2\varepsilon - 1)}\frac{2\gamma}{2\varepsilon - 1}$$

Using the steady – state identity $(Q^*)^{2\varepsilon} = \frac{2C\omega E^*}{1 - \beta - 2\gamma E^*}$, the eigenvalue can also be written purely in terms of E^* and primitives as:

$$\lambda = \omega - \left[1 - \frac{E^*}{1 - \beta - 2\gamma E^*}\frac{2\gamma}{2\varepsilon - 1}\right]$$

Consequently, the steady state E^* is locally asymptotically stable iff $\lambda < 0$, i.e. any of the equivalent stability conditions

$$\omega < \frac{(Q^*)^{2\varepsilon}}{2C}\frac{2\gamma}{2\varepsilon - 1} \text{ or } \qquad 2\gamma\frac{E^*}{1-\beta-2\gamma E^*} > 2\varepsilon - 1$$

holds.

Proof
In the Appendix

Economic interpretation of Lemma 5

The eigenvalue λ can be seen as the net "self-reinforcing" pressure on the environmental stock when it deviates from equilibrium. Stability ($\lambda < 0$) means any deviation triggers forces that push the system back to E^*.

- Term's ω economic intuition is: This term is the natural, biological momentum of the system. If E increases above E^*, a higher ω means it grows *even faster*, pulling the system further away. If E falls below E^*, a higher ω means its regenerative capacity is weaker at low levels (in proportional terms, ωE is smaller), making recovery slower and potentially leading to collapse. Thus, a higher ω makes the system more "brittle" or "explosive," acting as a destabilizing force.
- Term $\frac{(Q^*)^{2\varepsilon}}{2C}$, measures the equilibrium level of resource extraction/degradation ($h \propto Q^{2\varepsilon}$), moderated by its cost (C). A larger, more profitable extraction sector creates a stronger *potential* corrective force—if policy is responsive.
- γ: This is the most critical behavioral parameter. A high γ means the extracting firm's valuation $V(E)$ is highly sensitive to the environmental stock. In practice, this could reflect:
  - Long-term planning: The firm internalizes that over-exploitation today destroys future profits.
  - Regulatory risk anticipation: The firm expects stricter penalties if the stock gets too low.
  - Technological adaptation: The firm's costs or productivity are highly dependent on the resource base. A high γ makes the firm's effort U^* highly responsive to E. If E falls, the firm *sharply* reduces extraction, aiding recovery. If E rises, it increases extraction more cautiously. This pro-cyclical dampeningis the core stabilizing behavior.
- $1/2\varepsilon - 1$ term: since $2\varepsilon - 1 > 0$ all the term is positive. The elasticity ε measures how sensitive total harvest is to the quota Q. A higher ε gives the social planner a more powerful policy instrument—a small change in the quota Q leads to a large change in extraction. This amplifies the effectiveness of the planner's adaptive rule $Q^*(E)$.

Implications for Policy Design

Lemma 5 provides a design blueprint for sustainable regulation:

(a) Foster Foresight in Firms ($\uparrow \gamma$): Stability can be promoted by policies that increase γ—the firm's sensitivity to the resource stock. This can be achieved through:

(i) Secure property rights/long-term concessions: So, the firm values the future stock.
(ii) Transparent ecosystem monitoring:So, the firm can accurately assess E.
(iii) "Tripwire" mechanisms: Clear, pre-announced penalties that intensify as E approaches critical thresholds.

(b) Choose Powerful Policy Instruments (Manage ε): The regulator should prefer control variables to which the harvest is highly sensitive (high ε). For example, a quota on total catch (ε high) is a more potent stabilizer than a tax on fishing effort (U) if effort has a diminishing return (π low).

(c) Calibrate Policy to Ecology (ω): The required strength of the feedback loop depends directly on the ecosystem's growth rate ω. Managing a fast-growing, volatile resource requires a much more agile and forceful regulatory apparatus than managing a slow-growing one.

(d) The Threshold Insight: The alternative condition $2\gamma \frac{E^*}{1-\beta-2\gamma E^*} > 2\varepsilon - 1$ suggests that stability is easier to achieve when the steady-state stock E^* is sufficiently high relative to a benchmark. This points to a precautionary principle: aiming for a higher target stock level E^* inherently makes the system more resilient and easier to stabilize, as it provides a larger buffer and enhances the firm's incentive to conserve.

In conclusion, Lemma 5 is not just a mathematical result; it is the formalization of a crucial insight: Environmental sustainability under strategic interaction is not guaranteed by optimal policy alone. It requires a carefully calibrated system where the adaptive reflexes of the economic agents are strong enough to counteract the innate dynamics of the ecosystem. The feedback Stackelberg equilibrium, by making both regulator and firm responsive to the environment, creates the possibility for such a self-correcting system, and Lemma 5 defines the exact conditions for its success.
Below we provide a numeric example that illustrates the stability threshold and how it depends on the primitives.

A numeric example for Lemma 5

Recall the closed form eigenvalue of Lemma:

$$\lambda = \omega - \frac{(Q^*)^{2\varepsilon}}{2C}\frac{2\gamma}{2\varepsilon - 1}$$

Setting $\lambda = 0$ the critical curvature becomes:

$$\gamma_{crit} = \frac{\omega C(2\varepsilon - 1)}{(Q^*)^{2\varepsilon}}$$

We set specific values for the parameters:

$\omega = 0.5,\ \varepsilon = 1.2,\ C = 1.$

We evaluate three equilibrium candidates: $Q^* = 0.8, 1.0, 1.2$

Thus: $(Q^*)^{2\varepsilon} = Q^{2.4}$ and $\gamma_{crit} = \frac{0.5\times1\times1.4}{(Q^*)^{2\varepsilon}}$

(a) $Q^* = 0.8: 0.8^{2.4} \approx 0.585$ and $\gamma_{crit} \approx \frac{0.7}{0.585} \approx 1.2$

(b) $Q^* = 1.0: 1^{2.4} = 1$ and $\gamma_{crit} = \frac{0.7}{1} = 0.7$

(c) $Q^* = 1.2: 1.2^{2.4} \approx 1.548$ and $\gamma_{crit} \approx \frac{0.7}{1.548} \approx 0.45$

So, the higher equilibrium Q^* the lower the required γ for stability (due to the feedback multiplier $(Q^*)^{2\varepsilon}$)

Now we check sample eigenvalues for a common test curvature $\gamma = 0.5$

$$\lambda = 0.5 - \frac{0.5(Q^*)^{2\varepsilon}}{1.4}$$

Plugging numbers:

(a) $Q^* = 0.8: \lambda \approx 0.5 - \frac{0.585\times0.5}{1.4} \approx 0.291$ unstable

(b) $Q^* = 1.0: \lambda \approx 0.5 - \frac{1.0\times0.5}{1.4} \approx 0.143$ unstable

(c) $Q^* = 1.2: \lambda \approx 0.5 - \frac{1.548\times0.5}{1.4} \approx -0.053$ locally stable

Interpretation

- The formula γ_{crit} shows that larger intrinsic growth rate ω and larger $2\varepsilon - 1$ increase the required γ for stability (harder to stabilize), while larger equilibrium extraction Q^* reduces γ_{crit} because the stabilizing effect of a given γ is amplified by $(Q^*)^{2\varepsilon}$.

- In the numeric example: with modest curvature $\gamma = 0.5$ a small quota $Q^* = 0.8$or moderate quota $Q^* = 1.0$ yield positive λ (i.e. instability), while a larger quota $Q^* = 1.2$ flips the sign and stabilizes the system. This highlights the non–trivial interactions: increasing Q^* both raises extraction (which tends to destabilize in other respects) but also increases the multiplier on the stabilizing curvature term in this closed–loop model, so the net effect depends on parameter values.

Below in Figure 2 is depicted the critical follower curvature γ_{crit} required for stability

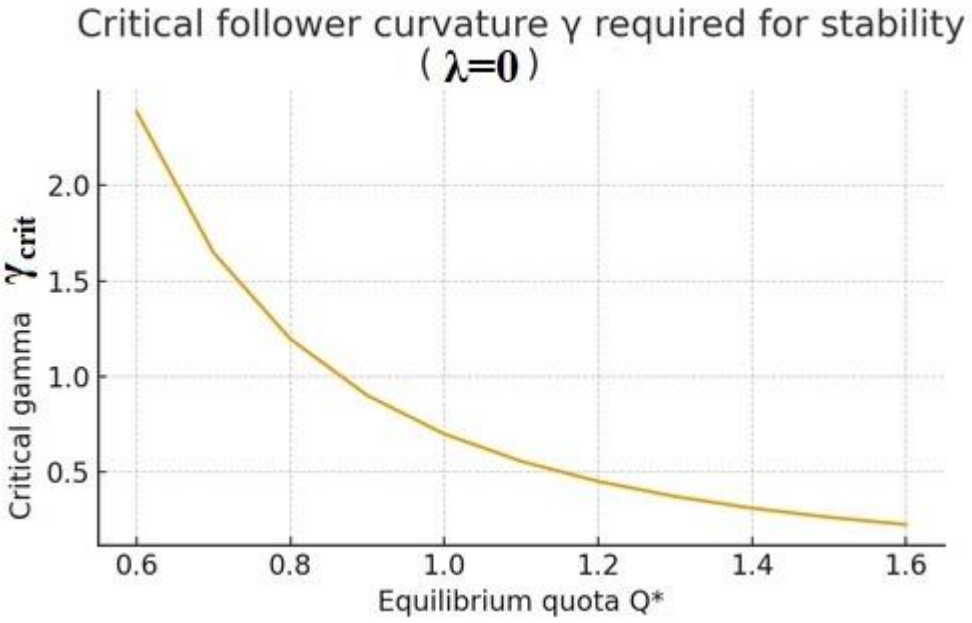


Figure 2: the equilibrium quota Q^* vs γ_{crit} for the specific values of example based on Lemma 5.The chart depicts the $\gamma_{crit} = \frac{\omega C(2\varepsilon-1)}{(Q^*)^{2\varepsilon}}$ as function of Q^*. Points above the curve indicate parameter combinations that yield stability ($\gamma > \gamma_{crit}$).

6. Environmental state–dependent taxes

In this section we introduce an E −depedent per unit extraction tax $\tau(E)$, therefore there be modifications on the follower feedback strategy, depletion function and the linearized eigenvalue. We keep the model consistent with the earlier setup, i.e. the elasticity $\pi = \frac{1}{2}$, the follower's value function remains quadratic $V(E) = \alpha + \beta E + \gamma E^2, \gamma > 0$, and harvesting $h(U,Q) = U^{\pi}Q^{\varepsilon}$.
After the tax cost introduction into the follower's payoff, the latter payoff becomes:

$$\big(1-\tau(E)\big)U^{\pi}Q^{\varepsilon} - CU - D(E) - \Psi(Q)$$

6.1. Follower feedback and harvesting under taxation

The next proposition 10 gives the follower's feedback equilibrium strategy and harvesting with taxes.

Proposition 10.

With the tax introduction, the follower's feedback policy$U(E;Q)$ and the depletion function $h(U,Q)$ are given by:

$$U(E;Q) = \left[\frac{(1-\tau(E)-\beta-2\gamma E)Q^{\varepsilon}}{2C}\right]^2$$

and

$$h(E,Q) = \frac{(1-\tau(E)-\beta-2\gamma E)Q^{2\varepsilon}}{2C}$$

respectively.

Proof
The HJB is modified as:

$$\rho_1 V(E) = \max_{U\geq 0}\{(1-\tau(E))U^{\pi}Q^{\varepsilon} - CU - DE - AQ + V'(E)(\omega E - U^{\pi}Q^{\varepsilon})\} \qquad (19)$$

and, the FOC is:

$$\pi U^{\pi-1}Q^{\varepsilon}(1-\tau(E)-V'(E)) = C$$

Setting $\pi = \frac{1}{2}$ and $V'(E) = \beta + 2\gamma E$, the follower's optimal strategy is:

$$U(E;Q) = \left[\frac{(1-\tau(E)-\beta-2\gamma E)Q^{\varepsilon}}{2C}\right]^2$$

Substituting the follower's feedback control into the harvesting function $h(E,Q) = \sqrt{U(E;Q)}Q^{\varepsilon}$ *the depletion becomes:*

$$h(E,Q) = \frac{(1-\tau(E)-\beta-2\gamma E)Q^{2\varepsilon}}{2C}$$

6.2.The stabilization condition

In order to check the environmental stability, consider the system at the steady state (E^*, Q^*), therefore:

$$\omega E^* = h(E^*,Q^*) = \frac{(1-\tau(E^*)-\beta-2\gamma E^*)Q^{*2\varepsilon}}{2C}$$

The next Lemma 6 gives the scalar eigenvalue of the system.

Lemma 6.
Consider the Stackelberg game under taxation, at which the environmental stock evolves according to:

$$\dot{E} = \omega E - h(Q(E),E)$$

Where:

$$h(E,Q) = \frac{(1-\tau(E)-\beta-2\gamma E)Q^{2\varepsilon}}{2C}$$

and $\varepsilon > \frac{1}{2}, C > 0, \gamma > 0, \beta$ are model parameters, $\tau(E)$ is a differentiable per–unit tax schedule, and the social planner uses a (differentiable) feedback quota $Q(t)$. Let (E^*, Q^*)be a stationary equilibrium satisfying

$$E^* = h(E^*, Q^*)$$

Then the linearization of the scalar state equation around E^* has the single eigenvalue

$$\eta = \omega - \frac{(Q^*)^{2\varepsilon}}{2C}\frac{\tau'(E^*) + 2\gamma}{2\varepsilon - 1} \qquad (22)$$

Proof
In Appendix

The next Proposition 11 gives the exact condition that ensures environmental stability.

Proposition 11.
Under the assumptions of Lemma 6 the environmental stability is ensured if the following condition:

$$\omega < \frac{(Q^*)^{2\varepsilon}}{2C}\frac{\tau'(E^*) + 2\gamma}{2\varepsilon - 1}$$

holds.

Proof

From Lemma 6 it suffices the eigenvalue η to be less than zero, therefore accordingly

$$\eta = \omega - \frac{(Q^*)^{2\varepsilon}}{2C}\frac{\tau'(E^*) + 2\gamma}{2\varepsilon - 1} < 0 \Rightarrow \omega < \frac{(Q^*)^{2\varepsilon}}{2C}\frac{\tau'(E^*) + 2\gamma}{2\varepsilon - 1}$$

Economic intuition of Lemma 6

The intuition on how the parameters of the model influence environmental stability, taking into account the eigenvalue expression $\eta = \omega - \frac{(Q^*)^{2\varepsilon}}{2C}\frac{\tau'(E^*)+2\gamma}{2\varepsilon-1}$, could be the following:

A higher tax responsiveness $\tau'(E)$ strengthens the corrective feedback between the state of the environment and extraction incentives, thereby lowering the eigenvalue η and promoting stability. Conversely, a weakly responsive or negative tax slope destabilizes the system. The follower's curvature γ of its own value function measures the behavioral inertia, which means a higher γ dampens extracting firms' reactions to changing incentives, producing smoother adjustment paths and a more stable equilibrium. The technological elasticity ε affects the sensitivity of extraction to quota changes, i.e. when ε is large, extraction reacts strongly to small policy or create variations to state variations, magnifying fluctuations and thus reducing stability.

The steady state quota Q^* acts as a multiplier, that means large equilibrium extraction volumes amplify the feedback loop and make stability harder to maintain. The environmental regeneration ω represents the system's intrinsic tendency to expand or contract, i.e. a higher ω accelerates natural dynamics and can dominate the stabilizing policy feedback, leading to oscillations or divergence. In short, stability requires that the combined stabilizing effects of policy (large $\tau'(E^*)$) and behavioral (large γ) offset the destabilizing forces of natural growthω and extraction sensitivity (Q^*, ε).

From the policy perspective, the stability condition highlights how a regulator can design and calibrate instruments to ensure environmental resilience. The most direct lever is the tax schedule, that means by choosing a sufficiently steep and state – responsive tax ($\tau'(E^*) > 0$), the regulator introduces a corrective mechanism that automatically tightens incentives when the environment improves and relaxes them when it deteriorates, thereby counteracting cyclical overshooting, increasing the behavioral curvature γ. For instance, through institutional or contractual mechanisms that make extracting firms more forward – looking or risk–averse, thereby stability enhanced by reducing aggressive extraction responses. Technological and cost–side parameters provide complementarity stabilization channels, by encouraging higher extraction costs (C) or less elastic production technologies (lower ε) dampens firms' responsiveness to environmental fluctuations. Conversely, policies that constrain steady – state extraction levels Q^*, such as quota reductions, further reduce destabilizing feedbacks. Finally, when the natural regeneration rate ω is high (fast ecological turnover), stronger state dependence in taxation are necessary to maintain convergence.

7. Discussion and Contribution

Discussion

The feedback Stackelberg framework developed above highlights the dynamic interaction between a regulating leader and a resource–extracting follower. Unlike the open–loop formulation (where the leader commits to predetermined policy path), the feedback structure allows the leader to adjust regulation continuously in response to the evolving environmental state. This endogeneity introduces adaptive stabilization forces that shape both the equilibrium extraction and the steady state environmental quality.

The follower's optimal response, $U^*(E;Q) = \left[\frac{C}{(1-V'(E))\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}}$ which in the case of the quadratic value function $V(E) = \alpha + \beta E + \gamma E^2$ becomes $U^*(E;Q) = \left[\frac{C}{(1-\beta-2\gamma E)\pi Q^{\varepsilon}}\right]^{\frac{1}{\pi-1}}$, indicates that higher environmental degradation, i.e. larger E, or stronger environmental sensitivity $(\gamma > 0)$ reduce extraction intensity. The follower thus becomes more conservative as environmental conditions deteriorate, generating a natural feedback dampening effect.

Anticipating this reaction, the leader chooses a feedback policy

$$Q^*(E) = K(1 - \beta - 2\gamma E)^{-\frac{1}{\pi-1+\varepsilon}}$$

which links the control variable (e.g. tax, quota) directly to the environmental stock. The negative exponent implies that the leader tightens policy (reduces Q) as E increases, embodying an adaptive regulation rule. This dynamic feedback contrasts with a fixed open–loop path, which cannot react to shocks or unforeseen deviations in environmental quality.

Substituting both feedback laws into the state equation produces an autonomous environmental dynamic:

$$\dot{E} = \omega E - \Phi(1 - \beta - 2\gamma E)^{-\frac{\pi}{\pi - 1 + \varepsilon}}$$

Where Φ captures the effective extraction intensity under equilibrium feedback. The steady state condition

$$\omega E = \Phi(1 - \beta - 2\gamma E)^{-\frac{\pi}{\pi - 1 + \varepsilon}}$$

defines the long–run balance between environmental regeneration and extraction pressure. The local stability criterion,

$$f'(E^*) = \omega - \frac{2\gamma\pi\Phi}{\pi - 1 + \varepsilon}(1 - \beta - 2\gamma E)^{-\frac{\pi}{\pi - 1 + \varepsilon} - 1} < 0$$

reveals that stability depends critically on the relative magnitudes of the natural regeneration rate ω and the regulatory responsiveness captured by γ, π and ε. Higher curvature in the follower's value function (large γ) or stronger sensitivity of the leader's policy to environmental conditions enhances stability by strengthening the feedback control mechanism. In contrast, a high natural regeneration rate or weak feedback elasticity can generate oscillatory or divergent environmental dynamics.

Overall, the feedback equilibrium illustrates how endogenous policy adaptation stabilizes the system even when agents act strategically. The leader effectively internalized the follower's state–dependent behavior, translating micro–level responsiveness into macro–level environmental stability.

Contribution

This paper makes a foundational theoretical contribution to the economics of renewable resource management. Specifically, it proves that stability is impossible under rigid, pre-committed rules and is only attainable under adaptive, state-dependent policies that create a corrective feedback loop between ecological conditions and economic incentives. Analytically, the core contribution relies in the following:

(a) *The paper* provides a rigorous game-theoretic justification for the failure of rigid, long-term regulatory plans. It argues that sustainability cannot be "set and forgotten." That means under the open-loop information structure, where the regulator commits to a fixed quota path at the start of the game, the resulting steady state is locally unstable.

(b) Identification of the Critical Condition for Stability under Adaptive Regulation. The paper demonstrates that simply moving to a feedback structure is not sufficient.

- If the firm uses a linear value function ($V(E) = \alpha + \beta E$), its feedback strategy becomes unresponsive to the stock level and the resulting environmental dynamics is unstable.
- Stability emerges if and only if the firm's valuation of the resource is sufficiently sensitive to the stock. The paper proves this requires a convex (quadratic) value function ($V(E) = \alpha + \beta E + \gamma E^2$ with $\gamma > 0$), $\gamma > 0$ means the firm's *marginal* valuation of the resource stock increases as the environmental stock grows.This state-dependent dampening is the core stabilizing behavior.The paper shows that such a quadratic value function is a consistent solution to the firm's problem only when the elasticity of effort in the harvest function is $\pi = 1/2$.

(c) The paper doesn't just identify the condition for stability; it derives the form of the regulator's optimal adaptive policy that exploits this condition.

- The social planner's optimal feedback quota is $Q^*(E) = K(1 - \beta - 2\gamma E)^{-1/(2\varepsilon-1)}$
- The Policy Interpretation is: This is a precise state-contingent rule: the allowed extraction decreases as the environmental stock increases.It curbs extraction during booms to preserve the high stock that enables future prosperity, thereby creating a self-correcting regulatory feedback loop.

(d) The paper provides the quantification of the stability condition and its drivers. That means moves beyond a yes/no stability check to provide the exact mathematical condition for local asymptotic stability (Lemma 5):

$$\omega < \frac{(Q^*)^{2\varepsilon}}{2C}\frac{2\gamma}{2\varepsilon - 1}$$

- This condition makes the drivers of stability transparent, i.e.:

(i) Firm Foresight (γ): Higher sensitivity of the firm to the stock promotes stability.
(ii) Policy Potency (ε): A higher elasticity of harvest to the quota makes the regulator's tool more powerful.
(iii) Ecological Growth (ω): Faster natural regeneration makes the system harder to stabilize, demanding stronger feedback responses.
(iv) Steady-State Stock (E^*): The stability condition implies E^* must be above a threshold, formally justifying precautionary, higher stock targets.

(e) The paper enhancing stability with state-dependent taxation: The contribution is extended by showing how a policy instrument can be designed to directly strengthen the stabilizing mechanism. Introducing a per-unit tax $\tau(E)$ that increases with the stock ($\tau'(E) > 0$) modifies the stability condition to:

$$\omega < \frac{(Q^*)^{2\varepsilon}}{2C}\frac{\tau'(E^*) + 2\gamma}{2\varepsilon - 1}$$

The above condition implies the tax responsiveness $\tau'(E)$ and the firm's behavioral sensitivity γ are additive in promoting stability. This provides a formal rationale for "smart" tax schemes that automatically adjust to ecological conditions.

Concluding, the paper's overarching contribution is to shift the focus of resource regulation from static optimization "*What is the optimal quota level*?" to dynamic system design "*How do we design a rule ($Q^*(E)$), and shape the institutional environment (to raise γ), so that the coupled socio-ecological system is inherently stable and self-correcting*?"

8. Conclusion

This study has examined the dynamic interactions between a resource-extracting firm and an environmental regulator within a Stackelberg differential game framework, under both open-loop and feedback (closed-loop) information structures. The analysis was conducted for renewable resources governed by exponential growth dynamics, capturing distinct ecological and economic realities.

In the open-loop setting, where strategies are committed at the outset, the regulator's optimal emission tax policy and the firm's extraction trajectory were derived analytically. The results demonstrate that the optimal tax is positively related to the firm's extraction effort, but inversely related to the natural regeneration capacity of the resource. The phase diagram analysis revealed that stability is attainable when the intrinsic regeneration rate outweighs the depletion rate induced by extraction. Thus, a sufficiently strong natural recovery mechanism can offset extraction-induced degradation, ensuring convergence to a steady-state equilibrium.

In the feedback (closed-loop) formulation, where policies respond to the current state of the resource, the leader (regulator) dynamically adjusts taxation in response to evolving resource conditions. The resulting Markovian strategies reflect adaptive management: when the resource stock diminishes, the regulator raises the tax to deter extraction, while recovery triggers a relaxation of control. This feedback mechanism enhances the system's resilience, as it internalizes ecological feedbacks in real time.

The stability analysis confirms that, under realistic parameter conditions, the feedback equilibrium leads to a more robust and sustainable steady state than its open-loop counterpart.

Comparing both information structures, the feedback Stackelberg equilibrium yields superior environmental outcomes and improved social welfare. The open-loop model, though analytically tractable, risks over-extraction due to the absence of adaptive control. Conversely, the feedback strategy embodies precautionary and self-correcting features, aligning economic incentives with ecological sustainability.

From the policy perspective, a central message emerges: rigid, pre-committed policies are not enough. When the planner relies on open-loop strategies, the system lacks the ability to correct itself in response to environmental fluctuations. The resulting steady states are unstable, and even small shocks can push the economy–environment system onto divergent paths. This

fragility reflects a deeper structural issue: without feedback, neither the planner nor the firm adjusts behavior when the resource stock changes and the ecological dynamics are left to drift.

In contrast, feedback strategies fundamentally change the picture. When decisions are allowed to depend on the current state of the environment, the strategic interaction becomes self-correcting. The firm's valuation of the resource stock—captured through its shadow price—becomes a channel through which ecological information influences economic behavior. When this valuation is sufficiently sensitive, as under a quadratic value function, the system acquires a stabilizing mechanism that is absent in the open-loop case. The stable manifold derived in the analysis formalizes this mechanism, showing the unique path along which the economy can converge to a sustainable steady state.

The introduction of a state-dependent tax strengthens this stabilizing feedback even further. By tying the tax burden directly to environmental conditions, the planner amplifies the responsiveness of private extraction decisions. This creates a tighter alignment between private incentives and ecological health, offering a clear rationale for adaptive taxation schemes in renewable resource management. The tax does not merely raise revenue—it becomes an instrument for ecological resilience.

Taken together, these findings underscore a broader lesson: sustainability is an active, adaptive process. It cannot be achieved through static rules or one-time policy commitments. Instead, it requires regulatory frameworks that evolve with ecological conditions, anticipate strategic responses, and incorporate real-time information about the state of the resource.

Overall, the results underscore the importance of dynamic and adaptive environmental policies in managing renewable resources. Incorporating feedback mechanisms enables regulators to anticipate and correct market behaviors that threaten long-term sustainability.

Future research could extend the model with thelogistic growth function, stochastic environments, multi-agent extraction, or threshold-based ecological dynamics, where the role of feedback and adaptive regulation is likely to be even more pronounced.

Analytically, a future research agenda could include the directions: (a) richer ecological dynamics such as logistic growth and/or Gompertz growth function or age–structured modeling. Such extensions could reveal whether adaptive feedback policies remain stabilizing when the environment itself becomes more complex or uncertain. (b) expanding the strategic structure of the game into multi-firm differential game modeling, decentralized regulators with imperfect coordination, or transboundary and multi-country resource systems. This extension would shed light on how strategic interactions amplify or mitigate ecological risks. (c) provide more sophisticated policy instruments as: dynamic permit systems, endogenous quota adjustment rules, hybrid tax–quota instruments, or incentive schemes that reward conservation effort. Understanding how these instruments perform in a strategic dynamic setting would help bridge theoretical insights with practical policy design.

Appendix

Proof of Lemma 1

Let $V(E)$ denote the value function. The HJB equation is

$$\rho_1 V(E) = \max_{U>0}\{U^{\pi}Q^{\varepsilon} - CU - DE - AQ + V'(E)(\omega E - U^{\pi}Q^{\varepsilon})\}$$

Rewrite the above as

$$\rho_1 V(E) = \max_{U>0}\{(1 - V'(E))U^{\pi}Q^{\varepsilon} - CU - DE - AQ + \omega E V'(E)\}$$

Make the affine ansatz $V(E) = a + \beta E$, then $V'(E) = \beta$(constant), so the maximization above is over a function that no longer depends on E except through linear terms, the first – order condition for an interior maximizer U^* is:

$$\frac{\partial}{\partial U}[(1-\beta)U^{\pi}Q^{\varepsilon} - CU] = 0 \Rightarrow (1-\beta)\pi Q^{\varepsilon}(U^*)^{\pi-1} - C = 0$$

Which yields the expression for U^* given above, provided $1 - \beta > 0$ to ensure $U^* > 0$. Substitute $V(E) = a + \beta E$ and the maximizer U^* back into the HJB and equate coefficients of E and constants. Collect the terms multiplying E:

Coefficient of E: $\rho_1\beta = -D + \beta\omega$

So since $\rho_1 \neq \omega$

$$(\rho_1 - \omega)\beta = -D \Rightarrow \beta = -\frac{D}{\rho_1 - \omega}$$

Having determined β, the constant part of the HJB gives:

$$\rho_1 a = (1-\beta)(U^*)^{\pi}Q^{\varepsilon} - CU^* - AQ \Rightarrow a = \frac{(1-\beta)(U^*)^{\pi}Q^{\varepsilon} - CU^* - AQ}{\rho_1}$$

Because the HJB is satisfied by this affine V with the interior U^*, and the ansatz produces a legitimate maximizer under the stated parameter conditions, the value function is indeed affine in E.

Proof of Lemma 2

Write the stationary HJB equation for the problem:

$$\rho_1 V(E) = \max_{U>0}\{U^{\pi}Q^{\varepsilon} - CU - DE - AQ + V'(E)(\omega E - U^{\pi}Q^{\varepsilon})\}\,(A.1)$$

For an interior maximizer use the first–order condition (FOC) w.r.t.U. Denote $V'(E)$by v. The derivative of $(A.1)$ w.r.t. U is:

$$\frac{\partial}{\partial U}[U^{\pi}Q^{\varepsilon}(1-v)-CU]=\pi U^{\pi-1}Q^{\varepsilon}(1-v)-C$$

and the FOC gives:

$$\pi U^{\pi-1}Q^{\varepsilon}(1-v)=C\Rightarrow U^{*}(E)=\left[\frac{C}{\pi Q^{\varepsilon}(1-v(E))}\right]^{\frac{1}{\pi-1}} \qquad (A.2)$$

Substituting $(A.2)$ back into $(A.1)$, the terms that depend on U gives a combination of the form

$$(U^{*})^{\pi}Q^{\varepsilon}(1-v(E))-CU=\kappa(1-v(E))^{-\frac{1}{\pi-1}}$$

where κ is a constant depending only on the parameters C,π,Q^{ε}.

Therefore, after maximization the HJB becomes:

$$\rho_1 V(E)=\ \kappa(1-\beta-2\gamma E)^{-\frac{1}{\pi-1}}+\text{terms that are affine or quadratic in } E \qquad (A.3)$$

The left – hand side of $(A.3)$,$\rho_1 V(E)$ is a polynomial of degree 2 in E. All other terms in the HJB except the κ –term are at most quadratic (indeed linear or quadratic) because they are linear combinations of E and $v(E)$ (which is affine). Thus, compatibility of the ansatz requires the κ term

$$(1-\beta-2\gamma E)^{-\frac{1}{\pi-1}}$$

to be polynomial in E of degree ≤ 2.

Set

$$\eta:=-\frac{1}{\pi-1}$$

The term $\kappa(1-\beta-2\gamma E)^{\eta}$ of $(A.3)$ to be a polynomial in E it is sufficient $\eta\in\mathbb{Z}_{\geq 0}$ (to be a nonnegative integer), because non – integer or negative integer powers of an affine function produce non – polynomial expressions (rational or fractional powers). Moreover, since the left side is degree 2, we require the polynomial degree η to satisfy $\eta\leq 2$, hence the only admissible integer values are $\eta=0,1,2$.

Solve for π from $\eta=-\frac{1}{\pi-1}$:

$$\eta=0 \qquad \Rightarrow \qquad -\frac{1}{\pi-1}=0 \text{ (impossible)}$$

$$\eta=1 \qquad \Rightarrow \qquad -\frac{1}{\pi-1}=1 \quad \Rightarrow \ \pi=0 \text{ (degenerate model case)}$$

$$\eta = 2 \quad \Rightarrow \quad -\frac{1}{\pi - 1} = 2 \quad \Rightarrow \quad \pi = \frac{1}{2}$$

The only non–degenerate admissible solution is therefore $\pi = \frac{1}{2}$. For any other π the exponent η is not an integer in $\{0, 1, 2\}$ and so $(1 - V'(E))^{-\frac{1}{\pi - 1}}$ is not a polynomial of degree ≤ 2. Consequently, the RHS of the HJB cannot match the quadratic LHS $\rho_1 V(E)$, and the quadratic ansatz is inconsistent with the HJB.

Now we set $\pi = \frac{1}{2}$ to see whether the quadratic value function is indeed a solver for the HJB function. The followers' (extracting firm) problem is modified as:

$$\rho_1 V(E) = \max_{U>0} \left\{ U^{\frac{1}{2}} Q^{\varepsilon} - CU - DE - AQ + V'(E)\left(\omega E - U^{\frac{1}{2}} Q^{\varepsilon}\right) \right\} (A.4)$$

and let $V'(E) = v$

taking the FOC:

$$\frac{\partial}{\partial U}\left[U^{\frac{1}{2}} Q^{\varepsilon}(1 - v) - CU\right] = 0 \Rightarrow \frac{1}{2} U^{-\frac{1}{2}} Q^{\varepsilon}(1 - v) - C = 0 \Rightarrow$$

$$U = \left[\frac{Q^{\varepsilon}(1 - v)}{2C}\right]^2 (A.5)$$

Substitute $(A.5)$ into HJB $(A.4)$ yields

$$\rho_1 V(E) = Q^{\varepsilon} \frac{Q^{\varepsilon}(1 - v)^2}{2C}(1 - v) - C\left[\frac{Q^{\varepsilon}(1 - v)}{2C}\right]^2 - DE - AQ + v\omega E \Rightarrow$$

$$\rho_1 V(E) = \frac{Q^{2\varepsilon}(1 - v)^2}{2C} - \frac{Q^{2\varepsilon}(1 - v)^2}{4C} - DE - AQ + v\omega E \Rightarrow$$

$$\rho_1 V(E) = \frac{Q^{2\varepsilon}(1 - v)^2}{4C} - DE - AQ + v\omega E \qquad (A.5)$$

Since:

$$V(E) = \alpha + \beta E + \gamma E^2 (A.6)$$

$$v(E) = \beta + 2\gamma E \qquad (A.7)$$

Plug $(A.6)$ and $(A.7)$ into HJB $(A.5)$

$$\rho_1(\alpha + \beta E + \gamma E^2) = \frac{Q^{2\varepsilon}}{4C}[(1 - 2\gamma E - \beta)]^2 - DE - AQ + \omega E(2\gamma E + \beta) \Rightarrow$$

$$\rho_1\gamma E^2 + \rho_1\beta E + \rho_1\alpha = \frac{Q^{2\varepsilon}}{4C}[(1-\beta)^2 - 4\gamma E(1-\beta) + 4\gamma^2E^2] - DE - AQ + 2\gamma\omega E^2 + \omega\beta E \quad (A.8)$$

In $(A.8)$ equating the terms with the same power of E we have:

E^2 −term:

$$\rho_1\gamma = \frac{Q^{2\varepsilon}}{4C}4\gamma^2 + 2\gamma\omega \underset{\gamma\neq 0}{\Rightarrow} \gamma = \frac{C(\rho_1 - 2\omega)}{Q^{2\varepsilon}} \qquad (A.9)$$

E −term:

$$\rho_1\beta = -\frac{Q^{2\varepsilon}}{4C}4\gamma(1-\beta) - D + \omega\beta \Rightarrow \beta\left(\rho_1 - \frac{Q^{2\varepsilon}\gamma}{C}\right) = -\frac{Q^{2\varepsilon}\gamma}{C} - D \qquad (A.10)$$

Constant term:

$$\rho_1\alpha = \frac{Q^{2\varepsilon}}{4C}(1-\beta)^2 - AQ \qquad (A.11)$$

The three algebraic equations $(A.9), (A.10), (A.11)$ given the parameters $Q, \varepsilon, C, D, A, \omega, \rho_1$they have three unknowns α, β, γ.

Concluding, the quadratic value function $V(E)$ solves the HJB equation, if and only if $\pi = \frac{1}{2}$.

Proof of Lemma 3

The FOC of the follower HJB is:

$$\pi U^{\pi-1}Q^{\varepsilon}(1 - V'(E) = C$$

Setting $= \frac{1}{2}$, the follower feedback control solves

$$U(E;Q) = \left[\frac{2C}{(1-V'(E))Q^{\varepsilon}}\right]^{-2} = \left[\frac{(1-V'(E))Q^{\varepsilon}}{2C}\right]^2 \quad (A.12)$$

The depletion (harvesting) function is by definition $h(U,Q) = U^{1/2}Q^{\varepsilon}$and substituting the feedback control $(A.12)$, the depletion function becomes

$$h(E,Q) = \frac{(1-V'(E))Q^{2\varepsilon}}{2C} = \frac{(1-\beta-2\gamma E)Q^{2\varepsilon}}{2C} \qquad (A.13)$$

the differentiation of$(A.13)$ w.r.t. E yields:

$$h_E(E,Q) = \frac{-\gamma Q^{2\varepsilon}}{C}$$

Linearizing $\dot{E} = \omega - h(E, Q^*)$ around E^* (holding Q^* at equilibrium) yields the eigenvalue:

$$\eta_{lin} = \omega - h_E(E, Q) \Rightarrow \eta_{lin} = \omega + \frac{\gamma Q^{2\varepsilon}}{C} (A.14)$$

At the steady state

$$\dot{E} = 0 \Rightarrow \omega = h(E^*, Q^*) \Rightarrow \omega = \frac{(1 - \beta - 2\gamma E^*)Q^{2\varepsilon}}{2C}$$

Hence,

$$\frac{Q^{*2\varepsilon}}{C} = \frac{2\omega E^*}{1 - \beta - 2\gamma E^*} (A.15)$$

Substitute $(A.15)$ into $(A.14)$:

$$\eta_{lin} = \omega + \gamma \frac{2\omega E^*}{1 - \beta - 2\gamma E^*} \quad \Rightarrow$$

$$\eta_{lin} = \omega \frac{1 - \beta}{1 - \beta - 2\gamma E^*} \text{Q. E. D.}$$

Proof of Lemma 4.

Step 1.

Integrate W_E to get quadratic value function W.

Having the assumption (15) i.e. $W_E(E) = M(1 - \beta - 2\gamma E)$, we integrate w.r.t. E

$$W(E) = a + \int M(1 - \beta - 2\gamma E)dE = a + M(1 - \beta)E - M\gamma E^2$$

so $b = M(1 - \beta)$ and $c = -M\gamma$. This proves (1).

Step 2.

From the HJB pointwise maximization, the interior FOC is:

$$W_2 - W_E(E) \frac{\varepsilon(1 - \beta - 2\gamma E)}{C} Q^{2\varepsilon - 1} = 0 \qquad (A.16)$$

Substituting $W_E(E) = M(1 - \beta - 2\gamma E)$ into $(A.16)$

$$Q^{2\varepsilon-1} = \frac{W_2 C}{\varepsilon M}(1-\beta-2\gamma E)^{-2} \Rightarrow Q^*(E) = \left(\frac{W_2 C}{\varepsilon M}\right)^{1/(2\varepsilon-1)} (1-\beta-2\gamma E)^{-2/(2\varepsilon-1)} (A.17)$$

This proves (2).

Step 3.
The stationary HJB is:

$$\rho_2 W(E) = W_1 E + W_2 Q^* + W_E(E)\big(\omega E - h(E, Q^*(E))\big)$$

Substitute $W(E) = a + bE + cE^2, W_E = b + 2cE = M(1-\beta-2\gamma E)$, and the formulae for $Q^*(E)$

and $h(E,Q) = \frac{(1-\beta-2\gamma E)Q^{2\varepsilon}}{2C}$. After substitution the HJB becomes an identity of the form

$$\rho_2 \alpha + P_1(E) = 0$$

Where $P_1(E)$ is a polynomial (indeed every term is proportional to some power of the factor $(1-\beta-2\gamma E)$ and/or linear quadratic in E. Because the left-hand side must hold for every admissible E, and because by construction the dependence on E cancels out when the parameters satisfy the implied algebraic relations arising from the FOC, what remains is a constant equation for α. Thus α can be chosen (unique) to make the HJB hold identically provided no further contradictions arise among parameters. This proves (3).

Step 4
Interior solution requires the base inside the power to be positive:

$$\frac{W_2 C}{\varepsilon M}(1-\beta-2\gamma E)^{-2} > 0 \Rightarrow M(1-\beta-2\gamma E) > 0$$

On the admissible domain so $Q^*(E) > 0$. The second order condition for maximization w.r.t. Q requires the second derivative of pointwise objective in Q to be negative at $Q^*(E)$; computing gives

$$\partial_Q^2 \mathrm{L} = -W_E(E)\frac{\varepsilon(2\varepsilon-1)(1-\beta-2\gamma E)}{C} Q^{2\varepsilon-2}$$

Using $W_E = M(1-\beta-2\gamma E)$, this equals:

$$-\frac{M(2\varepsilon-1)\varepsilon}{C}(1-\beta-2\gamma E)Q^{2\varepsilon-2}$$

Since $2\varepsilon - 1 > 0, Q^{2\varepsilon-2} > 0$ for $Q > 0$ the second derivative is negative if and only if $M > 0$. Therefore choosing $M > 0$ ensures a local maximum in Q (together with the sign condition on

$1 - b - 2\gamma E$); if $M < 0$ the FOC would give a local minimum. Thus pick $M > 0$ consistent with feasibility to get an interior maximum.

This completes the proof

Proof of Lemma 6

Linearize $\dot{E} = \omega E - h(Q(E), E)$ around E^*. The linearized coefficient is:

$$\eta = \omega - \frac{d}{dE}[h(Q(E), E)]_{E=E^*} = \omega - \left(h_E + h_Q Q'(E)\right)_{E=E^*}$$

where subscripts denote partial derivatives.

Setting:

$$a(E) \coloneqq 1 - \tau(E) - \beta - 2\gamma E \qquad (A.18)$$

the harvesting function becomes

$$h(E, Q) = \frac{a(E)Q^{2\varepsilon}}{2C} \qquad (A.19)$$

The differentiation of$(A.19)$ gives:

$$\frac{d}{dE}h\big(E, Q(E)\big) = \frac{1}{2C}[a'(E)Q^{2\varepsilon} + a(E)2\varepsilon Q^{2\varepsilon-1}Q'(E)] \qquad (A.20)$$

The optimal feedback quota $(16)$from Lemma 4, becomes:

$$Q(E) = Ka(E)^{-1/(2\varepsilon-1)} \qquad (A.21)$$

Taking logs of $(A.21)$

$$\ln Q(E) = \ln K - \frac{1}{2\varepsilon - 1}\ln a(E) \Rightarrow \frac{Q'(E)}{Q(E)} = -\frac{1}{2\varepsilon - 1}\frac{a'(E)}{a(E)} \qquad (A.22)$$

Substitute$(A.22)$ into $(A.20)$

$$\frac{d}{dE}h\big(E, Q(E)\big) = \frac{Q^{2\varepsilon}}{2C}\left[a'(E) + 2\varepsilon a(E)\left(-\frac{1}{2\varepsilon - 1}\frac{a'(E)}{a(E)}\right)\right] = \frac{Q^{2\varepsilon}}{2C}a'(E)\left[1 - \frac{2\varepsilon}{2\varepsilon - 1}\right] \Rightarrow$$

$$\frac{d}{dE}h\big(E, Q(E)\big) = -\frac{Q^{2\varepsilon}}{2C}\frac{a'(E)}{2\varepsilon - 1} \qquad (A.23)$$

Differentiate$(A.18)$ to get

$$-a'(E) = \tau'(E) + 2\gamma \qquad (A.24)$$

And substitute $(A.24)$into$(A.23)$:

$$\frac{d}{dE}h\big(E,Q(E)\big) = -\frac{Q^{2\varepsilon}}{2C}\frac{\tau'(E)+2\gamma}{2\varepsilon-1} \qquad (A.25)$$

Since the eigenvalue η is:

$$\eta = \omega - \frac{dh}{dE} \qquad (A.26)$$

substituting $(A.25)$into$(A.26)$we get (evaluated at $E = E^*$)

$$\eta = \omega - \frac{(Q^*)^{2\varepsilon}}{2C}\frac{\tau'(E^*)+2\gamma}{2\varepsilon-1}$$

Which is exactly (22) into the main text.

Proof of Lemma 5.
Linearize the scalar ODE $\dot{E} = \omega E - h(Q^*(E), E)$ around E^*. The eigenvalue is

$$\lambda = \frac{d}{dE}\big(\omega E - h(Q^*(E),E)\big)|_{E^*} = \omega - \frac{d}{dE}\big(h(Q^*(E),E)\big)|_{E^*}$$

With $a(E) \coloneqq 1-\beta-2\gamma E$ and $h(E,Q) = \frac{a(E)Q^{2\varepsilon}}{2C}$, compute

$$\frac{d}{dE}\Big(h\big(E,Q(E)\big)\Big) = \frac{1}{2C}[a'(E)Q^{2\varepsilon} + a(E).2\varepsilon Q^{2\varepsilon-1}Q'(E)]$$

Using the quota law $Q(E) = Ka(E)^{-1/(2\varepsilon-1)}$ we get

$$\frac{Q'(E)}{Q(E)} = -\frac{1}{2\varepsilon-1}\frac{a'(E)}{a(E)}$$

Substitute and simplify

$$\frac{d}{dE}h = \frac{Q^{2\varepsilon}}{2C}a'(E)\left(1-\frac{2\varepsilon}{2\varepsilon-1}\right) = -\frac{Q^{2\varepsilon}}{2C}\frac{a'(E)}{2\varepsilon-1}$$

Since $a'(E) = -2\gamma$, this reduces to

$$\frac{d}{dE}h = \frac{Q^{2\varepsilon}}{2C}\frac{2\gamma}{2\varepsilon-1}$$

Because it is required $\lambda < 0$ we get

$$\omega < \frac{Q^{2\varepsilon}}{2C}\frac{2\gamma}{2\varepsilon-1}$$

and using the steady state identity $\omega E^* = \frac{a(E^*)(Q^*)^{2\varepsilon}}{2C}$ to eliminate $(Q^*)^{2\varepsilon}$ finally get

$$2\gamma\frac{E^*}{1-\beta-2\gamma E^*} > 2\varepsilon - 1$$

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EUNICoast

Abstract

EUNICoast is an innovative European University Alliance dedicated to addressing the unique challenges and harnessing the opportunities of Europe's island and coastal regions. Integrating sustainability, education, research, innovation, and community engagement, EUNICoast aims to highlight the human and dynamic dimension of ports and islands, two distinct yet deeply interconnected elements of Europe's identity and development. Bringing together 12 member universities and 88 associated partners, the Alliance promotes a multicultural, multilingual, and inclusive environment for learning, research, and innovation, open to the world. Its mission is to strengthen the collective capacity of universities to effectively respond to the social, economic, and environmental challenges faced by coastal and island communities. EUNICoast envisions a future where ports act as hubs of innovation and cultural exchange, and islands serve as catalysts for sustainable development. Through collaboration, knowledge exchange, and joint initiatives, the Alliance seeks to place universities at the core of Europe's Blue Economy, empowering a new generation of conscious, engaged, and globally minded citizens committed to sustainability and resilience.

Conceptualizing the Symbiosis Maturity for Nature-based Solutions: A SWOT-driven framework across technical, environmental, management and institutional domains

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Abstract

Nature-based solutions (NBS) are increasingly deployed to deliver ecological, social, and economic co-benefits under the scopes of circular economy transition, one health integration, and sustainable development goals (SDGs) achievement. However, there is a lack of a holistic framework that mutually reinforces these solutions across systems that remain limited. This paper introduces the Symbiosis Maturity Level (SML) for NBS and proposes a SWOT-driven assessment framework spanning four development domains: technical (TML), environmental (EML), management (MML), and institutional (IML). The relationship between the concepts is not made explicit in literature, therefore, the novelty is the provision of the four maturity-level terms, addressing this literature gap and aims to provide conceptual clarity by distinguishing the terms and synthesising the different types of relationships between them. The objective is the application of the SWOT analysis in order to inspect the strengths, weaknesses, opportunities, and threats within each domain and to highlight the cross-domain interdependencies. The overview covers 79 publications in the period 2010–2024 from Scopus, Web of Science, and Google Scholar. The resulting SML provides a transparent way to benchmark maturity, reveal bottlenecks, and prioritize actions across NBS portfolios. Ultimately, the reframing of NBS evaluation through a symbiosis framework offers a practical pathway for policymakers, practitioners, and researchers to guide decisions toward more robust, durable, and scalable NBS.

Keywords: *nature-based solutions; SWOT; maturity modelling; strategic planning; governance; evidence synthesis; symbiosis framework.*

JEL Codes: Q01, Q55; Q57; Q58

Session 5.

Circular Economy: Water & Waste Management

Water management practices in Ancient Greece

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Abstract

This paper analyzes the water management practices that were introduced in Ancient Greece with emphasis in Classical Athens (508 – 323 BCE). It argues that their success should be attributed to two main factors that functioned in combination: investing on water management infrastructure and introducing effective water management institutions. Infrastructure included extensive public works such as the building of public wells, fountains, springs, aqueducts and cisterns, as well as the building of an underground water supply network, and the building of a sewage underground network for wastewater management. Institutions included the introduction of a series of public magistrates who were assigned to implement the city-states' water management strategy. Their duties are analyzed in detail in the paper. The paper finally discusses if and how water management practices in Ancient Greece at the Classical times may be seen as an inspiration for modern societies on related environmental issues.

Keywords: *Ancient Greece, Classical Athens; public infrastructure, public goods; water management institutions; environmental sociology*

JEL Codes: H41; H76; K20; N43; N53; Q28, Q58

Join the dots: A rapid temporal appraisal of the bioeconomy in NUTS II regions in Greece

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Abstract

The present paper aims to present for the first time a temporal bioeconomy assessment in the 13 NUTS II regions in Greece. The research builds upon Maroulis et al. (2025) and Kalimeris et al. (forthcoming). There the main objective was to assess and promote the transition to bioeconomy on a regional scale by analysing EU regions (NUTS II Level) with a group of selected bio-indicators with the latest available data. Primarily based on the results of BIO2REG project, the paper aspires to put the dimension of time into the evaluation of bioeconomy performance and provide a more comprehensive application of the bioeconomy on a regional level. Using a set of 26 pre-selected bioeconomy related indicators, it will be investigated how Greek NUTS II regions have performed during the period 2010-2022. This temporal assessment will enhance the credibility of the bioeconomy assessment framework of our existing work and will constitute the basis of expanding the temporal bioeconomy assessment to other EU Member States. Furthermore, it aspires to provide the first blueprint for revealing the model bioeconomy regions and the potential EU-wide pathways to promote regional bioeconomy.

Keywords: Bioeconomy; regional development; circular bioeconomy; sustainable development

JEL Codes: Q57; Q56; Q43; Q2

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Kalimeris, P., Koronaios, P., Maroulis, G., & Rovolis. A. (forthcoming). Circular Bioeconomy and the regions: Developing a two-step Multi-Criteria Assessment (MCA) framework to evaluate regional bioeconomy potential in 8 selected European countries. Cleaner and Circular Bioeconomy.

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1. Introduction

The European Union (EU) is widely known as one of the leading international entities in the promotion and implementation of climate related policies and actions which aim to lead to a sustainable, inclusive, and resilient future society. In recent years, a systematic effort to reform production and consumption systems has taken place in order the European Green Deal to be achieved. Towards this end, bioeconomy is presented as a prominent transformational pathway (Sardianou et al., 2024; European Commission, 2025). The transition efforts reflect the EU's broader commitment to decarbonization, resource efficiency, and environmental sustainability. Despite its growing policy importance, the concept of bioeconomy remains subject to multiple and diversified definitions worldwide, as well as varying interpretations of the objectives this alternative socio-economic model seeks to achieve.

Within this diversified landscape, the EU perception for bioeconomy follows the bioresource vision, which focuses on the replacement of non-renewable and fossil-based resources with biological and renewable ones to produce food, feed, materials, energy, and fuels (Proestou et al., 2024; Patermann & Aguilar, 2021). The EU's strategic engagement with the bioeconomy began with the adoption of the first EU Bioeconomy Strategy in 2012, followed by an updated and more comprehensive version in 2018. In 2025, the European Commission launched a new bioeconomy strategy during the Danish Presidency of the Council of Europe, further reinforcing the central role of bioeconomy in achieving climate neutrality and sustainable development goals (European Commission, 2025). Notably, policy developments after 2018 indicate a shift toward regionality and circularity, highlighting the importance of local micro-characteristics in the successful implementation of bioeconomy policies.

This shift has led to the conjecture that regions constitute a critical level of governance for advancing the green transition and facilitating bioeconomy adoption. Regions differ significantly in terms of natural resource capacities, sectoral and industrial structures, and socio-cultural characteristics. Consequently, assessing bioeconomy performance at the regional level is essential for capturing these heterogeneities as well as in the formulation of successful and efficient policies.

The current scientific endeavor builds upon the methodological frameworks proposed by Maroulis et al. (2025) and Kalimeris et al. (2025). Specifically, an extensive literature review was conducted, drawing upon four sources of potential bioeconomy indicators. This process resulted in the identification of 897 bioeconomy-related indicators. A Multi-Criteria Assessment (MCA) framework was used to systematically evaluate and narrow down this extensive set, leading to the selection of 41 indicators which were suitable for monitoring regional bioeconomy potential. Based on the above-mentioned approach, 26 pre-selected indicators out of 41 were used to investigate the performance of Greek NUTS II regions over the period 2010–2022.

The present study is structured as follows. First, a comprehensive literature review on regional bioeconomy is presented, establishing the theoretical and empirical background of the analysis. Secondly, a methods and data section is presented, in which the proposed

methodological framework is described in detail. Subsequently, the empirical results for the Greek case are presented, focusing on the performance and evolution of bioeconomy activities across Greek regions. The study concludes with discussion and conclusions.

2. Literature Review

There is a growing body of academic studies and official policy reports at the European Union level which emphasize the regional aspects of bioeconomy. The review of the literature indicates that existing work on the regional bioeconomy in the EU mainly focuses on the analysis of regional bioeconomy strategies, governance frameworks, and the development of bio-based sectors at the sub-national level. In particular, the Joint Research Centre has identified a rapidly increasing number of regional bioeconomy strategies across EU regions, highlighting their differences based on their objectives, sectoral focus, and implementation efforts (Haarich et al, 2022). This diversity reflects the heterogeneity across economic structures, and institutional capacities that shape bioeconomy pathways at the regional level.

In this context, academic research consistently investigates the need for tailor made suitable policy approaches in the bioeconomy field, recognizing that local biomass availability, value chain structures, innovation ecosystems, and stakeholders' characteristics differ across EU regions (Overbeek et al., 2016; Briers et al., 2024). Such place-based approaches are considered essential for unlocking regional bioeconomy potential and ensuring that bioeconomy strategies are both economically viable and socially and environmentally sustainable (Gider et al., 2024). However, despite the increasing interest for more efficient strategies, this momentum has not been accompanied by corresponding improvements in monitoring systems and data availability. Literature highlights persistent gaps in indicators' existence as well as in the creation of robust monitoring framework. (Bogdanski et al., 2021; Mubareka et al., 2023). In addition, data availability remains particularly insufficient for non-economic dimensions of the bioeconomy, such as environmental and social parameters, further constraining comprehensive evaluation and comparison across regions (Jander et al., 2020). Consequently, recent studies stress the importance of strengthening regional bioeconomy monitoring systems through the development of indicator frameworks, improved regional level data collection, and closer alignment with EU-level monitoring efforts, in order to enhance accountability, policy learning, and the long-term sustainability of the EU bioeconomy transition (Haarich et al., 2022).

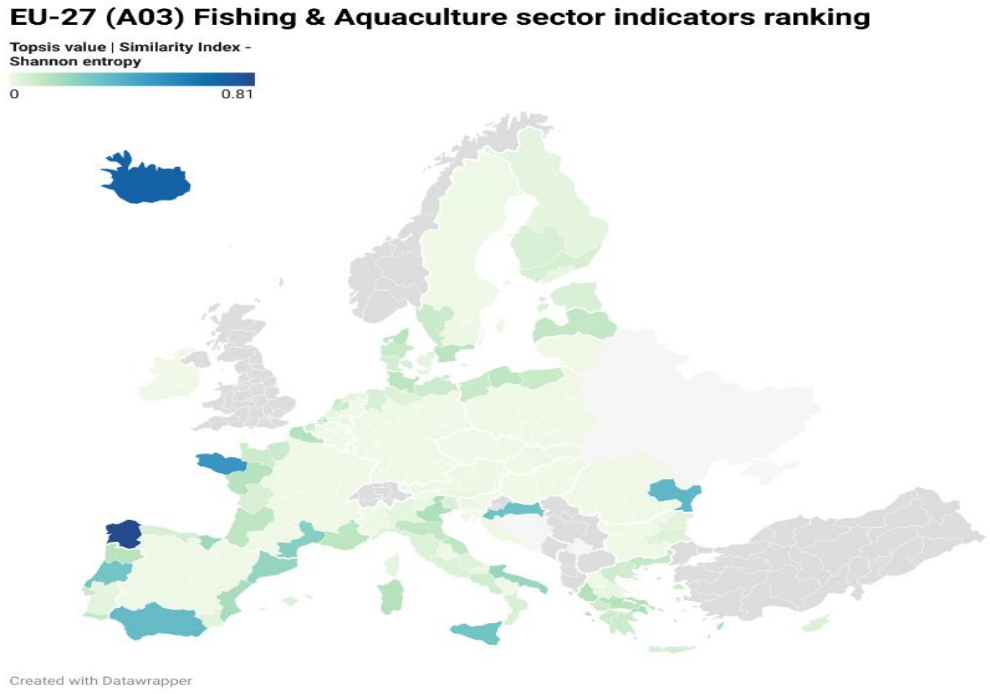
3. Methods and Data

A four-pillar literature review was conducted, drawing upon: (a) peer-reviewed scientific literature; (b) reports from international organizations and non-EU countries; (c) European Union reports and bioeconomy-related strategies of EU Member States; and (d) outputs from scientific projects focusing on the development and application of bioeconomy indicators. This comprehensive review process resulted in the identification of 897 bioeconomy-related indicators, which were subsequently classified into three main thematic dimensions, namely economic, social, and environmental. The initial pool of 897 indicators was then systematically screened and filtered according to seven predefined criteria, including data availability at the NUTS II regional level, resulting in a reduced and analytically manageable set of 41 indicators.

A more detailed description of the indicator selection process is provided in Maroulis et al. (2025), while a holistic presentation of the overall methodology and data sources can be found in Kalimeris et al. (2025).

To rank EU regions according to their bioeconomy performance within each sector, a multi-criteria ranking methodology based on two alternative cases were applied. The first case represents a baseline case in which equal weights are assigned to all indicators, and regional rankings are derived using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Under this approach, all indicators contribute equally to the final regional performance score. The second case is a weighted one, employing a modified TOPSIS framework in which regional rankings are determined using data-driven indicator weights. These weights are calculated automatically from the dataset using the Shannon entropy method (Shannon, 2001), allowing indicators with higher informational content and variability to exert greater influence on the final ranking (Kalimeris, 2025; Maroulis, 2025).

Figure 1. Results in the bioeconomy sector "Fishing & aquaculture sector), for the second (weight's ranking) scenario. Source: Kalimeris et al., 2025.



For both cases, the ranking process is performed for the next group of bioeconomy indicators (Kalimeris et al., 2025):

- Economy group: Ranking is performed into three sub-groups, namely:
  - Pure economy indicators ranking
  - Bioeconomy & innovation indicators ranking
  - Sectoral bioeconomy indicators ranking (All sectors aggregated)
- Society group: Group ranking is performed as it is.
- Environment: Group ranking is performed as it is.

- Bioeconomy per sector: A more targeted ranking per sector of bioeconomy
- Total Bioeconomy: All groups of indicators are unified in one group, and the ranking is performed together for all.

The end- result included a ranking of different EU regions under the above-mentioned scenarios (e.g., s. Figure 1).

This research concluded the first stage of the research. However, it was crucial not only to look at the static picture, based on the latest available, but a focus on the temporal dimension of bioeconomy could bring additional research benefits. For that reason, this initial analysis adopts a pilot, small-scale implementation logic (only the 13 NUTS II regions of Greece) and focuses on the most recent data available, while explicitly incorporating a temporal dimension for the period 2008–2020.Furthermore, "*Bioeconomy per sector*" scenario is utilized to assess bioeconomy performance across the 13 Greek NUTS II regions over the period 2008–2022. The indicators employed capture key dimensions of economic performance, specifically value added, turnover, and employment. These indicators can be characterized as sectoral in nature and refer to eight bioeconomy sectors defined according to the NACE classification, namely: Agriculture; Forestry; Fishing and Aquaculture; Food, Beverages and Tobacco; Bio-based Textiles; Wood Products and Furniture; Pulp and Paper; and Bio-based Chemicals. The required data were extracted from the BioRegEU pilot dataset (Lasarte López et al., 2023).

4. Empirical Results

Figure 2: Agriculture sector in 2008,2014 and 2020 in 13 NUTS II regions of Greece.

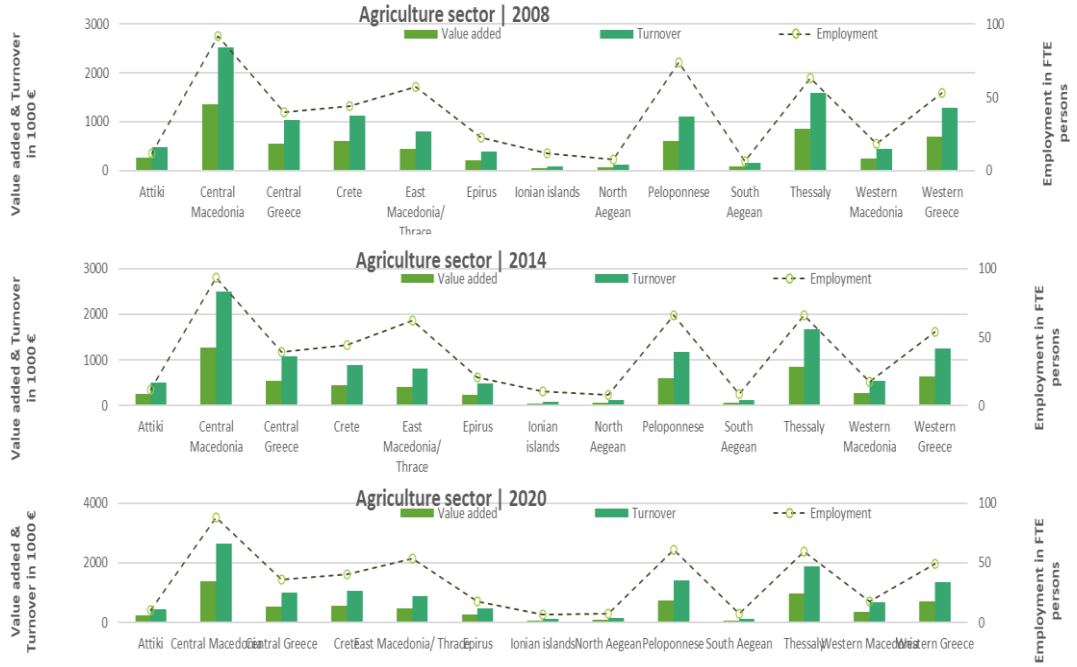


Figure 2-9 includes the research results of the temporal comparison of the three indicators i.e., value added, turnover, and employment for three key years: 2008, a year prior to the economic crisis; 2014, a year deep into the economic recession; and 2020, a year following the economic crisis period.

Across sectors, a highly uneven spatial distribution of bioeconomy activity is observed. The Attiki (Attica) region consistently ranks first or among the top performers in most industrial and manufacturing-oriented bioeconomy sectors, including biobased chemicals, paper, wood products and furniture, and food, beverage and tobacco. This dominance reflects the strong concentration of industrial capacity, research infrastructure, and market access in the metropolitan core.

In contrast, regions with a predominantly rural or peripheral profile tend to perform relatively better in primary-sector-oriented bioeconomy activities. Agriculture, forestry, and fishing and aquaculture display a more dispersed regional pattern, with several non-metropolitan regions achieving comparatively high rankings. However, even in these sectors, performance gaps between leading and lagging regions remain substantial.

Figure 3: Forestry sector in 2008,2014 and 2020 in 13 NUTS II regions of Greece.

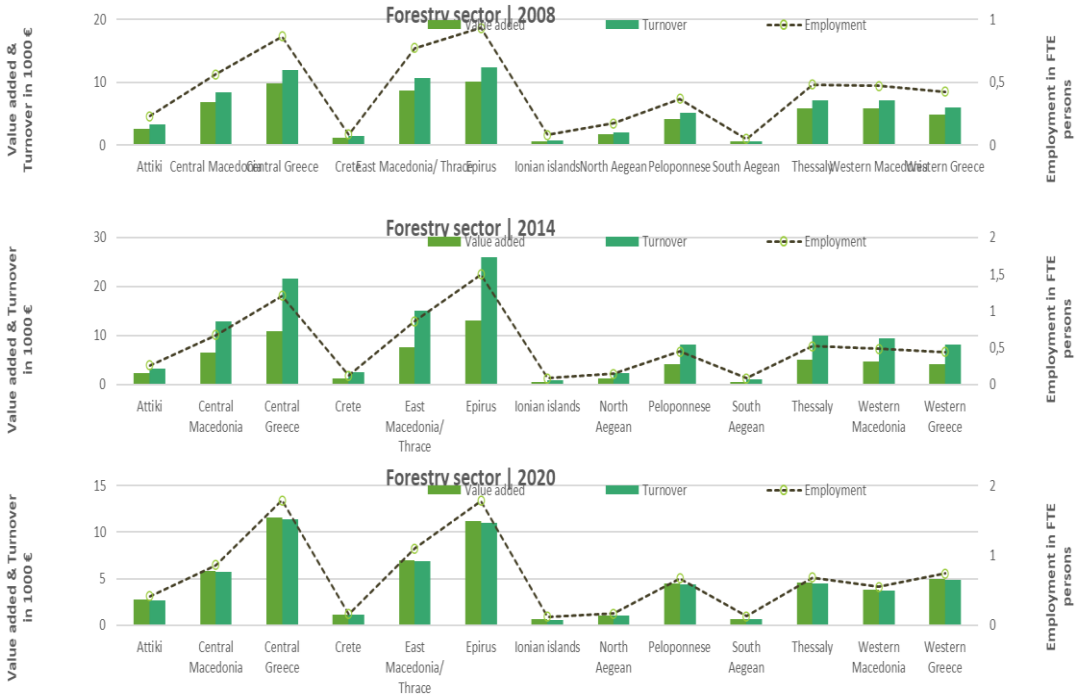


Figure 4. Fishing and aquaculture sector in 2008,2014 and 2020 in 13 NUTS II regions of Greece.



Figure 5. Food, Beverage and Tobacco sector in 2008,2014 and 2020 in 13 NUTS II regions of Greece.



Figure 6. Bio-based textiles sector in 2008,2014 and 2020 in 13 NUTS II regions of Greece.



Figure 7. Wood products sector in 2008,2014 and 2020 in 13 NUTS II regions of Greece.

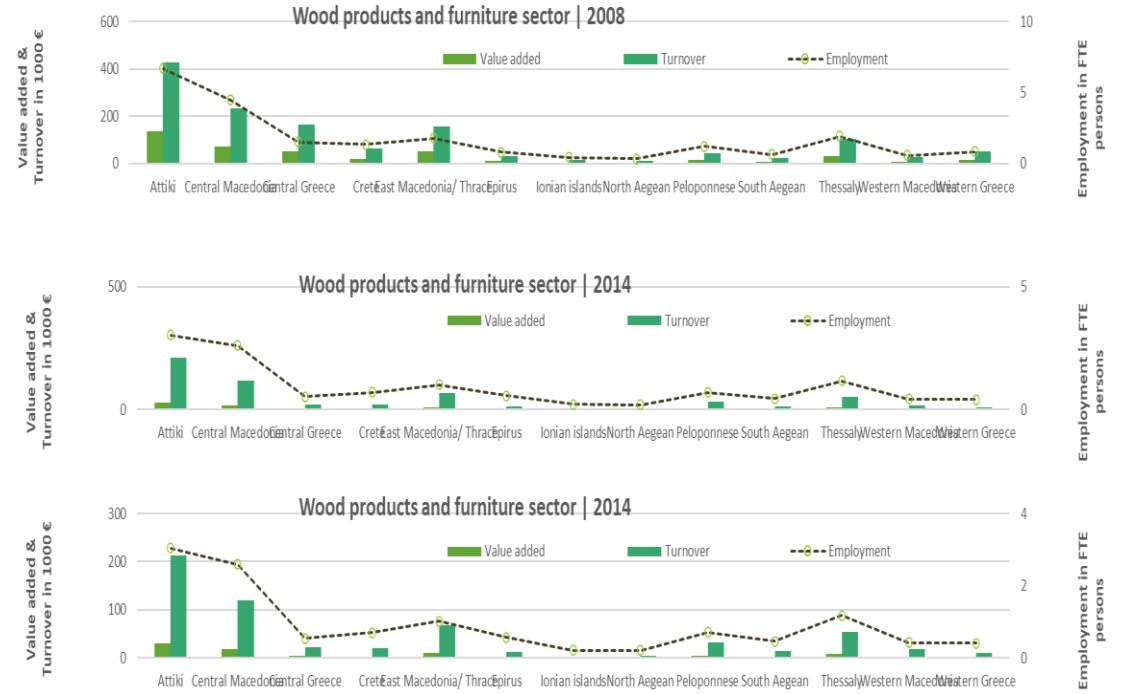


Figure 8. Paper industry sector in 2008,2014 and 2020 in 13 NUTS II regions of Greece.

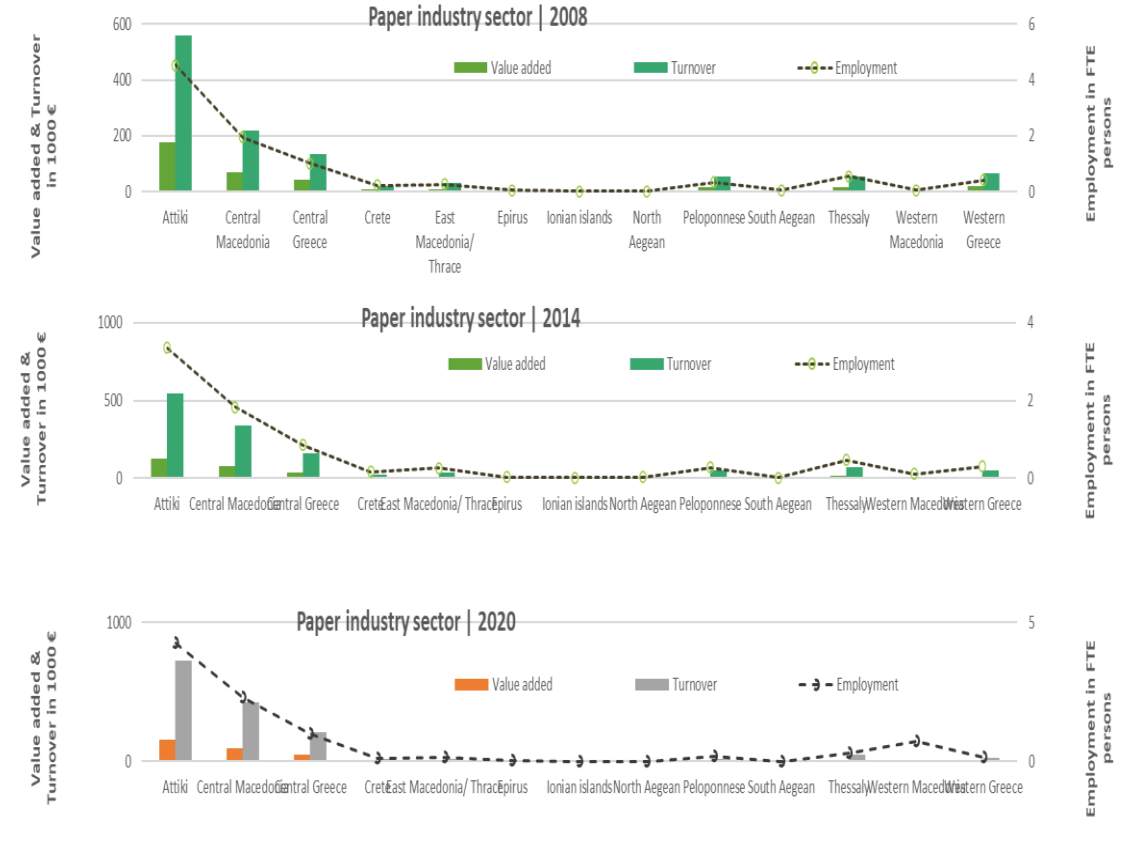


Figure 9. Bio-based chemicals sector in 2008,2014 and 2020 in 13 NUTS II regions of Greece.



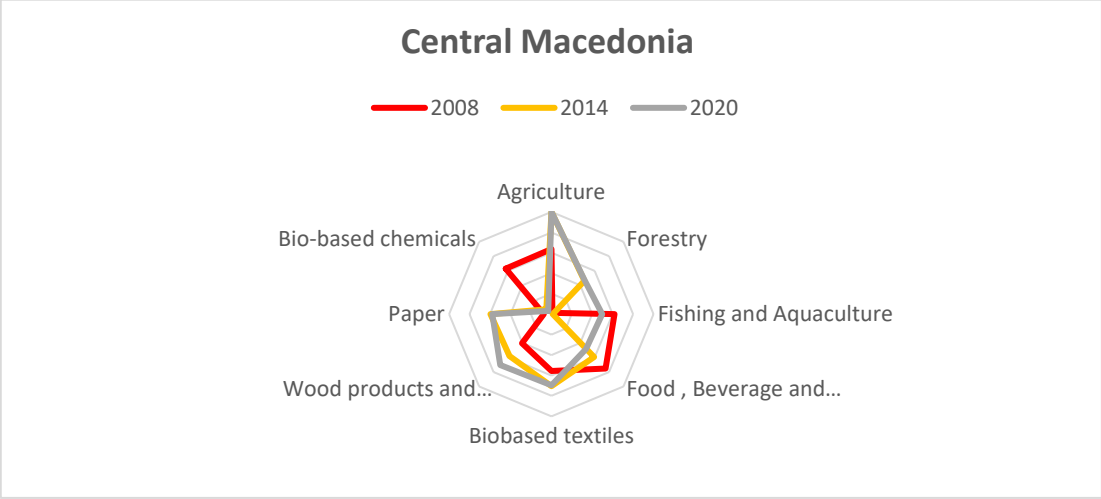
The fishing and aquaculture sector exhibits a distinctive regional pattern compared to industrial bioeconomy sectors. Coastal and island regions demonstrate relatively stronger performance, reflecting geographic endowments and long-standing sectoral traditions. Nonetheless, the overall ranking distribution indicates a limited number of regions with sustained high performance over time, while most regions display moderate to low scores.

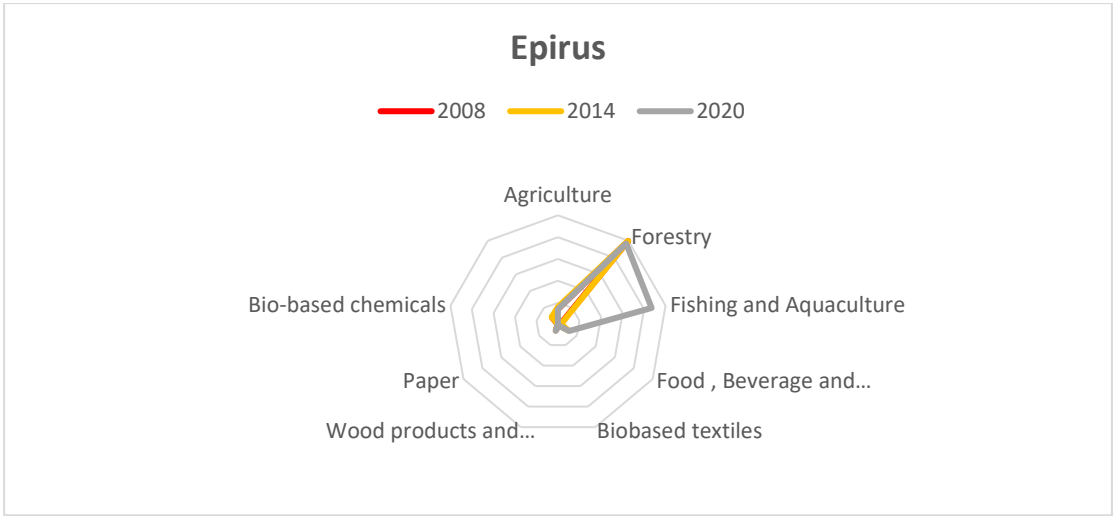
Temporal analysis suggests that the sector is characterised by slow recovery dynamics following the economic crisis period. Improvements in relative ranking are generally incremental rather than transformative, indicating structural constraints related to scale, technological upgrading, and integration into higher value-added segments of the bioeconomy.

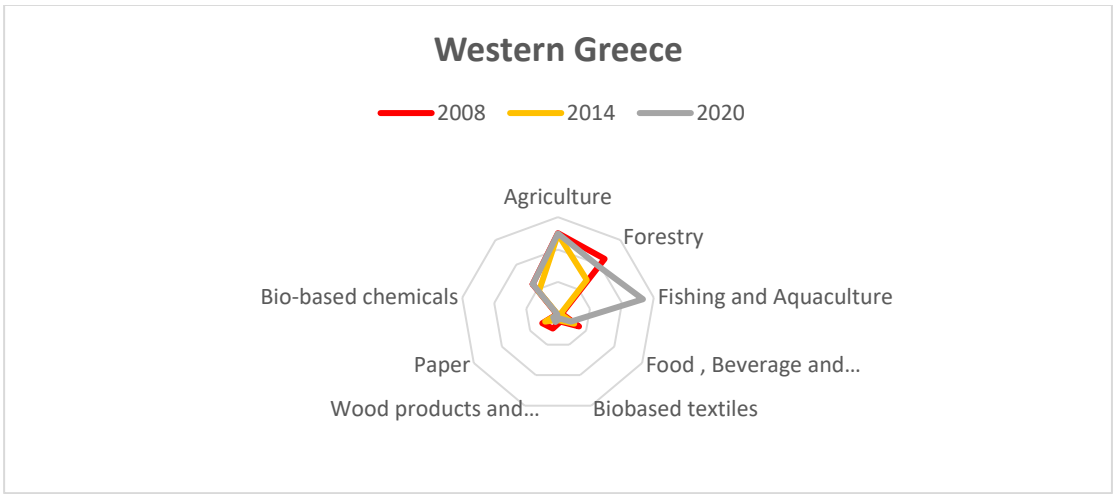
Another example is the biobased chemicals, pharmaceuticals, plastics and rubber sector, which is among the most concentrated bioeconomy sectors in Greece. Attiki's dominance is particularly pronounced, with a clear gap separating it from all other regions. This outcome reflects the capital-intensive nature of the sector, the need for advanced R&D capabilities, and proximity to national and international markets.

Other regions exhibit limited participation in this sector, and where activity exists, it tends to be small-scale or highly specialised. The ranking results highlight the challenges of achieving spatial diffusion of advanced biobased manufacturing activities beyond the metropolitan core under current structural conditions.
At a second stage, a TOPSIS was performed and the results for 3 Greek regions are presented *(Fig.10)*.

Figure 10. TOPSIS for Central Macedonia, Epirus and Western Greece.







These results reinforce the conclusions drawn from the descriptive ranking analysis. Attiki emerges as the benchmark region in most sectors, particularly those with higher technological and industrial intensity.

For other regions, TOPSIS scores indicate that improvements tend to be marginal and often insufficient to close the gap with the leading region. In several cases, regions cluster closely at low or medium performance levels, suggesting limited differentiation and weak competitive dynamics within specific sectors.

Importantly, the TOPSIS analysis also reveals that strong performance in one sector does not necessarily translate into strong performance across the bioeconomy. This finding underscores the fragmented nature of regional bioeconomy development in Greece and highlights the importance of sector-specific policy approaches.

5. Conclusions

Overall, the results confirm a highly asymmetric bioeconomy landscape in Greek NUTS II regions. Metropolitan dominance, sectoral specialisation, and strong path dependency define the current structure of the bioeconomy. Primary-sector-oriented activities offer some scope for regional differentiation, but they are generally characterised by lower value added and slower productivity gains.

The pilot nature of the analysis and its focus on available data limit the scope for causal interpretation. Nevertheless, the consistency of the results across scenarios, sectors, and time lends robustness to the main findings. The evidence points to the need for targeted, regionally differentiated bioeconomy strategies, improved data availability, and the development of more specific bioeconomy indicators to better capture structural change over time.

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Knowledge, aspects and habits of the residents of Zakynthos, regarding solid waste recycling in the island

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Abstract

Zakynthos Island has suffered severely for the last 18 years by the inefficient waste management, especially during peak seasons. The massive tourism growth since the decade of 1990, combined with the lack of timely planning, have caused serious environmental deterioration, irreversible in certain cases, whereas more often than not since 2015 garbage heaps have created the conditions for potential disease outbreak. The embarrassing photos picturing bins overflowing with garbage have repeatedly travelled around the world. Trying to capture the aspects of the residents of Zakynthos concerning the island's hottest issue, a questionnaire was designed, and distributed through the online version of the local newspaper "Imera" (www.imerazante.gr) and personal contacts. The answers gathered between August 20 and September 20, 2024 were processed and revealed interesting results. In the context of introducing new measures and policies, it is of critical importance to depict the current situation as accurately as possible and take into consideration the conclusions inferred by statistical analysis.

Keywords: *solid waste, recycling, local authority.*

JEL Codes: Q53; Q58.

Toward sustainable Waste for Electrical and Engineering Equipment indicators: Addressing missing values with Coverage mapping, Imputation and Validation

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Abstract

This paper maps data coverage and the morphology of missing values across 13 WEEE management operations for EU27 in 2005-2023. Coverage is profiled for each country and operation, and gaps are characterized by their position at the beginning or end of the series and by the longest interior run, which records timing and persistence. A transparent feasibility scheme converts these diagnostics into rules for action. Based on predefined criteria, five operations are selected for imputation: Products put on the market (MKT), Waste collected (COL), Recovery (RCV), Recycling and preparing for reuse (RCY_PRP_REU) and Waste treatment (TRT). Imputation follows a conservative, gap aware protocol. Linear interior interpolation with slope caps based on local first differences is applied. When needed, linear edge extension with geometric damping is performed, a zero floor keeps all imputed values including edge extensions non-negative and a complete audit trail is maintained to preserve the temporal structure. The resulting national series are aggregated to EU27 and are then validated against official Eurostat indicators, including Gross Domestic Product (GDP), Household final consumption expenditure (HFCE), Harmonized index of consumer prices (HICP), Retail trade volume index (RTV) and Population (POP). These external datasets provide the reference needed to confirm that the imputed values follow the wider European trends and remain coherent with related operations. Internal checks further assess cross operation consistency. The outcome is a reproducible pipeline that improves continuity without imposing artificial smoothing and delivers coherent time series ready for downstream modelling and comparative analysis.

Keywords: WEEE, missing values, imputation, external validation, Eurostat

JEL Codes: Q53; C81; C82; E01; C43.

1. Introduction

Waste electrical and electronic equipment (WEEE) is among the fastest-growing waste streams, driven by shorter product lifecycles and expanding consumption of electrical and electronic equipment (UNITAR et al., 2024). Its policy relevance stems from a dual character. WEEE contains hazardous substances that require controlled management, while also embedding recoverable materials that are increasingly important to the EU's circular economy and critical raw materials agenda (European Commission, 2020; European Parliament and Council, 2024). As a result, weak collection and substandard treatment can simultaneously increase environmental and health risks and reduce secondary material recovery (UNITAR et al., 2024).

In the European Union, the WEEE Directive establishes extended producer responsibility and quantitative obligations that are monitored through nationally reported time-series (European Parliament and Council, 2012). A key compliance route evaluates collection against 65% of the average equipment put on the market in the three preceding years, while an alternative route is defined with reference to WEEE generated (European Parliament and Council, 2012). Because the 65% route relies on a moving-average denominator, discontinuities in either the put-on-market series or the collected series can propagate into derived indicators. This complicates cross-country benchmarking even when only one component series is affected (European Parliament and Council, 2012). Recent monitoring continues to show uneven performance across Member States, which reinforces the practical need for robust and comparable time-series when interpreting compliance trajectories and policy gaps (European Environment Agency, 2025).

Eurostat provides the main public infrastructure for EU-wide WEEE statistics through annual country values across waste-management operations, supported by methodological metadata (Eurostat, 2025a, 2025b). In practice, administrative reporting can exhibit missingness that is clustered rather than random, including late starts, long interior gaps, and end-of-series omissions linked to reporting lags, revisions, and heterogeneous compilation capacity (Eurostat, 2025b). These patterns are not neutral. When gaps coincide with scope changes or institutional adjustments, naive treatments can impose dynamics that were never observed, and reconstructed values can be misread as substantive change (Little and Rubin, 2019). From an official-statistics perspective, any continuity improvement therefore needs transparent rules and documented quality criteria so that the provenance of each value remains clear (International Monetary Fund, 2003; United Nations, 2014; Eurostat, 2017).

This paper develops an audit-first workflow to improve continuity in Eurostat WEEE time-series for the EU27 over 2005-2023, with decisions and parameters recorded to support reproducibility (Peng, 2011; Sandve et al., 2013). The approach maps reporting coverage, diagnoses gap structure, and applies conservative reconstruction only where country series remain sufficiently anchored to support defensible gap filling, consistent with evidence that

reconstruction risk depends strongly on gap position and duration (Khayati et al., 2020). The workflow is then applied to five operations that are central to EU monitoring and exhibit adequate continuity for repair and aggregation of MKT, COL, RCV, RCY_PRP_REU and TRT (Eurostat, 2025a, 2025b). External coherence checks against Eurostat macroeconomic and demographic indicators provide an additional plausibility layer for reconstructed trajectories, aligned with documentation and stability principles used in official statistics (Eurostat, 2017, 2025c).

2. Literature review

WEEE policy performance in the European Union is evaluated through indicators that must be comparable across Member States and stable over time. The WEEE Directive formalizes binding collection and recovery obligations and specifies alternative compliance routes, including a 65% collection target calculated against the average equipment placed on the market in the three preceding years. Because the collection rate combines both collected and placed-on-market series, discontinuities in either component can mechanically shift reported rates and complicate interpretation, even when underlying performance has not changed materially. For this reason, policy and technical discussions treat time-series integrity as a practical condition for credible benchmarking and policy inference (European Parliament and Council, 2012).

EU-wide empirical assessments rely primarily on Eurostat's WEEE database, which provides annual country values across multiple waste-management operations and is supported by reference metadata on definitions, scope, and comparability (Eurostat, 2025a, 2025b). A consistent theme in the official-statistics literature is that missing values in administrative series tend to be structured rather than isolated, appearing as delayed starts, contiguous interior gaps, or end-of-series omissions linked to reporting lags, revisions, methodological updates, and heterogeneous compilation capacity. This structure matters because it influences both the defensibility of reconstruction and the uncertainty that should be associated with any filled segment, especially when gaps coincide with institutional or measurement changes (Eurostat, 2025b, 2017).

From a missing-data perspective, official reporting gaps are rarely compatible with a missing completely at random assumption. A missing at random mechanism can sometimes be used as a pragmatic working model when non-reporting is plausibly related to observed information, such as earlier values, auxiliary covariates, or documented breaks in reporting practice, but credibility still depends on explicit choices and transparent justification (Rubin, 1987; Little and Rubin, 2019). Where missingness is driven by unobserved values or unrecorded structural shifts, a missing not at random mechanism becomes more plausible, and imputation can introduce systematic bias if the mechanism is ignored (Little and Rubin, 2019). In policy-facing settings, this reinforces the need to prioritize auditability and interpretability over aggressive attempts to reconstruct short-term variability (Eurostat, 2017).

Methodologically, time-series imputation spans deterministic rules, such as interpolation, and model-based approaches. Comparative evaluations consistently show that performance depends strongly on gap length and position, with boundary gaps and long runs typically involving higher risk than short interior gaps (Khayati et al., 2020). In inferential contexts, multiple imputation is often recommended because it propagates uncertainty across several plausible datasets and can be implemented under missing at random assumptions, for example via chained equations (Rubin, 1987; Buuren and Groothuis-Oudshoorn, 2011). By contrast, when the objective is a transparent reporting series for monitoring and benchmarking, official-statistics practice often favors conservative single-imputation approaches paired with explicit flags and diagnostic reporting, because this supports traceability and enables sensitivity checking (Eurostat, 2017; Peng, 2011; Sandve et al., 2013).

Within the WEEE domain, research also notes that monitoring based solely on aggregated weight can obscure differences in material composition and the recovery of valuable or critical substances, motivating complementary indicators and stronger data foundations (Arduin et al., 2020). Reviews and policy studies further document persistent gaps between e-waste generated and formally collected, and they highlight that cross-country variation reflects not only operational performance but also measurement and reporting arrangements (European Commission, 2014; Baldé et al., 2020; UNITAR et al., 2024). Together, these strands support a morphology-aware and conservative approach to missing WEEE values that couples coverage diagnostics with cautious reconstruction and transparent validation, so that trends remain interpretable and comparable for policy use (Khayati et al., 2020; Eurostat, 2017; Little and Rubin, 2019).

3. Data and study design

The empirical basis of this study is Eurostat's WEEE database, which provides annual country series intended to support EU-wide monitoring and cross-country comparison under harmonized definitions and reporting rules (Eurostat, 2025a). Because these series are used in compliance monitoring and policy interpretation, continuity and comparability are treated as first-order quality requirements, consistent with the European Statistics Code of Practice (Eurostat, 2017).

The study covers 2005-2023 for the EU27 Member States. The unit of analysis is a country-operation annual time-series. Each series is treated as an administrative reporting product that may contain discontinuities, rather than as a fully observed stochastic process. This framing keeps attention on what the source can credibly support and on how gaps can distort both trend interpretation and between-country comparisons (Eurostat, 2025b, 2017).

The study design therefore begins with coverage mapping and gap-morphology characterization. Missing values are not handled automatically. They are diagnosed first

because reconstruction credibility depends on whether missing segments are short and locally anchored or instead reflect systematic non-reporting patterns. On that basis, imputation is restricted to operations where missingness is sufficiently limited to allow conservative, gap-aware repair without manufacturing long histories that the source does not justify (Eurostat, 2025b, 2017). The workflow proceeds with five policy-relevant operations that are central to EU monitoring and empirically amenable to continuity improvement under conservative rules: MKT, COL, RCV, RCY_PRP_REU and TRT (Eurostat, 2025a).

For these operations, the reconstruction protocol is intentionally designed to be simple, explicit, and repeatable. Repairs are performed with local rules that limit intervention, preserve anchoring in observed values, and constrain reconstructed values to remain non-negative. The procedure is deterministic, meaning that fixed inputs and parameters yield fixed outputs, which supports auditability and facilitates sensitivity checks without embedding key decisions inside opaque model fitting (Eurostat, 2017).

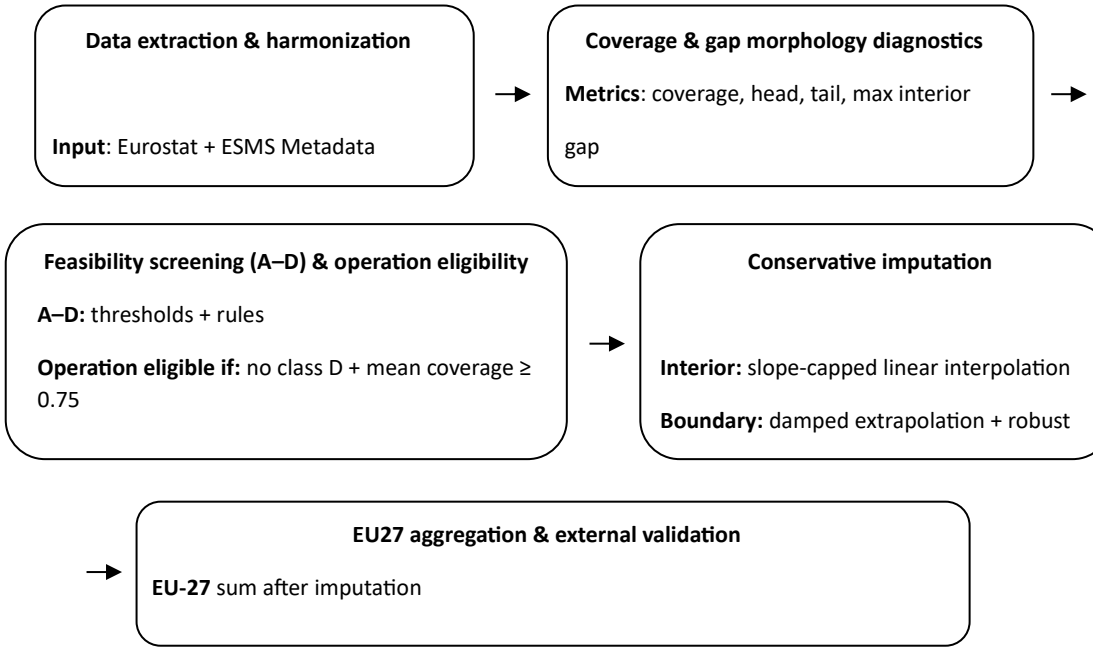
After country-level series are repaired, EU27 totals are computed by summing across Member States. Aggregation is performed after imputation to avoid propagating missingness into EU totals and to keep provenance anchored at the country-operation level (Eurostat, 2017). External validation then benchmarks reconstructed trajectories against official Eurostat macroeconomic and demographic indicators used as broad coherence references, including GDP, HICP, retail trade volume and turnover indicators, and population (Eurostat, 2025c, 2025d, 2025e, 2025f). These checks are not presented as causal explanations. They operate as plausibility screens to reduce the risk that repaired series drift into idiosyncratic patterns that are difficult to reconcile with wider European dynamics.

Finally, the study is implemented as a reproducible pipeline that records reconstruction points and parameter choices, enabling downstream users to distinguish observed from imputed values and to rerun the procedure under alternative parameterizations where sensitivity is a concern (Eurostat, 2017).

4. Methodology

This study applies an audit-first workflow to construct continuity-improved annual WEEE time-series from Eurostat reporting. The workflow is designed to be reproducible and transparent. It moves from coverage and gap-morphology diagnostics to feasibility screening, conservative country-level imputation, EU27 aggregation, and external validation with stability checks and a composite plausibility index (Eurostat, 2025a, 2017; United Nations, 2014; Khayati et al., 2020).

Figure 1. Workflow for auditing, reconstructing, and validating Eurostat WEEE time-series.



4.1. Data extraction and harmonization

Annual country series are extracted from Eurostat's WEEE database and interpreted using the accompanying ESMS metadata to ensure consistent definitions, scope, and comparability (Eurostat, 2025a, 2025g). To preserve traceability under potential revisions, dataset identifiers and retrieval dates are recorded, in line with official-statistics quality principles and reproducible research practice (Eurostat, 2017; Peng, 2011; Sandve et al., 2013). The reference window is 2005-2023 and the analytical unit is a country-operation annual series.

4.2. Coverage and gap-morphology indicators

Missingness is treated first as a reporting property to be diagnosed before any filling is attempted. For each country-operation series, coverage is computed as the proportion of years in 2005-2023 with a valid reported value, yielding a normalized indicator on [0,1]. Coverage alone can be misleading, so three additional morphology indicators are computed to describe how gaps are distributed over time: head gap (initial consecutive missing years), tail gap (terminal consecutive missing years), and maximum interior gap (longest run of missing years bounded by observed values). These descriptors are used because imputation risk depends strongly on where gaps occur, and boundary gaps are generally more assumption-sensitive than short interior gaps (Khayati et al., 2020).

4.3. Feasibility classification and operation-level eligibility

Each country-operation series is assigned to a feasibility class (A-D) using explicit thresholds that combine coverage and gap morphology. The classification provides a transparent basis for deciding whether conservative reconstruction is defensible. Class A indicates strong anchoring, class B indicates acceptable completeness with modest gaps, class C indicates moderate completeness requiring strict caution, and class D captures structurally discontinuous cases without sufficient anchors (Little and Rubin, 2019).

Table 1. Feasibility classes (A-D) based on coverage, gap morphology and operation-level eligibility rules for conservative reconstruction.

Feasibility class	Coverage threshold	Head gap	Tail gap	Max interior gap	Interpretation
A	≥ 0.80	≤ 2	≤ 1	≤ 1	High completeness and strong anchoring; conservative reconstruction is considered methodologically safe when needed
B	≥ 0.70	≤ 4	≤ 2	≤ 2	Good completeness with modest gaps; reconstruction is acceptable under conservative, local rules
C	≥ 0.50	≤ 6	≤ 6	≤ 4	Moderate completeness; reconstruction only under strict caution and conservative constraints
D	Otherwise (fails A-C thresholds)	-	-	-	Insufficient anchoring / structurally discontinuous; reconstruction is not considered defensible

Eligibility is decided at the operation level to avoid selectively repairing only well-documented countries and thereby changing cross-country representativeness. Operations are excluded if any country series is class D. Otherwise, they proceed only if mean coverage across countries is at least 0.75 (Eurostat, 2017; Khayati et al., 2020; United Nations, 2014).

4.4. Conservative imputation protocol for country series

Imputation is intentionally local and morphology-aware, with the method determined by whether missingness occurs within an observed segment or at the beginning or end of the series. Short interior gaps are filled using linear interpolation between adjacent observed endpoints. Annual changes are constrained using slope caps derived from each series' observed first-difference behavior to reduce implausible step changes and prevent isolated repairs from distorting local dynamics (Khayati et al., 2020; Hyndman and Athanasopoulos, 2021).

Boundary gaps are treated separately because they require extrapolation. The protocol estimates a local boundary slope from the nearest observed segment and extends it outward using geometric damping, so that the influence of the extrapolated trend decays with distance from observed anchors. This follows the logic of damped-trend approaches, which are used to avoid overconfident long-horizon extrapolation when trend persistence is uncertain (Gardner and McKenzie, 1989; McKenzie and Gardner, 2010). When slope estimation is sensitive to isolated fluctuations, a robust slope estimator is used to stabilize directionality before damping is applied (Sen, 1968). Reconstructed values are constrained to be non-negative and are flagged to distinguish reported from imputed points. The procedure is deterministic conditional on fixed parameters to support exact replication and transparent sensitivity checks (Eurostat, 2017; Khayati et al., 2020; United Nations, 2014).

4.5. EU27 aggregation

After country-level repair, EU27 totals are computed by summation across Member States for each operation and year. Aggregation is performed after imputation to prevent EU totals from inheriting missingness driven by a single country series. This sequencing also preserves an audit trail that supports attribution of EU-level changes to observed versus reconstructed components (Eurostat, 2025a, 2017; United Nations, 2014).

4.6. External validation, stability checks, and composite index

External validation assesses whether reconstructed trajectories remain coherent with independent Eurostat macroeconomic and demographic indicators used as broad alignment references, including GDP, household final consumption expenditure, HICP, retail trade indicators, and population (Eurostat, 2025c, 2025d, 2025e, 2025f). Coherence is examined using complementary diagnostics, including first-difference correlation, log-growth correlation, and log-level regression. Using multiple views reduces reliance on any single criterion and aligns interpretation with established guidance on correlation use and forecast evaluation (Hyndman and Koehler, 2006; Schober et al., 2018).

Country-level documentation labels are assigned through a majority rule across three positive criteria derived from the best-performing external driver for each country and operation, yielding sufficiently documented (ET), marginally documented (OT), and insufficiently documented (AT) outcomes. Temporal stability is assessed by examining whether conclusions persist across subperiods and under small perturbations of thresholds. Finally, a composite validation index (CVI) summarizes label distribution, fit quality, and stability on a 0-100 scale, following composite-indicator guidance and official-statistics quality principles (Nardo et al., 2005).

5. Results

This section reports what the workflow yields in practice. It begins with a coverage and gap-morphology audit across the Eurostat WEEE operations, then summarizes the imputation footprint for the operations that pass the eligibility rules, presents the external validation outcomes for reconstructed country series, and concludes with implications for EU27 aggregates and downstream use.

5.1. Coverage mapping and readiness for imputation across the 13 operations

The coverage audit shows substantial heterogeneity across the 13 WEEE management operations, even under a common reference window (2005-2023) and a uniform reporting framework. Using the 27-country by 19-year grid (513 potential observations per operation), the heatmap indicates that usable longitudinal signal is concentrated in a small subset of operations. In several operations, series onset is delayed for many countries and historical anchoring is weak, which makes conservative reconstruction difficult to justify at scale.

Table 2. Coverage and feasibility summary for the five eligible operations (2005-2023).

Operation	Mean coverage	Missing values (out of 513)	Feasibility classes A/B/C/D
COL	90.64%	48	25 / 2 / 0 / 0
MKT	91.81%	42	27 / 0 / 0 / 0
RCV	85.96%	72	19 / 7 / 1 / 0
RCY_PRP_REU	86.35%	70	19 / 8 / 0 / 0
TRT	89.28%	55	23 / 4 / 0 / 0

Applying the eligibility rules, five operations meet the criteria for conservative reconstruction because they combine high mean coverage with no class-D country series. These are COL, MKT, RCV, RCY_PRP_REU, and TRT. All five exceed the 0.75 mean-coverage threshold and retain anchors across the full window for every country, which limits

reconstruction exposure to short, locally supported segments rather than long, model-dependent histories (Khayati et al., 2020; Little and Rubin, 2019).

In contrast, the remaining operations are excluded either because mean coverage is very low or because class-D series are present, implying insufficient anchoring for defensible reconstruction. Indicatively, waste generated is extremely sparse and includes many structurally discontinuous series. Recycling (RCY) does not contain class-D series, but its mean coverage remains low, so the historical structure is too incomplete for safe gap filling at scale. Some operations exhibit relatively high mean coverage while still failing eligibility due to class-D presence, notably cross-border or location-specific treatment series, where reconstruction would weaken comparability and complicate EU-level traceability.

5.2. Imputation footprint in the five eligible operations

Across the five eligible operations, reconstruction confirms that missingness is largely an early-window phenomenon. Most fills occur in 2005 and 2006, with a smaller number near 2022-2023, while interior gaps are comparatively rare and usually limited to single-year breaks, distribution which is important for interpretation. The protocol intervenes mainly where reporting begins late and leaves mid-window dynamics largely anchored in observed values rather than reshaped by long interpolated segments.

At operation level, the required fills remain modest relative to the full grid and follow a consistent pattern. Once reporting starts for these operations, it tends to remain stable, so the reconstruction burden falls primarily on the first one to three years of the window. Terminal fills are limited in all five operations, indicating broadly strong recent completeness, although not uniformly across all countries.

5.3. External validation outcomes for reconstructed values

External validation indicates that reconstructed trajectories remain broadly coherent with independent macroeconomic and demographic series for most countries across all five operations. Documentation labels are dominated by ET and OT, while AT classifications are confined to a minority of cases. This is consistent with an anchor-preserving protocol. It produces continuity-improved series that remain stable and interpretable, while still leaving persistent borderline cases visible rather than smoothing them away.

Table 3 summarizes validation outcomes at operation level. Country-level diagnostics are retained for supplementary material because they are informative for audit and sensitivity analysis but too granular for the core results narrative. Two points are worth noting. First, MKT performs particularly strongly among the series requiring reconstruction, with no AT cases and

the highest operation-level validation index. Second, TRT is the most conservative case in the validation layer, with a higher share of AT than the other operations, even though stability remains very high. This indicates that the weaker score reflects a small set of persistently marginal cases rather than volatile classifications that flip under minor rule changes.

Table 3. External validation summary for imputed country series (countries requiring imputation only).

Operation	Countries validated	Labels (ET / OT / AT)	Operation-level validation index	Stability (scenario agreement)
COL	20	30% / 60% / 10%	72.0%	High (most labels unchanged)
MKT	20	50% / 50% / 0%	82.5%	Very high (near-unanimous)
RCV	25	44% / 48% / 8%	77.6%	Very high (median agreement 100%)
RCY_PRP_REU	25	36% / 60% / 4%	76.2%	Very high (mean ~98%, median 100%)
TRT	22	22.7%/ 63.6%/ 13.6%	68.2%	Very high (mean ~98%, median 100%)

Across operations, the same few countries tend to reappear among the lower-performing cases in this dataset, which is analytically useful. It suggests where additional documentation, coverage improvement, or targeted sensitivity testing would add the most value for EU-wide comparability.

5.4. Implications for EU27 aggregates and downstream analysis

After reconstruction, the five eligible operations become fully continuous over 2005-2023 at country level, allowing EU27 aggregation without mechanically inheriting missingness from individual national gaps. This sequencing preserves traceability because EU totals remain a transparent sum of either reported or explicitly flagged reconstructed values, rather than a direct imputation on an already aggregated series that would obscure provenance. Taken together, the coverage audit, the limited and front-loaded imputation footprint, and the stable external validation outcomes support using these continuity-improved series as the operational backbone for subsequent comparative analysis and modelling steps.

6. Discussion and conclusions

The results show that missingness in EU WEEE reporting is strongly operation-specific, even within Eurostat's harmonized dissemination framework. Several operations remain structurally sparse across 2005-2023, while a smaller subset provides the continuity and anchoring needed for defensible EU-wide interpretation. This matters for policy indicators because compliance-relevant rates depend on the stability of the underlying operational series. Discontinuities can propagate into derived metrics and distort comparisons across time and countries.

A central implication is that gap handling should not be approached as a generic missing-values exercise. Reconstruction risk depends on gap position and contiguity, and the risk profile differs substantially across operations. In the eligible operations, missingness is dominated by early-window head gaps, which is consistent with a gradual maturation of administrative reporting and stabilization of compilation practice. Boundary gaps are more assumption-sensitive because they require extrapolation with weaker anchoring, whereas short interior gaps are bounded by observed endpoints and are typically less risky to repair. The feasibility screen therefore functions as a guardrail. It restricts reconstruction to operations that remain anchored across all countries and excludes cases where filling would amount to creating long histories that the source does not support (Khayati et al., 2020; Little and Rubin, 2019; Eurostat, 2017; United Nations, 2014).

For the eligible operations, the imputation strategy is deliberately conservative and aligned with official-statistics expectations on transparency and auditability (Eurostat, 2017). Slope-controlled interpolation is used only for short interior breaks. For boundary gaps, damped extrapolation retains local direction while limiting long-horizon influence, consistent with damped-trend logic used to reduce overconfident extensions when trend persistence is uncertain (Gardner and McKenzie, 1989; McKenzie and Gardner, 2010). Robust slope estimation reduces sensitivity to isolated annual fluctuations that can arise from revisions or reporting shifts (Sen, 1968). The outcome is a continuity-improved series in which interventions remain limited, explicitly flagged, and reproducible under fixed parameters.

External validation provides an additional plausibility layer. Reconstructed trajectories are generally coherent with independent Eurostat macroeconomic and demographic indicators, and stability checks indicate that conclusions are not driven by narrow thresholds. The composite framing treats credibility as a combination of documentation, fit, and stability rather than a single statistic. This helps keep marginal cases visible instead of forcing binary pass or fail judgements (Nardo et al., 2005; Schober et al., 2018).

There are clear limitations. The procedure produces single deterministic imputations rather than propagating uncertainty as in multiple imputation, and validation is a coherence check rather than a causal model. Boundary reconstruction remains more assumption-sensitive than interior repair and should be interpreted accordingly. Even so, the integrated audit-first design provides a defensible basis for EU27 aggregation and more consistent indicator construction. It also highlights where improved national documentation and coverage would yield the largest gains in comparability and interpretability (Peng, 2011; Eurostat, 2017).

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Session 6.

Digitization in Sustainable Tourism

The Digitization of Archaeological Museums as a tool for Sustainable Tourism and Local Development: Evidence from Central Macedonia Greece

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Abstract

The current paper examines the role and impact of the digitization in archaeological museums, focusing on the developments that have been occurred in the case of Central Macedonia, Greece. The research explores how digital technologies such as multimedia applications, virtual and augmented reality, are being used to improve visitor experience, extend accessibility, and encourage inclusion, especially for people with disabilities. By interviewing local museum representatives and analyzing current practices, the study identifies both the opportunities and the challenges of adopting digital strategies in cultural heritage management. The findings indicate that digitization can contribute to sustainable tourism by attracting a wider audience, increasing visitor numbers, and increasing the involvement of museums in the local economy. Furthermore, the paper emphasizes the importance of the role of digital transformation in supporting environmental and cultural policy tools that can support a long-term local development and sustainable cultural tourism. This information provides useful information for local authorities, tourism and cultural professionals and whomever might be interested in embracing innovation for cultural and economic development.

Keywords: *Sustainable Cultural Tourism, Digital Innovation, Regional Development, Environmental Sustainability, Multimedia Applications*

JEL Codes: Z32; Q55; R11; Q56; L82

1. Introduction

1.1. Research Scope

The integration of digital technologies and multimedia in archaeological museums constitutes a key development in contemporary cultural heritage management. Technologies such as Virtual Reality (VR), Augmented Reality (AR), and interactive multimedia enhance visitor engagement, support museum education, and expand accessibility, while contributing to cultural tourism and local economic development. Digital tools—including virtual museums, mobile applications, and online collections—enable new forms of interaction with cultural content beyond the physical museum space.

Greek archaeological museums, established primarily in the 19th century, were initially linked to the construction of national identity and the preservation of cultural heritage. Over time, and particularly in the 21st century, these institutions have adapted to changing social and tourism demands by incorporating digital and interactive technologies (Voudouri, 2013; Chourmouziadis, 2006; Mouliou, 2016). The development of hybrid and virtual museum environments reflects a broader shift towards participatory, accessible, and visitor-oriented museology.

The use of VR and AR allows for immersive and personalized experiences, facilitating virtual exploration of archaeological sites and enhanced interpretation of exhibits (Pavlogeorgatos et al., 2022; Liapi, 2018). International initiatives, such as META-MUSEUM and Metaseum, illustrate the growing role of digital platforms in extending museum outreach and promoting cultural tourism at a global level.

Museums increasingly function as drivers of cultural branding and local development. Through strategic digitalization, major institutions enhance visibility, accessibility, and educational impact, reinforcing their role within contemporary cultural tourism networks (Schweibenz, 2019; Piekkola et al., 2014).

1.2. Digitalization and Tourism

Information and Communication Technologies (ICT) have reshaped tourism through e-tourism practices, including online promotion, digital ticketing, mobile applications, and interactive guides. In the Greek context, ICT facilitates pre-visit planning, on-site engagement, and post-visit interaction, strengthening the tourism experience and supporting museum visibility and regional development (Buhalis, 2004; Sheldon, 1993; Poon, 1993).

1.3. Challenges and Research Focus

Despite their potential, digital initiatives face challenges related to funding, infrastructure, and staff training, while ensuring accessibility for diverse audiences remains a key concern. This study examines the implementation of VR, AR, and multimedia tools in archaeological museums of Central Macedonia, focusing on their contribution to visitor engagement, museum education, accessibility, and tourism-driven development.

2. Theoretical Framework and Evolution of Museums

2.1. Museums, Cultural Tourism, and Local Development

Museums are central cultural institutions whose role has expanded from collection preservation to education, social engagement, and contribution to local development. Within cultural tourism, museums enhance destination identity, support place branding, and stimulate economic activity through increased visitation and related services (Schweibenz, 2019; Wallace, 2006).

Cultural branding allows museums to differentiate themselves through thematic narratives and digital outreach, while flagship institutions often act as catalysts for urban regeneration and tourism growth (Răzvan & Ruxandra, 2013). In Greece, museums such as the Acropolis Museum demonstrate how international visibility and digital strategies reinforce heritage promotion and economic sustainability (Mouliou, 2016; Ntaflou, 2011).

2.2. Archaeological Museums in Greece

Greek archaeological museums emerged in the 19th century as instruments of nation-building, linking antiquities to national identity (Chourmouziadis, 2006). During the 20th century, increasing tourism and educational demands encouraged gradual shifts towards visitor-oriented approaches, despite the absence of a unified museum policy (Petrakos, 2011).

From the late 20th century onwards, museums increasingly adopted educational, social, and technological roles, responding to contemporary audiences and positioning themselves as dynamic cultural institutions (Plantzos, 2017).

2.3. Digital Technologies in Museums

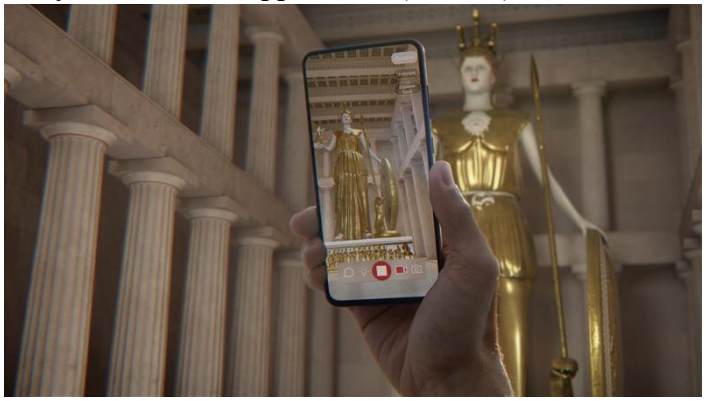
Digital technologies have transformed museum interpretation and communication through multimedia applications, mobile platforms, and online collections (Hermon & Hazan, 2014). VR enables immersive reconstructions and remote access, while AR enriches physical exhibits with contextual digital information (Karagianni, 2019; Pavlogeorgatos et al., 2022).

Artificial Intelligence (AI) further enhances museum functionality by enabling personalized content delivery, intelligent guidance systems, and data-driven management. AI-supported tools contribute to the development of "smart" museums, improving learning outcomes, accessibility, and institutional efficiency (Skamantzari et al., 2016; Mello et al., 2024).

2.4. ICT, E-tourism, and Cultural Heritage

ICT plays a central role in cultural heritage tourism by facilitating access to information, interpretation, and audience engagement (Buhalis, 2004). In Greece, digital platforms, mobile applications, and QR codes support interactive and personalized museum experiences, although implementation remains uneven across institutions. Effective ICT integration contributes to sustainable tourism strategies and enhances competitiveness within the cultural sector.

Figure 1. CHRONOS by COSMOTE Application (AR use)



2.5. The CHRONOS Application

CHRONOS is a digital application developed by COSMOTE in collaboration with the Hellenic Ministry of Culture, combining AR, AI, and 5G technology to enhance museum and site interpretation (Fig. 1). Implemented at major cultural sites, it exemplifies the potential of integrated digital solutions to support experiential learning, accessibility, and audience engagement.

3. Methodology

This study employs a three-phase methodological framework to document and analyze digital technologies used by archaeological museums in Central Macedonia, with particular emphasis on the Polycentric Museum of Aigai and its digital platform.

3.1. Documentation of Museums

Six institutions were examined: the Polycentric Museum of Aigai, the Archaeological Museums of Thessaloniki, Kilkis, Pella, and Amphipolis, and the Experiential Park of Leibethra. Data was collected through comparative tables documenting institutional characteristics and digital features, including websites, digital collections, virtual tours, mobile applications, AR/VR tools, audiovisual media, and QR codes. Digital adoption was recorded using binary indicators to enable comparative analysis.

3.2. Structured Interviews

Structured interviews were conducted with museum representatives between November 2024 and January 2025, aiming to contextualize documented data and explore challenges and future digital strategies (Robson, 2007). Interviews focused on digital tools, accessibility, and institutional priorities. Additional case-specific data for the Archaeological Museum of Thessaloniki are presented in Appendix A, while remaining interviews are included in Appendix B.

3.3. Analysis of Findings

Interview data were analyzed thematically. The Archaeological Museum of Thessaloniki was examined separately due to its advanced digital infrastructure. Regional museums were analysed collectively, while the Polycentric Museum of Aigai was treated as a distinct hybrid case combining physical and digital heritage interpretation.

4. Interview Results

4.1. Comparative Digital Maturity

The Archaeological Museum of Thessaloniki demonstrates advanced digital integration, supported by a comprehensive website, mobile applications, audiovisual installations, and accessibility-oriented digital tools. Although VR and AR are not yet fully embedded, experimental applications and inclusive initiatives indicate a coherent digital strategy.

By contrast, the museums of Kilkis, Amphipolis, and Pella exhibit limited digital maturity, relying mainly on centralized platforms and basic informational content. Funding constraints and institutional dependencies remain significant barriers, despite increasing awareness of the importance of digitalization.

The Experiential Park of Leibethra represents an intermediate but innovative model, integrating multimedia tools, QR codes, and accessibility-focused digital practices to support experiential learning.

4.2. Polycentric Museum of Aigai

The Polycentric Museum of Aigai (Fig. 2) constitutes a flagship example of hybrid heritage management, integrating monuments, landscape, and digital interpretation. Its Digital Museum, "Alexander the Great: From Aigai to the Oikoumene," extends interpretation globally through an online platform structured into thematic sections and multimedia content. The initiative highlights the role of digital heritage in cultural diplomacy and international outreach.

Figure 2. The Polycentric Museum of Aigai

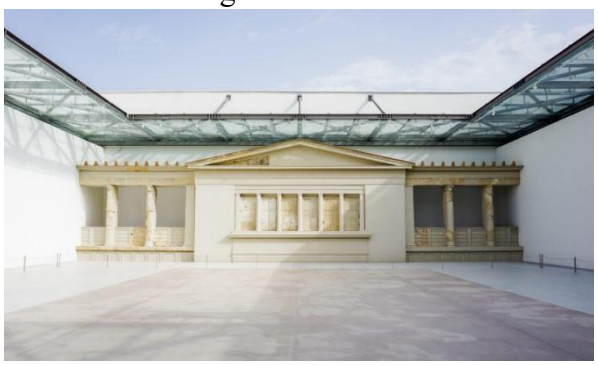


Figure 3. Comparative overview of digital tools implemented in archaeological museums of Central Macedonia.

Museum	Polycenter Museum of Aigai/ Digital Museum	Archaeological Museum of Thessaloniki	Archaeological Museum of Kilkis	Archaeological Museum of Pella	Archaeological Museum of Amphipolis	Experiential Park of Leibethra
Social media	Yes	Yes	Yes	Yes	Yes	Yes
Newsletter	No	Yes	No	No	No	No
Digital Collection of Exhibits	Yes	Yes	Yes	Yes	Yes	Yes
Virtual Tour 360°	No	No	No	No	No	No
Use of AR/VR	No	Yes	No	No	No	No
Screens/ Projectors	Yes	Yes	No	No	No	Yes
QR Codes	Yes	Yes	No	No	No	Yes
Mobile/ Tablet apps	No	Yes	Yes	No	Yes	Yes

4.3. Synthesis

Overall, findings reveal uneven but evolving digital development among archaeological institutions in Central Macedonia (Fig3). While leading museums demonstrate strategic digital integration, regional institutions remain constrained by structural limitations. Digital tools are perceived as complementary to traditional practices, enhancing accessibility, visitor engagement, and cultural tourism, underscoring the need for coordinated digital strategies and policy support.

5. Conclusions and Policy Recommendations

5.1. Comparative Conclusions

This study investigated the extent and forms of digitalization implemented in selected archaeological museums and cultural sites in Central Macedonia, identifying both best practices and structural constraints. The findings reveal a heterogeneous digital landscape, ranging from advanced and strategic digital ecosystems to early-stage, fragmented, or analogue approaches.

5.1.1 Digitalisation and Visitor Experience

The Archaeological Museum of Thessaloniki (AMTh) emerges as the most digitally mature institution in the sample. Its integrated use of digital platforms, mobile applications, and experimental VR/AR tools enhance visitor engagement, interpretation, and access to urban and archaeological narratives, particularly for younger and international audiences. Digital storytelling and interactive content function as effective complements to traditional museological practices.

In contrast, regional museums in Kilkis, Amphipolis, and Pella remain at an early stage of digital development. Their digital presence is limited to basic informational tools, audio guides, tablets, or pilot initiatives, while immersive applications and structured digital collections are absent. Nevertheless, these institutions demonstrate increasing awareness of the value of digital technologies and express intent for future expansion, primarily dependent on funding availability and institutional approval.

The Experiential Park of Leibethra represents a distinct model, integrating multimedia applications, educational digital tools, and experiential learning within an open archaeological landscape. While advanced immersive technologies remain under development, the park demonstrates how digital media can successfully support interpretation and engagement in non-conventional museum settings.

5.2. *Accessibility and Inclusion*

Digital accessibility varies across the examined institutions. The Archaeological Museum of Thessaloniki demonstrates a systematic and inclusive approach, incorporating digital services designed for visitors with disabilities and reinforcing equitable access to cultural content. Other museums focus primarily on physical accessibility, while digital accessibility tools—such as assistive applications or enhanced audiovisual interpretation—remain limited or at a planning stage. Positive practices, including audio guides and accessible web design, are evident at the Experiential Park of Leibethra. Overall, digital accessibility remains an underdeveloped dimension requiring coordinated strategic planning and investment.

5.3. *Cultural Diplomacy and International Outreach*

The Multicenter Museum of Aigai and its Digital Museum constitute a flagship example of hybrid museology. By combining physical heritage with a globally accessible digital platform, the project extends cultural narratives beyond geographical boundaries and enhances Greece's international cultural presence. Multilingual content, thematic organization, and non-linear exploration position the Digital Museum of Alexander the Great as a tool for cultural diplomacy, education, and research, while also supporting cultural tourism and regional development.

5.4. *Challenges and Limitations*

Despite positive developments, several persistent challenges hinder systematic digital transformation. Limited financial resources, dependence on external funding, bureaucratic delays, and insufficient staff training constrain long-term digital planning. In addition, the absence of independent institutional websites and unified digital policies reduces visibility and results in fragmented visitor experiences across the region.

5.5. *Policy Recommendations and Future Directions*

To strengthen digital cultural tourism in Central Macedonia, the study recommends:

- the development of coherent digital strategies at institutional and regional levels
- targeted investment in VR/AR applications, digital collections, and interactive platforms
- systematic enhancement of digital accessibility for people with disabilities
- continuous professional training for museum personnel in digital technologies
- expansion of international collaborations and coordinated digital promotion initiatives.

5.6. Final Remarks

Digitalization constitutes a critical factor for the sustainable development of cultural tourism in Central Macedonia. While leading institutions demonstrate the transformative potential of digital heritage, broader implementation requires coordinated action, stable funding mechanisms, and institutional commitment. Current technological and economic constraints should be viewed not as barriers, but as catalysts for collaboration and innovation, ensuring that cultural heritage remains accessible, inclusive, and globally relevant.

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Integrating multi-source data and visualization of heterogeneous time-series for lakes: NDWI surface, ERA5 precipitation, level and fishery production

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Abstract

The aim of this paper is to present a reproducible workflow for the organization and visualization of heterogeneous, multi-purpose environmental data, presented for Lake Doirani for the period 2011–2023. Satellite images from Landsat 7/8 (2011–2017) and Sentinel-2 (2018–2023) satellites are processed using the Python programming language to calculate the Normalized Difference Water Index (NDWI) within a small region of interest for the lake, yielding a monthly water extent time series. Monthly precipitation totals are derived from the ERA5 reanalysis after a small spatial subset around the lake. We have aggregated lake level and annual fishery production data and lake area and rainfall data and created a final master value table. We have time-aligned them by creating time series data with an annual step and produce an annual overview of four axes (lake area, lake level, local rainfall, fishery production). Preliminary patterns show that drought years and reduced lake area/level generally co-exist with lower fishery production, with an indicative lag of 0-1 year. These relationships are exploratory and are not stated as causal. The workflow emphasizes open data, transparent processing and portability: by changing only the area of interest and data sources, the same process is applied to other lakes. The contribution is methodological, how to structure, aggregate and present mixed environmental time series to support lake monitoring and decision-making.

Keywords: *Sustainable Development; Data Collection and Data Estimation Methodology; Computer Programs: General; Computational Techniques; Fishery; Large Data Sets: Modeling and Analysis.*

JEL Codes: Q01; C80; C63; Q22; C55

1. Introduction

The rapid development of digital technologies and the Internet has created a rich and dynamic environment for the exchange, organization and dissemination of information, enabling new forms of collaboration and faster access to environmental resources. (Andreopoulou et al. 2013).

Integrated monitoring of aquatic ecosystems requires a combination of heterogeneous data sources, as no single source is sufficient to simultaneously capture spatial variability, temporal dynamics and anthropogenic pressures. In the context of Environmental Informatics and Forest Informatics, the organization, management and visualization of such data is a crucial step for decision support and sustainable management of natural resources. (Andreopoulou, Z. S. 2013; Andreopoulou Z. & Kokkinakis A. 2006).

According to Konstantinidis & Andreopoulou (2024), in an investigation into the relationship between precipitation in Central Macedonia and indications of changes in the extent of Lake Koroneia, utilizing open climate data and simple digital measurements from online tools, the climate-water extent relationship is often complex and does not limit itself to a simple linear correspondence, which reinforces the need for more systematic and reproducible workflows, which will unify more types of data in a common time frame.

This paper develops a reproducible methodological workflow for Lake Doirani, aiming to:

(a) generate time series of water surface change,
(b) integrate climatic precipitation data from the ERA5 reanalysis and in situ level measurements,
(c) combine with annual fishery production figures.

The approach emphasizes the organization and visualization of multi-purpose data, demonstrating a practical way to integrate satellite, climate and in situ data into a common time frame. In this way, the proposed framework can serve as a methodological model that can be applied to other lakes or aquatic ecosystems with limited changes in input data and area of interest (AOI).

2. Data

Four main data categories were used to implement the analysis. First, Sentinel-2 satellite images (level L2A) for the period 2018–2023, as well as Landsat 7/8 (Collection 2, Level-2) for the period 2011–2017, with spatial coverage of the Doirani Lake basin, were utilized. Second, for the climate component, ERA5 data from the Copernicus Climate Data Store were used, specifically monthly values generated from daily total precipitation, for the period 2011–2023, which were extracted into a small spatial subset (box) around the lake. Third, available monthly/indicative lake level measurements for the period 2012–2023 were used, as documented in the relevant literature and in available archival sources.(Stoilas V. & Kokkinakis A., 2025; EKBY 2025). Fourth, annual fishery production values for the period 2011–2023 were used, from relevant works and data from competent services, such as the Kilkis Fisheries Directorate (2025), in combination with existing scientific documentation. (Καρβουνάρης

1973; Kokkinakis et al., 2018). Overall, the data comes from open sources (Copernicus/USGS) and from competent bodies and local archives, with an emphasis on the documentation of measurement units and metadata to ensure proper integration and reproducibility of the results.

3. Methodology

The implementation of the methodology was carried out in a Python environment, utilizing libraries and digital tools suitable for geospatial data processing, time series analysis and visualization of results. Specifically, rasterio and numpy were used for raster image processing, xarray and pandas for the management and transformation of climate/temporal data, as well as geometry tools (geopandas/shapely) and matplotlib for the production of maps and diagrams. The process was organized in distinct stages, from data collection to integration and final presentation.

3.1. Satellite image collection

Initially, satellite images were acquired for selected dates with low cloud cover (indicatively <12%) in order to limit errors in the detection of the water surface. Sentinel-2 level L2A data (atmospherically corrected) were used for the period 2018–2023, while Landsat 7/8 level-2 data were used for the period 2011–2017.

3.2. NDWI calculation and water mask extraction

To estimate the water surface, the NDWI (Normalized Difference Water Index) index was applied, which is based on the combination of the visible green (GREEN) band and the near infrared (NIR) band. The physical basis of the index is that water absorbs strongly in the NIR region (therefore exhibits low reflectivity), while it exhibits relatively higher reflectivity in green. Thus, the ratio:

$$NDWI = (Green - NIR) / (Green + NIR)$$

tends to give positive values for water surfaces and smaller or negative values for land/vegetation. For the calculation of NDWI, the corresponding spectral bands per satellite were used: Sentinel-2 (B03/B08), Landsat 8 (B3/B5) and Landsat 7 (B2/B4).

A spatial restriction (clip) was then applied to a small area of interest (AOI) around Lake Doirani (polygon/contour demarcation), so that the processing only concerns the relevant water surface and reduces noise from neighboring areas. Finally, a water detection threshold was adopted (indicatively NDWI > 0.20) and the result was converted into a binary water mask, where the values encode the categories water (1) and land (0).

3.3. Calculation of water surface area

Based on the binary water mask, the area of the water surface was calculated as the product:

$$Area = (number\ of\ \text{“water”}\ pixels) \times (pixel\ area)$$

where the pixel area is derived from the spatial resolution of the image. The area was converted from m² to km² and stored as a time series for the available dates/months.

3.4. Climate data extraction and transformation (ERA5)

In parallel, precipitation data from the Copernicus Climate Data Store (ERA5) were used. A small geographical sub-area (bounding box) was selected around Lake Doirani and a spatial average was applied over the area of interest. The data were converted to monthly totals (mm/month), with a transformation from m/day to mm/month via the number of days per month, in order to obtain a comparable monthly precipitation time series.

3.5. Lake level

Available monthly/indicative level measurements for the period 2012–2023 were used, as documented in the relevant literature and available archival sources. (Stoilas V. & Kokkinakis A., 2025; EKBY 2025).

3.6. Fishery production

Annual fishery production values for the period 2011–2023 were used, from relevant works and data from competent services, such as the Kilkis Fisheries Directorate (2025), in combination with existing scientific documentation. (Καρβουνάρης 1973; Kokkinakis et al., 2018).

3.7. Time series integration and visualization

In the final stage, all available data were consolidated into a central consolidated table for the period 2012–2023, at an annual step, so that the variables are time-aligned and directly comparable. This table incorporated both the "standalone" data (annual mean lake level from monthly values and annual fishery production) and the "processed" data (annual totals/means from lake area via NDWI and from ERA5 precipitation). Based on the consolidated table, a summary time series chart was produced with the years 2012–2023 as the time axis and four variables in real units, distributed over multiple axes (area, level, precipitation, fishery production). Visualization allows for the simultaneous observation of trends and possible synchronizations between variables, without implying a causal relationship (the analysis remains exploratory).

3.8. Reproducibility and reuse

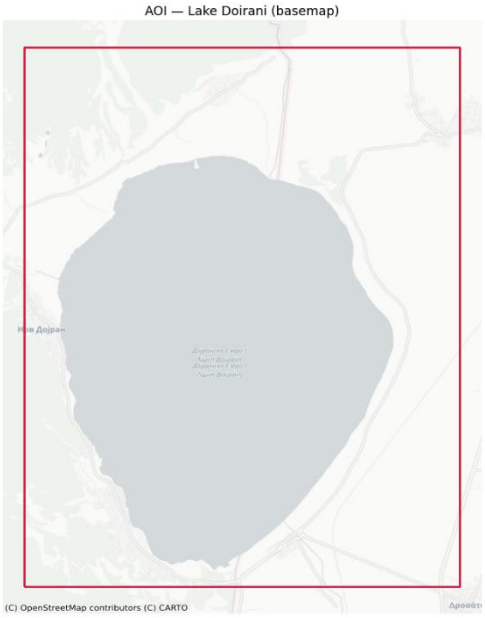
Finally, the workflow was designed in a way that is easily scalable: the same methodology can be applied to other lakes or aquatic ecosystems by changing mainly the input data and the area of interest (AOI), while keeping the basic processing, integration and visualization logic constant.

4. Results

By implementing the proposed workflow, a time series of changes in the water surface of Lake Doirani was created for the period 2011–2023, combining Landsat 7/8 data for the years 2011–2017 and Sentinel-2 for the years 2018–2023. Processing with NDWI on a fixed area of interest (AOI) allowed the extraction of comparable area estimates at a monthly level, which were then summarized at an annual step for the integrated visualization.

Precipitation from ERA5 (2011–2023) showed strong interannual variations, which are reflected in both the variability of the area and the level of the lake. In general, the expected positive relationship is observed: periods of increased precipitation are accompanied by higher level values and/or larger water surface, while decreases occur in drier phases. At the same time, the response is not immediate and seems to be influenced by seasonality and the hydrological characteristics of the basin, with possible lags of weeks to a few months.

Figure 1. Spatial extent of study, area of interest in Lake Doirani



Regarding fishery production, the available annual data for the years 2012–2023 show indications that productivity may be linked to the hydrological state of the lake (level/area), particularly in years characterized by drought or reduced water volume. However, interpretation requires caution, as fishery production is also influenced by other factors not yet included in the present dataset (e.g. fishing effort, temperature, water quality, management measures). For this reason, the findings are treated as exploratory and not as proof of a causal relationship.

The final unified visualization in an annual multi-axis diagram offers a condensed "panoramic" image of the four variables (area, level, precipitation, fishery production). As a result, it functions as a practical tool for quick visual diagnosis to identify years with drought

or high precipitation and for a first assessment of how hydrological changes may be linked to lake productivity.

Figure 2. Example of NDWI map from Sentinel-2 (07-2023), with water mask overlay (NDWI>0.20.

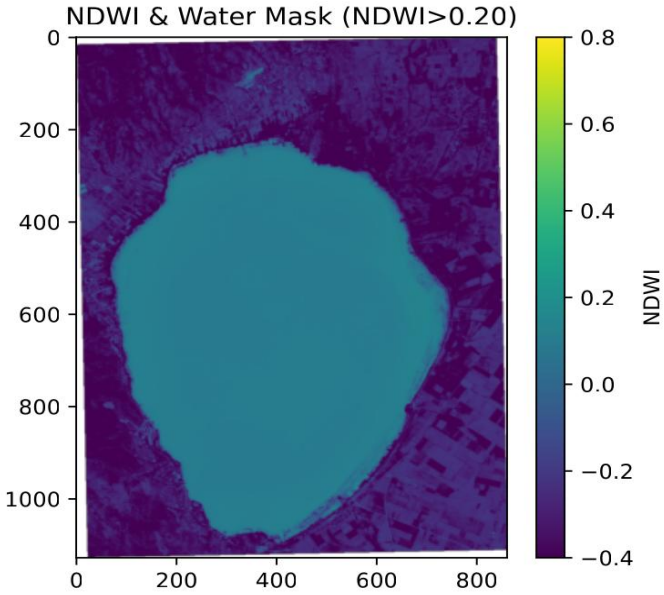
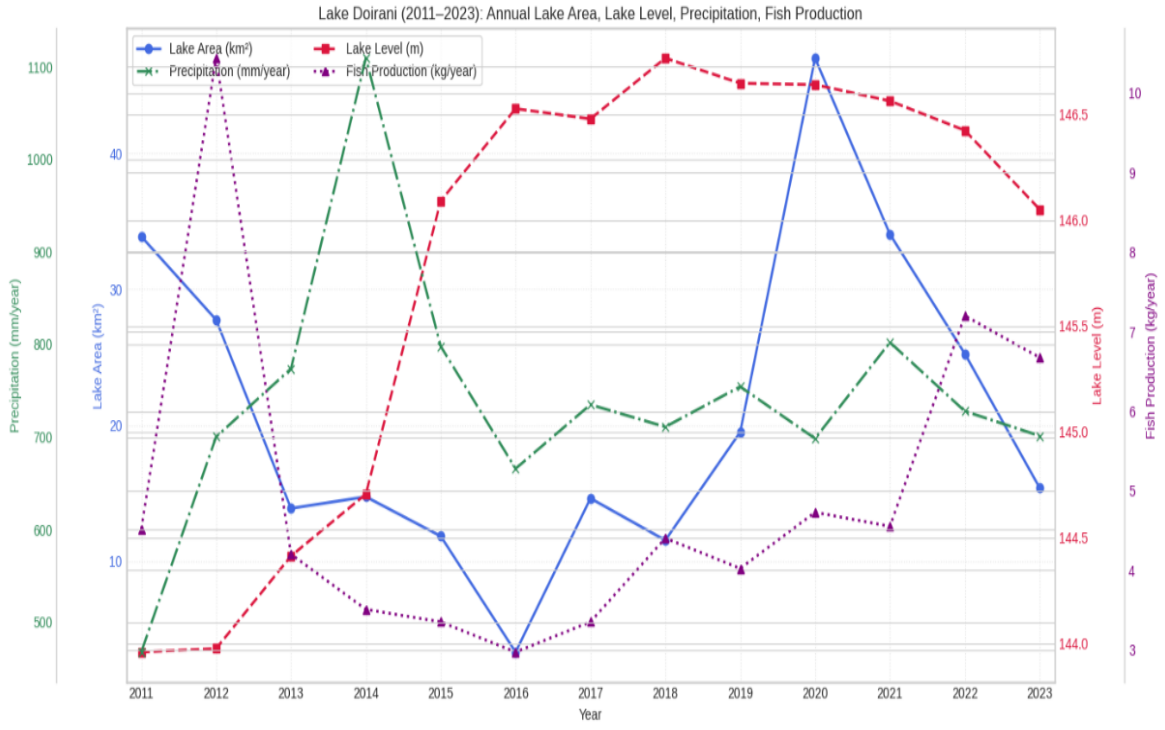


Figure 3. Annual graph of continuous time series of digital recordings of Area, Level, Annual Precipitation and Fishery Production, of Lake Doirani (2012-2023).



5. Conclusion

This paper presents a fully documented and reproducible methodological workflow for the combined recording and visualization of heterogeneous environmental data in Lake Doirani for the period 2012–2023 (with satellite coverage of the area from 2011–2023). The approach integrates satellite images (Sentinel-2 and Landsat 7/8) to produce an area time series via NDWI, climate data (ERA5) for precipitation, in-situ level recordings, as well as annual fishery data. The integration of these sources into a common temporal format and the production of concise multi-axis diagrams allows for the simultaneous monitoring of key quantities describing the hydrological and productive state of the ecosystem. Overall, the method provides a fast, low-cost and scalable solution, useful for monitoring and decision support in water resources management and sustainable utilization of lake ecosystems. Given that the core of the workflow remains stable and is mainly adapted through changing the area of interest and input data, it is proposed as a template that can be applied to other lakes with minimal adaptations.

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Sustainability in Tourism in Greece using e-tourism: the case of Ecohotels and Expedia online platforms in e-Reputation

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Abstract

The present study investigates the correlation between sustainable certification and the e-reputation of hotels, acknowledging the critical importance of sustainable tourism and the pivotal role of e-Tourism in shaping consumer choices. While sustainability has become a central criterion for the travel industry, the quantitative impact of certifications on online competitiveness remains unclear. To address this research gap, the study adopts a quantitative comparative methodology, analyzing data from two distinct platforms: Ecohotels.com and Expedia. Specifically, the research compares the sustainability scores from Ecohotels, a specialized platform for ecological accommodations, with the ranking and overall customer sustainability rating provided by Expedia, one of the largest online travel agencies. The analysis aims to determine whether hotels with higher environmental certifications achieve improved online visibility and increased positive evaluation. The anticipated findings will contribute substantially to hotel strategic management, providing evidence-based insights into the value of integrating and communicating sustainable practices within the digital environment.

Keywords: *Sustainable Tourism, e-Reputation, e-Tourism, Sustainability Certifications*

JEL Codes: L82, L86, Q56, Z32, Z33

1. Introduction

Sustainable tourism has become a priority for policymakers and travelers alike, as reflected in the United Nations' 2030 Agenda, which includes 17 Sustainable Development Goals (SDGs) to balance economic growth with environmental protection and social equity (United Nations, n.d.). In tourism, this involves ensuring that development "meets the needs of present tourists and host regions while protecting and enhancing opportunities for the future" (Gebhard et al., 2009). As part of this effort, many hotels obtain eco-certifications (e.g., Green Key, ISO 14001) to demonstrate their environmental commitment (Hellenic Society for the Protection of Nature). At the same time, the rise of e-Tourism means consumers increasingly rely on online platforms for booking decisions. Major OTA platforms like Expedia report that 90% of travelers now seek sustainable options when booking, although 70% feel overwhelmed by the available information (Expedia Group, 2022). Therefore, a hotel's e-reputation—its online ratings and customer reviews—may be influenced not only by service quality but also by how clearly its green practices are communicated.

Despite the significance of these trends, the exact impact of sustainability certifications on a hotel's online reputation remains uncertain. Previous studies indicate that online eco-ratings often correlate more strongly with overall guest satisfaction than with actual environmental performance (Martin-Fuentes et al., 2025). Our research addresses this gap by directly comparing certification levels to customer review metrics. We analyze 40 Greek hotels listed on EcoHotels.com (a platform dedicated to eco-certified hotels) and on Expedia.com, investigating whether higher certification scores lead to higher e-rankings or sustainability ratings. This study could help hotel managers and online platforms understand if and how eco-labels enhance digital competitiveness and booking appeal.

2. Literature Review

The concept of sustainable tourism combines environmental, economic, and socio-cultural factors to ensure long-term success (Gebhard et al., 2009). It requires tourism businesses to maximize positive impacts, such as local development, while reducing negative effects like pollution. One way to encourage eco-friendly practices is through sustainability certification. These third-party labels (e.g., Green Key, ISO 14001, Green Key Global, IHG Green Engage, Accor Planet 21) establish strict standards for environmental management and social responsibility. For example, the Green Key program – used by 60% of our sample – is an international eco-label certifying hotels that meet high sustainability standards; over 8,500 properties in more than 90 countries are Green Key–certified (Foundation for Environmental Education, n.d.). These certifications aim to signal a hotel's commitment to guests and stakeholders, and they help consumers identify more responsible accommodations.

The digital transformation of tourism (commonly called e-tourism) involves using information and communication technologies throughout the entire travel value chain (Buhalis, 2003). Buhalis (2003) emphasizes that e-tourism "addresses the digitization of all processes and value chains in the tourism, travel, hospitality, and catering industries," which fundamentally changes how hotels promote themselves and interact with guests. Corporate reputation is the perceived ability of a company to meet the expectations of all stakeholders

(Fombrun, 1996). Expanding on this digital interaction, Sebastia et al. (2009) highlight the evolution of e-tourism through recommender systems and planning applications that offer personalized suggestions to travelers, significantly influencing their decision-making and itinerary planning. Specifically, customer reviews and ratings on online platforms are crucial to a hotel's online reputation. In more recent research focusing on the Greek market, Papathanasiou et al. (2025) emphasize that innovative services are a decisive factor in shaping a hotel's reputation, highlighting the strategic importance of digital adaptation in a competitive environment. This digital dissemination of information is vital, as customer reviews and ratings on online platforms now serve as the most influential indicators of a hotel's online reputation. A positive online reputation can increase bookings and foster loyalty, whereas negative reviews can discourage travelers. For instance, research indicates that online ratings and reviews are key factors in hotel decision-making, often serving as the first "lens" through which potential guests assess a property. However, the relationship between sustainability information and e-reputation is complicated. Martin-Fuentes et al. (2025) found that consumer "eco-friendliness" ratings on Expedia are almost entirely driven by overall guest satisfaction, with actual sustainability practices playing little role in the rating (Martin-Fuentes et al., 2025). This indicates that unless travelers are explicitly told about a hotel's eco-credentials, the certification itself may not significantly affect customer perception. In short, a green certification might not directly improve a hotel's online rating unless it has clear, visible indicators (such as mention on the booking site or labels on review pages). Industry reports support this: Expedia Group recommends making sustainable travel information easier to find and understand, as travelers increasingly expect brands to show genuine commitment to sustainability (Expedia Group, 2022).

In summary, although sustainable certifications are theoretically connected to improved environmental practices, their effect on guest satisfaction and online reputation remains debated. Existing research indicates that service quality (such as cleanliness and comfort) usually has a stronger influence on guest ratings, potentially overshadowing the certification label itself (Martin-Fuentes et al., 2025). Our study expands on this by empirically examining Greek hotels' certification scores alongside their online reputation metrics.

3. Methods and Data

3.1. Methodology

We conducted a comparative quantitative analysis of 40 Greek hotels (convenience sample) listed on two platforms: EcoHotels.com and Expedia.com. Twenty hotels were selected from Athens and twenty from Thessaloniki – the two largest cities featured on EcoHotels – ensuring comparability by geographic market. All selected hotels had at least one sustainability certification and appeared on both platforms. From EcoHotels.com, we recorded each hotel's sustainability score (based on its certifications).

From Expedia.com, we obtained each hotel's overall ranking and its customer "sustainability rating" (Expedia's post-stay rating of eco-friendliness). Additional variables collected included the number of customer comments, average overall customer rating (0–10 scale), and sub-scores for Room, Service, Location, and Cleanliness (all on a 0–5 scale), as well

as star rating and cost per night. These variables reflect the hotel's e-reputation and operational features.

We formulated three research questions (RQs): RQ1: How do hotel quality attributes differ across various sustainability certifications? (i.e., do hotels with different eco-labels show different averages in room quality, service, location, cleanliness, amenities, etc.?). RQ2: Which eco-certifications significantly influence a hotel's reputation? (i.e., is there a statistically significant difference in average customer ratings between hotels with different certifications?). RQ3: How does the Green Key certification relate to key reputation factors? (Focusing on hotels with the Green Key label, we examined correlations between their overall rating and cleanliness, amenities, and location.).

For RQ1, we calculated descriptive statistics and compared mean scores of service attributes (Room, Service, Location, Cleanliness, Amenities) across groups defined by certification (Green Key, ISO 14001, Green Key Global, IHG Green Engage, Planet 21). For RQ2, we applied Levene's test for homogeneity of variances, followed by a one-way ANOVA ($\alpha = 0.05$), to determine whether mean customer ratings differed by certification category. For RQ3, we computed Pearson correlation coefficients between overall rating and the factors (Cleanliness, Amenities, Location) for the subset of Green Key–certified hotels (n=5 in the Athens sample). All analyses used standard statistical methods (e.g., SPSS).

3.2. Data

Sample characteristics: Out of 40 hotels, 60% were Green Key certified (24 hotels), highlighting Green Key's prominence in Greece. Hotels in Athens showed a wider variety of certifications than those in Thessaloniki. Notably, 63.6% of Thessaloniki hotels and 58.6% of Athens hotels held the Green Key (Global) label. Regarding descriptive metrics, overall customer ratings on Expedia ranged from 7.2 to 9.8 (average ≈ 8.7), and sustainability ratings ranged from 5.0 to 9.8 (average ≈ 8.3). Customer sub-scores were also generally high (Room ~3.7/5, Service ~4.6, Cleanliness ~4.4, Location ~7.7/10).

RQ 1 – Certification vs. Service Attributes: We observed distinct patterns based on certification. Room Quality: Hotels with Green Key Global and IHG Green Engage had the highest average room quality scores (approximately 4.3), indicating that guests perceived these hotels as having very good rooms. In contrast, hotels with the basic Green Key label or ISO 14001 had lower average scores (~3.5).

Service Quality: Green Key Global (4.70) and ISO 14001 (4.55) also received top service ratings, while IHG Green Engage (4.30) and Planet 21 Accor (4.47) were scored slightly lower. Overall, service scores were consistently high across certifications (range of 4.3–4.7). Location: The highest location scores were for Green Key Global (4.60) and ISO 14001 (4.55), followed by IHG Green Engage (4.30). Planet 21 Accor scored notably lower (3.97) on location.Cleanliness: Cleanliness ratings peaked for Green Key Global (4.70), followed by ISO 14001 (4.25) and IHG Green Engage (4.00). Hotels under Planet 21 or Green Key had somewhat lower cleanliness scores (~3.9). Notably, higher-rated certifications tended to align with higher cleanliness ratings.

Amenities: The highest amenities scores were also in Green Key Global hotels (3.55) and Planet 21 (3.50). The IHG Green Engage group showed an anomalously low amenities score (0.00), likely due to missing data or the group being small. ISO 14001 held an intermediate amenities score (2.90).

Key insight: Internationally recognized certifications like Green Key Global and ISO 14001 consistently align with superior guest evaluations across most categories (rooms, cleanliness, service). Mid-level programs (e.g. basic Green Key, Planet 21) tended to perform moderately, and IHG Green Engage showed more mixed results (very high service but lacking amenities). This suggests that more rigorous or comprehensive certification programs may coincide with overall higher hospitality standards.

RQ2 – Effect on Reputation (ANOVA). We tested whether hotels with different certifications had different mean customer ratings. Levene's test confirmed homogeneity of variances ($p=0.816$). The one-way ANOVA showed no statistically significant difference between certification groups ($p=0.877$), indicating that having a particular eco-label did not significantly alter the average customer rating. In other words, hotels with Green Key, ISO 14001, Green Key Global, or Planet 21 certifications did not have systematically higher or lower ratings compared to each other. This suggests that, in our sample, the type of sustainability certification alone did not produce a statistically detectable difference in overall guest satisfaction scores.

RQ3 – Green Key Correlations: Focusing on the subset of 5 Green Key–certified hotels (Athens sample), we examined how their overall ratings correlated with key factors. Cleanliness: Pearson $r \approx 0.96$, indicating a very strong positive correlation. Cleanliness had the greatest impact on customer ratings for Green Key hotels.

Amenities: $r \approx 0.91$, also a very strong correlation. Better amenities went hand-in-hand with higher guest ratings.

Location: $r \approx 0.70$, a moderately strong correlation. Location mattered, but less so than cleanliness or amenities.

Interpretation: For Green Key hotels, the reputation (as measured by customer ratings) was most closely tied to cleanliness and amenities, with location playing a secondary role. This emphasizes that even in certified hotels, tangible quality attributes drive e-reputation.

4. Discussion

Our findings suggest that certification correlates with better performance on specific hotel attributes but does not directly lead to higher online ratings. The fact that Green Key Global and ISO 14001 hotels received top scores in room cleanliness and service quality indicates that hotels pursuing rigorous certifications often invest in overall quality. These internationally recognized standards likely require hotels to meet multiple criteria, which can translate into an improved guest experience. This aligns with the idea that certifications are part of a

comprehensive management approach: for example, IHG Green Engage offers a system with hundreds of "Green Solutions" that could enhance various operational aspects simultaneously.

However, our ANOVA results, which show no significant difference in average ratings across certification groups, support prior research suggesting that consumer review scores are mainly driven by service satisfaction rather than awareness of eco-labels (Martin-Fuentes et al., 2025). This difficulty in translating sustainability into a competitive advantage aligns with the findings of Khan et al. (2023), who identify various barriers and challenges in implementing green concepts that can hinder a firm's performance. Although certified hotels generally scored higher on objective attributes, customers did not give them higher overall ratings on Expedia. A likely reason is a lack of customer awareness: if guests are not informed about a hotel's green certification, it won't influence their rating. Indeed, Martin-Fuentes et al. (2025) argue that travelers' eco-ratings are "explained almost entirely by overall guest satisfaction" rather than actual sustainability efforts. This means that eco-certification can establish a hotel's green credentials, but unless the guest recognizes and values that credential, it won't improve the hotel's online reputation.The strong correlations for Green Key hotels (cleanliness r=0.96, amenities r=0.91) highlight that core service factors are crucial in shaping reputation. This suggests that, to leverage eco-certification into a better online reputation, hotels should not only adopt green practices but also emphasize them in ways that increase perceived value among guests. In line with industry guidance, platforms and hotels should make sustainability credentials transparent: Expedia recommends that travel brands "make sustainable travel information easier to understand" and explicitly demonstrate their commitment to sustainability (Foundation for Environmental Education, n.d.). For instance, hotels could highlight certifications in property descriptions, use eco-badges in marketing, or encourage environmentally conscious reviews. This can help close the gap between a hotel's sustainable practices and the consumer's perception of the experience.

In summary, our data indicate that adopting strong environmental certifications is associated with improved guest satisfaction in specific areas (e.g., cleaner rooms), but by itself does not automatically boost the e-reputation score. For hotel managers, this means green initiatives should be integrated with service excellence and effectively communicated through e-tourism channels. Hotels should aim not only for certification but also for staff training on sustainable service and online promotion of their green credentials. Strategically, aligning certification with visible quality improvements and targeted marketing can maximize the digital benefits of sustainability efforts.

5. Conclusions

This study examined the relationship between sustainable certifications and online reputation among hotels in Greece. We found that internationally recognized eco-labels (Green Key Global, ISO 14001) are associated with higher customer ratings on key hotel features, while less-known programs show mixed results. However, ANOVA results showed no significant difference in overall customer ratings across certification groups. In other words, simply holding a certification didn't necessarily lead to a better e-reputation score on Expedia. For Green Key hotels specifically, cleanliness and amenities were the main factors linked to reputation.

These findings have practical implications: although certifications signal a hotel's environmental efforts, their influence on customer perception depends on how effectively green practices enhance the guest experience and are communicated. This strategic communication is a key element of Green Informatics; as Andreopoulou (2012) states, it includes design and information dissemination techniques aimed at optimal environmental governance, promoting sustainability through smart energy management and increased public awareness. Hotels and OTAs should make sustainability information more visible (e.g., by highlighting eco-labels and green initiatives) to tap into the growing consumer interest in responsible travel (Expedia Group, 2022). Future research could expand the sample size, analyze other markets, and investigate whether guest awareness of eco-labels influences the certification–reputation relationship. Additionally, qualitative research (e.g., guest interviews) could offer insights into how certifications impact booking decisions and satisfaction. Ultimately, as the industry strives for a net-zero future, understanding the digital value of sustainable branding will remain a crucial strategic focus.

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The Significance of Photography and Video User Generated and Shared Content in Mountainous Sustainable Tourism: The Case of Mount Olympus National Park

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Abstract

This study investigates the critical role of user-generated photography and video content in advancing the sustainable tourism objectives of Mount Olympus National Park. Through a quantitative survey among the park visitors, the research aimed to establish an evidence base for integrating visual media into future governance and promotion strategies. The results demonstrated that around three quarters of the visitors engage in photo or video activities. A highly significant and moderately strong positive correlation was identified between taking photos and sharing them on social media. This suggests, these are interdependent behaviours that can be leveraged for promotion. The findings conclude that visitors visual content creation in social media offer an effective and cost-free method to promote visitation in mountainous regions. The research ultimately recommends creating designated "Instagramable spots" on protected area paths to manage increased visitor flow and mitigate environmental pressures from uncontrolled dispersion.

Keywords: *Photography, Video, Social Media Content Creation, Sustainable Tourism, Mount Olympus, National Park*

JEL Codes: Q20, Q26, Q28

1. Introduction

In the face of escalating global challenges, particularly climate change and economic marginalization, the adoption of Sustainable Mountain Tourism has become a critical imperative, serving as a robust framework for regional resilience and development (Romeo et al., 2021). Recognizing mountains as fragile ecosystems that provide vital services—including water and biodiversity—to a large portion of the global population (FAO, 2011), Sustainable Mountain Tourism is fundamentally built upon the integrated pillars of environmental stewardship, economic prosperity, and socio-cultural preservation. This approach strategically counters traditional mass tourism's destructive tendencies by fostering diversified, low-impact economic activities that provide reliable income streams and promote poverty reduction for local mountain communities (Mutana & Mukwada, 2018; UNWTO, 2018). Moreover, by empowering local actors and aligning tourism products with a growing market demand for authentic, less crowded, and environmentally responsible travel experiences, Sustainable Mountainous Tourism ensures the long-term viability of these destinations while preserving the unique cultural heritage essential to their appeal (Qu Dongyu & Pololikashvili, 2021). Consequently, Sustainable Mountainous Tourism is viewed not merely as a niche market, but as the essential future model for managing mountain resources in the context of the UN Sustainable Development Goals.

In the current digital environment, photography's role transcends traditional documentary function, establishing it as a foundational medium central to contemporary life and discourse. The explosion of image production, facilitated by ubiquitous computing and smart technologies, makes photography a pervasive cultural phenomenon (Kember, 2012). This shift reflects its adoption as a "human universal," deeply embedded in our cognitive frameworks for social expression and interaction (Kislinger & Kotrschal, 2021). Consequently, the photographic image operates not only as a crucial repository of cultural memory and historical evidence but also as a powerful agent in shaping collective narratives (Setiadi, 2017). Moreover, in a visually saturated media landscape, photographs directly influence public opinion and emotional response on pressing social and political issues with greater immediacy and impact than text alone (Catoto & Naik, 2022). Thus, 21st-century photography is fundamentally engaged with the processes of meaning-making, challenging and redefining the very boundaries of visual culture.

Photography operates as a multifunctional instrument essential to the achievement of sustainable mountain tourism objectives, transcending its traditional role as merely a promotional tool (Kaewnopparat, 2017). Its power to "prove and move" (Balomenou & Garrod, 2019) allows visual data to effectively bridge cognitive and communication gaps, enabling the sensory, emotional, and cognitive engagement necessary for fostering a conservation ethic in visitors (Mutana & Mukwada, 2018; UNWTO, 2018). Specifically, "eco-photography" and "conservation photography" serve as potent visual communication strategies that capture both the aesthetic and ecological components of fragile alpine environments, raising crucial

awareness regarding biodiversity loss and landscape change (Hobson, 2018). Furthermore, specialized niches, such as bird photography tourism, demonstrate a proven capacity to generate sustainable livelihoods for local mountain communities, providing new, low-impact income streams that reduce dependence on extractive practices and strengthen the self-governance mechanisms vital for long-term biodiversity conservation (Basnet et al., 2017; Xiao et al., 2022). Consequently, the visual narrative created by both professional and participant-generated photography is an indispensable asset for authentic destination branding, environmental education, and economic resilience in mountain regions (Umrbokievich, 2024).

The primary aim of this research is to explore the critical importance and contribution of photography to the sustainable tourism development of Mount Olympus. The study will systematically investigate how visual user-generated representations, can promote visitation and contribute to the development of mountainous areas. The goal is to establish an evidence base for integrating photography and visual media management into the future sustainable governance and promotion strategies for the Olympus National Park region.

2. Material and Methods

The purpose of this research is achieved by conducting a quantitative survey among visitors to Olympus National Park. By conducting quantitative research among visitors to protected areas, the attitudes, opinions, and behaviors of these visitors are investigated (Gross et al., 2023). Patterns and frequency of visits are identified (Balmford et al., 2015), and the value and economic dimensions that arise are understood and evaluated, along with the impacts on the natural environment (Marion et al., 2016).

Although there are various estimates of the number of visitors to the Olympus National Park, these vary significantly. Therefore, the sample size calculation will be performed for an unknown population size, with a specified confidence level of 95% and a margin of error of 4%, using the following formula (Cochran, 1977):

$$n = \frac{Z^2 \cdot p \cdot (1-p)}{e^2}$$

where:

- (n) is the sample size,
- (Z) is the Z-score corresponding to the confidence level (for 95%, the Z-score is 1.96) (Cochran, 1977),
- (p) is the expected proportion (usually 0.5 for maximum sample size) (Cochran, 1977),
- (e) is the margin of error.

Thus, for an unknown population, the calculated sample size is:

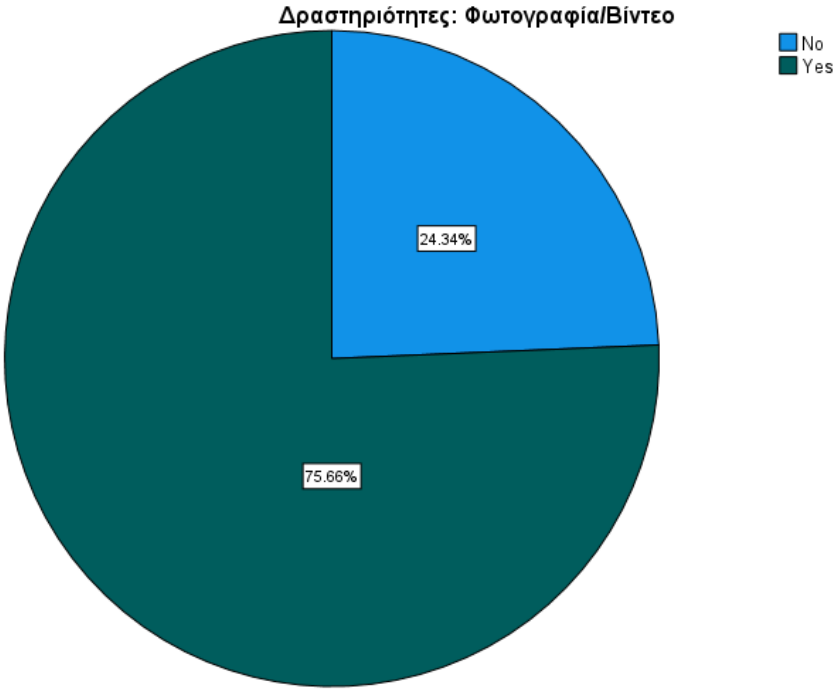
$$n = \frac{(1.96)^2 \cdot 0.5 \cdot (1-0.5)}{(0.04)^2} = 600.25$$

Therefore, the required sample size is 601 individuals. A total of 608 completed questionnaires were collected from visitors within Olympus National Park, from June to September 2024.

3. Results

The majority of individuals (75.7%) participate in photography or video activities. A smaller percentage (24.3%) do not participate in these activities (**Figure 1).**

Figure 1. Shooting Photography and/or Video during the stay in the Protected Area



A statistical analysis of 608 responses on the timing of Social Media content posting related to a visit reveals a primary tendency towards delayed sharing, with the largest group (37.3%) intending to post on a subsequent day. However, a significant portion of respondents opt for quicker sharing, with 24.5% posting on the same day and 14.1% posting during the visit. Notably, nearly a quarter of all participants (24.0%) indicated they will not post any content related to the experience (Figure 2).

A Spearman's Rho analysis revealed an extremely highly significant and moderately strong positive correlation between the two variables ($\rho = .477, p < .001$). The magnitude of the coefficient is the largest observed in the current set of analyses, suggesting that these two activities are closely related. Specifically, individuals who report higher levels of photo activity are highly likely to also report higher levels of posting on social media, and vice versa. This finding strongly suggests that, for this sample, the act of taking photos and sharing them on social media are interdependent behaviors (Table1).

Figure 2. Sharing or not on Social Media during the visit or afterwards

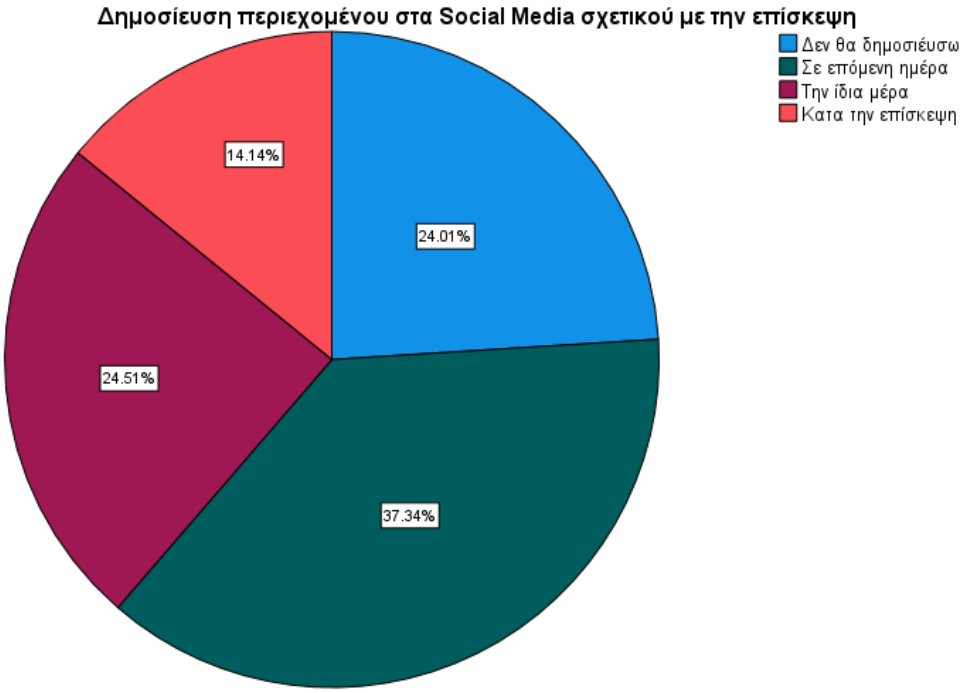


Table 1. Spearman's Correlation Analysis

Correlations

			Q3_Activity_Photo	Q7_Post_Social_Media
Spearman's rho	Q3_Activity_Photo	Correlation Coefficient	1.000	.477**
		Sig. (2-tailed)	.	<.001
		N	608	608
	Q7_Post_Social_Media	Correlation Coefficient	.477**	1.000
		Sig. (2-tailed)	<.001	.
		N	608	608

**. Correlation is significant at the 0.01 level (2-tailed).

4. Conclusion, Discussion

The empirical evidence from this study underscores the transformative role of user-generated content in the sustainable tourism framework of Mount Olympus National Park. With approximately three-quarters of visitors actively engaging in photography and video creation, visual documentation has moved beyond a simple hobby to become a core component of the mountainous travel experience. The identified highly significant and moderately strong positive correlation between taking photos and the intent to share them online suggests that these are interdependent behaviors. This digital synergy transforms visitors into organic ambassadors, providing a cost-free and effective method to promote visitation and environmental conservation efforts simultaneously.

Strategically, the findings support the integration of visual media management into the park's governance. The recommendation to establish designated "Instagrammable spots" along existing paths serves as a proactive tool for visitor management. By concentrating social media activity at specific, managed locations, authorities can effectively mitigate the environmental pressures caused by uncontrolled visitor dispersion, thereby protecting the fragile mountainous ecosystem. This approach aligns digital behavior with physical conservation, ensuring that the promotion of the area does not compromise its ecological integrity.

However, management strategies must remain inclusive of the diverse visitor profile identified in the research. As nearly a quarter of the sample does not utilize social media for sharing their experience, traditional monitoring and management methods remain essential to accurately track and manage the presence of all visitors.

Ultimately, leveraging the "prove and move" power of photography allows Mount Olympus to bridge the gap between aesthetic appeal and ecological awareness, enhancing visitors and tourists experience (Georgilas & Andreopoulou, 2023). As video can be a significant message carrier, the display of visitors and tourists photographic and video created content in the premises of the Protected Areas Info Centres can further promote ecological awareness (Andreopoulou et al., 2024). By harmonizing user-generated visual narratives with sustainable infrastructure, the region can foster economic resilience while safeguarding its unique natural heritage for future generations

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Session 7.

Environmental Pollution:
Urban, Health & Industrial Dimensions

Stairways to Heaven for European Industries: Multi-driving paths for CO_2 emissions generation

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Abstract

The European Commission (EC) acknowledges that industries play a significant role in global greenhouse gas emissions. Given the growing environmental and climate challenges, both the EC and national governments have implemented a range of environmental policy tools, such as laws and regulations, aimed at fostering innovative approaches to combat pollution and reduce CO_2 emissions. However, designing an effective policy package remains complex, as it must be customized to fit different social, economic, and technological environments. This study uses the Fuzzy-Set Qualitative Comparative Analysis (fsQCA) method to explore the intricate and interconnected factors influencing CO_2 emissions across European countries. The analysis examines the interaction between policy instruments and various social/economic contexts. By analyzing data from 2008 to 2020 across eleven manufacturing industries in 29 European countries, the study identifies several causal configurations that contribute to higher CO_2 emissions, including trade, energy mix, environmental taxes, and economic growth. The findings emphasize the critical role of appropriate policy, economic, energy, and technological tools and reveal that there is no single pathway to achieving sustainability. This research not only enhances our understanding of pollution dynamics but also offers valuable insights for developing effective policies in diverse social contexts.

Keywords: *European industries; Carbon emissions' determinants; Decoupling groups; Fuzzy set qualitative comparative analysis*

JEL Codes: Q53, Q56, L60, O13

Regulation schemes for pollutants. Multiple steady states and pollution traps

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Abstract

This paper develops a dynamic differential game between polluting firms and a regulating government to analyze the interaction between emissions, abatement, and taxation in environmental policy. The pollution stock evolves according to firms' emissions and the government's abatement effort, while payoffs reflect production benefits, taxation, and environmental damages. We characterize equilibrium strategies under both Nash and Stackelberg frameworks. In the Nash game, simultaneous decision-making leads to nonlinear dynamics that can generate multiple equilibria, including stable clean states and high-pollution traps. Comparative statics reveal that higher taxation efficiency and stronger abatement reduce emissions and enhance stability, but insufficient policy effort can destabilize the system. Under Stackelberg competition, outcomes crucially depend on leadership. When the government leads, it internalizes polluters' reactions, implementing stronger policies that eliminate high-pollution equilibria and stabilize the system. When polluters lead, firms exploit first-mover advantage to secure higher emissions, weakening policy effectiveness and destabilizing pollution dynamics. The results highlight the importance of credible government leadership in steering the economy away from environmental traps and towards sustainable steady states.

Keywords: *Nash differential game, Stackelberg differential game, Pollution traps, First mover advantage, taxation efficiency.*

JEL Codes: C61, C72, Q58, Q52

1. Introduction

Environmental protection remains one of the central policy challenges of modern economies. Industrial activities generate pollutants that accumulate in the environment, threatening public health, ecosystems, and long-run sustainability. Governments, in turn, face the difficult task of regulating emissions, balancing environmental objectives with the economic interests of firms. This conflict is inherently strategic: firms choose emission levels to maximize short-term profits, while governments attempt to curb pollution through abatement programs and enforcement mechanisms such as taxation or fines.

Because the stock of pollutants evolves dynamically, the effectiveness of environmental regulation depends not only on current actions but also on how firms and governments anticipate each other's responses over time. This makes **dynamic game theory** a natural tool for analysis. In particular, the **Stackelberg framework** captures asymmetric leadership: one player (either the government or the polluting firms) acts as a leader by committing to a strategy, while the other responds optimally as a follower. Such leadership structures are frequently observed in practice: governments may credibly commit to long-term environmental targets (leader government), or alternatively, firms may take the initiative in setting emission patterns, leaving regulators to react (leader is the polluters).

This paper develops and analyzes a differential game between polluters and the government under both **open-loop** (commitment to time paths) and **feedback** (state-contingent) Stackelberg equilibria. The model highlights several key policy-relevant features:

- **Environmental traps and tipping points**: multiple steady-state pollution levels may exist, so small changes in enforcement or natural purification can push the system into either a sustainable or a degraded regime.
- **The role of leadership**: when governments lead, they can steer the economy toward cleaner outcomes by credibly committing to strong policies. When polluters lead, regulatory responses tend to be weaker, raising the risk of high-pollution equilibria.
- **Policy sensitivity**: taxation efficiency, abatement allocation, and discount rates strongly shape the long-run trajectory of pollution. In particular, even marginal improvements in enforcement effectiveness can eliminate undesirable equilibria.
- **Stability conditions**: whether pollution converges to a steady state depends on the balance between natural purification, government abatement, and polluters' incentives to expand emissions.
-

These dynamics are directly relevant to current environmental policy debates. For instance, climate change negotiations often reflect a **leader–follower structure**: when governments credibly commit to carbon taxes or emission trading systems, firms adjust their investments toward cleaner technologies; but when firms lobby successfully and shape the pace of emissions, regulators are left in a reactive role, often weakening climate policy. Similar dynamics can be observed in industrial regulation of air pollutants or water contamination, where strong government leadership has historically led to cleaner environments, while lax enforcement or regulatory capture has allowed polluters to dictate outcomes at the expense of long-term sustainability.

We focus on the **Stackelberg differential game** formulation, which introduces asymmetry in timing and commitment. In the open-loop case, the leader (either polluters or government) commits to a control trajectory, while the follower optimizes given this path. In the feedback case, strategies are state-dependent and time-consistent, requiring the solution of coupled **Hamilton–Jacobi–Bellman (HJB) equations**. The Stackelberg structure modifies the canonical system relative to simultaneous-move Nash equilibria, since the leader internalizes the follower's adjoint dynamics.

According to the game theory, the leader's optimization problem is solved subject to both the environmental state dynamics and the follower's co-state equation. This leads to an extended Hamiltonian that includes the follower's adjoint variable as an additional state. The first-order condition for the leader's control is derived from this augmented system, producing a control law that is affine in the state and the follower's costate, and mediated by the leader's own shadow price. In the feedback case, the leader's HJB equation must be solved jointly with the follower's HJB, yielding a system of coupled nonlinear partial differential equations. These equations characterize the Markov-perfect Stackelberg equilibrium, in which strategies depend explicitly on the pollution stock.

The analysis of both open-loop and feedback equilibria requires the study of the **canonical system** of differential equations for the state and co-state variables. Stability properties of the steady states are derived from the Jacobian matrix of this system, which determines whether pollution trajectories converge to sustainable levels or diverge toward environmental traps. Comparative statics with respect to key parameters—such as the natural purification rate, abatement efficiency, and discount factors—allow us to characterize bifurcations in the system and identify thresholds beyond which stable equilibria collapse.

This framework not only generalizes the standard static model of pollution control but also provides insights into how leadership structures affect dynamic outcomes. In particular, when polluters act as leaders, the government's reactive regulation weakens the stabilizing force of policy, while government leadership strengthens convergence toward lower pollution states. By embedding the environmental policy problem in the language of **HJB equations and canonical systems**, we provide a rigorous mathematical foundation for comparing the efficiency and stability of alternative regulatory regimes.

Our analysis is guided by several pivotal questions: Under what conditions can an economy fall into a pollution trap? How does the government's ability to commit to a long-term strategy alter the strategic landscape and improve environmental outcomes? What is the precise role of policy instruments, such as the efficiency of taxation and the allocation of abatement funds, in triggering a regime shift from a high-pollution to a low-pollution equilibrium?

The rest of the paper is organized as follows: Section 2 reviews the relative literature, section 3 presents the model, section 4 examines the Stackelberg game with the government as leader. Section 5 considers the Stackelberg game with the polluters as leader, while section 6 makes comparative statics. Section 7 provide the affine form of the value functions for both players, while section 8 examines the possibility of pollution traps for the model. Section 9 makes the discussion of the paper results, and section 10 concludes.

2. Literature review

Pollution control has long been a critical issue in environmental economics. Early work by Comolli (1977) investigated whether pollution could be effectively regulated by an agent acting on behalf of society and identified conditions for effective control under limited or no information about marginal private costs and social damages.

In a dynamic context, Wirl (1997) analyzed the optimal extraction of non-renewable resources when resource consumption generates a stock externality—such as fossil fuel use contributing to global warming through carbon dioxide emissions.

In the field of pollution taxation, Benchekroun and Long (1998) characterized the optimal tax rule when emissions cause both present and future damages due to pollution accumulation. Assuming an oligopolistic market structure, their study accounted for firms' strategic interdependence, recognizing that each firm's current and future actions influence its rivals. Extending this framework, Benchekroun and Long (2002) derived corrective tax rules for a monopolist producing emissions that accumulate over time, showing how government tax schemes can correct both pollution externalities and market power distortions.

Addressing global environmental issues, De Zeeuw (2008) examined voluntary international cooperation in mitigating cross-border externalities such as global warming. Using an optimal control framework, he identified strategies for phasing out emissions over time at minimal cost.

In the context of leader–follower dynamics, Groot et al. (2003) proposed a differential Stackelberg game between a resource cartel (leader) and a competitive fringe (follower), providing a time-consistent solution for markets of exhaustible natural resources. Similarly, Jørgensen and Zaccour (2001) modeled two neighboring countries jointly managing pollution emissions through a differential game involving both emission and abatement investment as control variables. Their coordinated solution maximized joint welfare and could be implemented as an incentive equilibrium, with each country's emission strategy linearly dependent on the other's emission level.

For feedback Stackelberg differential games, Long and Sorger (2010) considered cases in which a principal induces an agent to exert effort on a shared state variable affecting both parties' welfare. They demonstrated that the leader's optimization problem could be reformulated as a standard optimal control problem. In comparing open-loop and feedback equilibria, Long et al. (1999) found that in resource depletion games, open-loop solutions tend to be more conservationist.

Martin-Herrán and Rincón-Zapatero (2005) contributed by developing a method to characterize Pareto-efficient Markov perfect Nash equilibria in nonlinear differential games, introducing a computational approach based on quasilinear partial differential equations. Shimomura and Xie (2008) explored dynamic "common-property resource games" to analyze leader–follower behavior, showing that Stackelberg equilibria may not always exist under

open-loop or feedback strategies and that restricting analysis to linear strategies can overlook superior nonlinear solutions.

Focusing on air pollution and global warming taxation, Ploeg and Withagen (2012) demonstrated that when the atmosphere is already heavily polluted with CO_2, it may be socially optimal to postpone fossil fuel depletion, mitigating further contributions to global warming while managing existing pollution stocks.

Regarding environmental traps and multiple equilibria, Wirl (2004) used the framework of Ayong Le Camma (2001) to highlight two properties not previously emphasized: stable limit cycles as optimal long-run intertemporal policies and multiple equilibria separated by a threshold curve in the state plane. The surprising possibility of history-dependent outcomes arose even within a strictly concave model. Mäler et al. (2003) studied pollution dynamics in shallow lakes using a highly nonlinear optimal control model, identifying multiple saddle equilibrium points and complex system dynamics. Kossioris et al. (2008) showed that for nonlinear differential games, the steady state of the best feedback Nash equilibrium (FBNE) may differ substantially from the optimal management steady state and that even when these steady states are close, the welfare value under FBNE can be significantly lower. Extending this, Kossioris et al. (2011) adapted the shallow lake model of Mäler et al. (2003) into a differential game, deriving optimal state-dependent tax structures that steer the economic-ecological system toward the optimal management trajectory and providing an algorithm for calculating such taxes.

More recently, De Zeeuw (2024) provided a modern synthesis of differential game applications in environmental economics, reviewing open-loop and Markov-perfect Nash equilibria, the maximum principle, and dynamic programming methods, with applications to international pollution control and ecological systems exhibiting tipping points. Building on this, Zhou et al. (2024) used a differential game framework to examine how carbon-trading policies affect firm production under different market structures. Their results show that firms with lower carbon emission quotas set higher product prices under a cap-and-trade system, while market competition levels critically shape the adoption of low-carbon technologies.

In related work, Zhang (2024) developed a dynamic game analyzing strategic interactions between carbon taxation by a coalition of resource consumers and energy pricing by a producers' cartel in the presence of potential innovation in low-cost, carbon-free technologies. Although innovation timing is uncertain, R&D investment can influence its arrival. The study finds that expectations of innovation reduce both initial carbon taxes and producer prices, leading to higher early-period resource extraction and emissions.

At the regional level, Tu et al. (2024) modeled asymmetric regions engaging in a differential game to compare governance regimes—non-cooperative Nash, cost-compensation, and collaborative cooperation—and found that cooperative approaches yield higher environmental and welfare outcomes. Meanwhile, Buccella et al. (2024) examined an N-firm oligopoly with abating and non-abating firms, analyzing how a regulator's dynamic tax policy influences firms' incentives to undertake emission-reduction investments. They showed that

the regulator's behavior—whether following a fixed or optimal rule—significantly affects the speed and extent of industry-wide abatement efforts.

In summary, these studies collectively emphasize the importance of dynamic modeling, strategic interactions, and optimal policy design in managing pollution and resource use. They provide a strong theoretical foundation for analyzing pollution control mechanisms through differential game theory and optimal taxation. Building on this literature, the present research focuses on developing a dynamic framework that integrates pollution accumulation, strategic behavior among economic agents, and optimal policy interventions aimed at achieving sustainable environmental outcomes.

3. The Model

3.1. Setup

The model considers the conflict between the government and polluters in a given region. The two players are:

1. **Polluters** (firms emitting pollutants)
2. **The government** (responsible for pollution control)

We assume an upper bound on the volume of pollutants and a stock of pollutants at time t, the growth of which is influenced by three factors:

- polluters' activities,
- natural purification, and
- government abatement efforts.

It is well known that polluters continually seek new cost-effective ways to dispose of pollutants (Halkos 1994). On the one hand, pollutant accumulation grows due to imitation effects among firms; on the other hand, new firms may enter the market, further increasing emissions. Thus, the evolution of pollutant accumulation follows a diffusion process, modeled as a logistic growth function. For now, we denote the growth function as $G(.)$ which is unimodal and symmetric around its inflection point. Let u represent the polluters' effort, interpreted as the time during which firms emit pollutants. Since the marginal effect of polluters' effort diminishes with increasing effort, the growth term in the system dynamics is denoted $G(u)$.

The pollutant stock decreases through two mechanisms:

1. **Natural purification**, occurring at rate δ, and
2. **Government abatement**, financed from pollution-control funds.

The government can allocate its budget between two instruments:

- **Abatement investment** (directly reduces pollutant stock), and
- **Taxation enforcement** (increases the risk of firms being caught and paying surcharges).

Let $a \in [0,1]$ denote the fraction of the budget allocated to abatement, while the remaining $(1-a)$ is devoted to taxation. The effect of abatement is given by the expression $A(x)$, where x is the pollutant stock and $A(x)$ is continuous over the relevant interval. Let v represent the government's total expenditure on pollution control.

We assume that, for a fixed abatement effort, the absolute volume of abated pollutants increases with the pollutant stock, though at a diminishing relative rate: $\frac{d}{dx}\left(\frac{A(x)}{x}\right) < 0$

This reflects the intuition that the more concentrated the pollutants, the more can be removed; however, the efficiency of abatement decreases unless resources are increased. Doubling the abatement effort will not double the success rate but will yield a smaller proportional increase.

The game is thus a **two-player, non-zero-sum differential game**, with the following features:

Control variables:
- u: effort of the polluting firms
- v: effort of the government in pollution control

State variable:

- x: stock of pollutants

Payoff structure:

- Polluters derive utility from emissions (monotonically increasing in u), but face compliance costs due to government taxation and surcharges. With no control actions by either side, compliance costs are zero: $C(0,0) = 0$, i.e. costs increase linearly in both the government's enforcement effort and the polluters' compliance effort
- The government faces costs from pollutant accumulation (damage function $D(x)$) and from its control efforts (cost function $K(v)$).

Both players discount future utilities at rates ρ_1, ρ_2, respectively.

Formally, the pollutant stock can be viewed as a continuously produced (renewable) "bad output": preserved by polluters, harvested by the government (Halkos and Papageorgiou, 2017). The system dynamics thus resemble a **harvesting model,** but with the distinctive feature that polluters' costs depend directly on government control efforts. Moreover, we denote the taxation efficiency by θ.

For tractability, we specify the following functional forms:

$$G(u) = u - \frac{1}{2}u^2, \qquad A(x) = avx, \qquad C(u,v) = \theta uv, \qquad D(x) = \frac{1}{2}x^2, \qquad K(v) = \frac{1}{2}v^2$$

With these specifications, the model retains the desired properties while remaining analytically manageable. We avoid the standard diffusion form for $G(u)$ to simplify the analysis, though the chosen function shares its qualitative properties.

The two-player game is therefore described as follows (with J_1 denoting the polluters' reward and J_2 the government's payoff):

$$\max_u J_1(u,v) = \int_0^\infty [u - \theta uv]\, e^{-\rho_1 t} dt$$

$$\max_v J_2(u,v) = \left[\int_0^\infty -\frac{1}{2}x^2 - \frac{1}{2}v^2\right] e^{-\rho_2 t} dt$$

Subject to the state dynamics:

$$\dot{x}(t) = G(u) - \delta x - avx, \qquad x(0) = x_0$$

3.2. The HJB equations

We suppose the players use feedback (state dependent) strategies. Denote the polluters' value function by $V_1(x)$ and the government's value function by $V_2(x)$. Under an infinite horizon discounted framework, the HJB equations are (for smooth $V_i, i = 1,2$).

Polluters (player 1):

$$\rho_1 V_1(x) = \max_{u\geq 0}\{U(u) - C(u,v(x)) + V_1'(x)[G(u) - \delta x - av(x)x]\} \qquad (1)$$

Where: $U(u) = u, \quad C(u,v(x)) = \theta uv,$

Government (player 2):

$$\rho_2 V_2(x) = \max_{v\geq 0}\left\{-\frac{1}{2}x^2 - \frac{1}{2}v^2 + V_2'(x)[G(u(x)) - \delta x - avx]\right\} \qquad (2)$$

The cost–to–go.

Since the first derivative $V_i', i = 1,2$ of both value functions V_i is the cost–to–go (Dockner et al, 2000), i.e. the avoided future environmental damages from reducing emissions today (this means the **shadow price of sustainability),** it quantifies what traditional economics often treats as "externalities" – the hidden costs of environmental degradation that don't appear in market prices but have enormous consequences for the social welfare. Therefore, it is plausible to clarify for that moment (and later more details) at least their signs.

The following Lemma 1 gives, in economic terms, the sufficient reasoning about the positivity of the polluters' marginal value V_1' that appears in the HJB equation (1).

Lemma 1.
Under the model assumptions:
$U(u) = u$ is strictly increasing in u
$G(u) = u - \frac{1}{2}u^2$
$C(u, v) = \theta uv$ with $\theta > 0$
v is a given (nonnegative) government enforcement path of a feedback rule $v(x) \geq 0$
Controls are admissible and chosen from a set of that allows arbitrarily small local perturbations (the hard lower/upper bounds other than $u(x) \geq 0$,
Discount rate $\rho_1 > 0$.
Then the polluters' value function $V_1(x)$ satisfies $V_1'(x) > 0$ at any state x where the optimal controls interior.

Proof
In the Appendix

Economic Interpretation of Lemma 1

A higher pollutant stock benefits polluters at the margin because:
- The government's purification and enforcement effectiveness decreases with a larger stock.
- Higher x relaxes the state equation $\dot{x} = G(u) - \delta x - avx$ in the sense that the marginal effect of new emissions on total stock is smaller.
- This increases the future payoff from emitting.

Thus: $dV_1/dx > 0$.

This matches the interpretation in differential games with renewable bads (e.g., Halkos–Papageorgiou, 2017).

Lemma 1 states:
Polluters' marginal value of the pollutant stock is positive: $V_1'(x) > 0$ that is, **when the pollution stock increases, polluters become better off at the margin** (as long as their optimal emission choice is interior).

The economic intuition is:
(a) More pollution reduces the effectiveness of government control: When the stock of pollutants is high, it is harder and more costly for the government to remove pollution through abatement. Abatement exhibits **diminishing returns, that means** when the stock of pollutants x is small, each unit of abatement removes a relatively large fraction of the pollutants; conversely when x is large, each unit of abatement removes only a small fraction.

(b) Polluters benefit from a "large buffer" of existing pollution: A large stock of pollution acts like a **shield** for polluters since it becomes politically and administratively harder for the government to intensify enforcement enough to bring pollution down. Moreover, high current pollution makes additional emissions less costly at the margin, and polluting firms know that in a polluted environment, the government would need **much larger** investments to effectively reduce the stock.

Thus, a higher stock today means:

- **lower expected future enforcement intensity,**
- **lower effective punishment from taxation,**
- **greater future opportunities to emit profitably.**

This raises the polluters' continuation value.

(c) Interior optimization requires enforcement to be strong enough: For polluters to choose an interior effort level (not zero and not maximum), enforcement must be strong enough to "tame" emissions. This implies:

- **the marginal cost of emissions is already high,**
- **but not high enough to shut polluters down.**

In this situation, any factor that *reduces* future enforcement pressure—such as a higher pollution stock—**increases the polluters' payoff**.

(d) Pollution today raises profits tomorrow: Because pollution is a renewable "bad":

- polluters *produce* it (emissions),
- government tries to *remove* it (abatement).

When the stock is larger:

- the government's ability to remove it weakens,
- the marginal effect of emissions is diluted,
- enforcement is less effective,
- polluters retain more profitable opportunities in the future.

Thus:

Polluters value a marginal increase in the stock because it improves their future payoff stream.

This is exactly why:

$$V_1'(x) > 0$$

For the government's marginal valuation of pollutants, we provide the following Lemma 2.

Lemma 2

Under the model assumptions:

(a) government instantaneous payoff is $R(x, v) = -\frac{1}{2}x^2 - \frac{1}{2}v^2$,

(b) the state evolves under any admissible pair $(u(.), v(.))$ as

$$\dot{x}(t) = G(u(t)) - \delta x(t) - av(t)x(t)$$

with $G(u) = u - \frac{1}{2}u^2$. The government control set is measurable and includes interior controls $v(t) \geq 0$

(c) the polluters path $u(.)$ is either fixed (follower case) or anticipated by the government (leader case); in either interpretation the realized $u(.)$ is nonnegative and measurable

(d) Discount rate $\rho_2 > 0$

(e) Value function $V_2(x) = \sup_{v(.)} J_2(v(.); x)$ exists and is differentiable in a neighborhood of the point of interest (this holds under standard HJB regularity assumptions and interior optimality).

Statement:
Under the above assumptions, for every $x > 0$ at which the government's optimal control is interior, the marginal valuation of the government for the pollutants is negative, i.e.,

$$V_2'(x) < 0$$

Proof
In the Appendix

Economic intuition of Lemma 2

- **Immediate damage rises with x.** The government pays an instantaneous damage cost $D(x) = \frac{1}{2}x^2$. A marginal increase in x raises current damage directly, lowering the present value of welfare.
- **Higher x forces more costly abatement in the future.** Abatement is costly ($\frac{1}{2}v^2$) and becomes less efficient per unit (recall diminishing returns). A larger stock raises the future control burden and expected future expenditures, reducing the government's continuation value.
- **Marginal tradeoff in the government's decision rule.** From the government's optimal strategy (see below equation(7)) $v^*(x) = -axV_2'(x)$, we see that when x rises the government responds by increasing v (since $-V_2'(x) > 0$). That response itself is costly. The negative $V_2'(x)$ captures both the **direct** extra damage from a marginal unit of pollution and the **indirect** effect of the extra costly control it induces.
- **Interpretation as a desire to reduce the "bad" stock.** While polluters value a larger x (a buffer, as in Lemma 1), the government values a smaller x. So, the marginal value is negative: the government would be willing to pay (in present-value terms) to reduce x by one marginal unit.

3.3. Best responses (simultaneous move game)

Proposition 1:
The feedback best strategies for both players are given by the following expressions:
For the polluters the feedback equilibrium policy is: $u^*(x) = 1 + \frac{1+a\theta xV_2'(x)}{V_1'(x)}$ (3)
For the government is: $v^*(x) = -axV_2'(x)$ (4)

Proof
The FOC of the polluters w.r.t. u is:

$$\frac{\partial\{U(u) - C(u, v(x)) + V_1'(x)[G(u) - \delta x - av(x)x]\}}{\partial u} = 1 - \theta v + V_1'(x)(1-u) = 0$$

and:

$$u^*(x) = 1 + \frac{1+a\theta xV_2'(x)}{V_1'(x)} \quad (5),$$

since $v(x) = -axV_2'(x)$.
The FOC for the government w.r.t. v is:

$$\frac{\partial\left\{-\frac{1}{2}x^2 - \frac{1}{2}v^2 + V_2'(x)[G(u(x)) - \delta x - avx]\right\}}{\partial v} = -v + V_2'(x)(-ax) = 0 \quad (6)$$

So, the government's optimal strategy will be:

$$v^*(x) = -axV_2'(x) \qquad (7)$$

3.4. Economic interpretation of the strategies

We have:
$u^*(x)$ is the polluters effort, i.e. the emissions
$v^*(x)$ is the government's control effort
$V_1'(x), V_2'(x)$ are the marginal values of an extra unit of pollution for each player

The government's strategy: $v^*(x) = -axV_2'(x)$:

- Since the government's value function decreases when pollution rises, $V_2'(x) < 0$ (Lemma 2).
- Therefore, $v^*(x) > 0$, i.e. the government invests in abatement or taxation to reduce pollution.
- The effort is proportional to the pollution stock, that means the higher the concentration of pollutants, the more the government invests in control policy.
- The proportionality is scaled by a: i.e. if the government allocates more of its budget to abatement (large a) the response to rising pollution is stronger.

Economic meaning: the government behaves like a regulator who reacts more aggressively as the environmental quality worsens. The linear dependence on the pollutants stock x reflects a policy that is "stage–contingent" rather than fixed in advance.
Some additional economic intuition is: the strategy $v^*(x) = -axV_2'(x)$ gives an intuitive feedback rule: the government's enforcement v is proportional to the product of the pollution stock x and the *absolute* marginal value of the stock $(-V_2')$. The larger the harm from pollution (more negative V_2') or the larger the stock, the stronger the enforcement effort. And, at the extreme, if the government is at a boundary $v = 0$ (no abatement), the necessary condition is $-axV_2'(x) \leq 0$, so $V_2'(x) \geq 0$ could occur — but economically that would represent states where abatement is not optimal at all (e.g., extremely small x or prohibitive abatement costs). For interior, economically relevant operating points, $V_2'(x) < 0$.

The polluters strategy: $u^*(x) = 1 + \frac{1+a\theta xV_2'(x)}{V_1'(x)}$

- The polluters' emissions decision depends on the marginal cost of pollution control faced by the government $V_2'(x)$, and the polluter's own marginal valuation of pollution $V_1'(x)$
- If government's marginal valuation of pollution is steep, i.e. $|V_2'(x)|$ is large, then the quantity $a\theta xV_2'(x)$ becomes strongly negative implying the numerator shrinks, which in turn implies that the polluters reduce emissions.
- Conversely, if government is relatively indifferent ($|V_2'(x)|$ is small), polluters tend to emit more, since the perceived risk of taxation or enforcement is low.
- The denominator $V_1'(x)$ captures how much polluters care about the future consequences of pollution (through taxation or compliance costs). If they discount heavily ($V_1'(x)$ is small), emissions rise.

The economic meaning of the polluters' strategy could be that: Polluters balance immediate gains from emissions with expected costs from government enforcement. Stronger regulatory effort (large a, efficient taxation θ) discourages emissions.

Government–polluters interaction

The government's abatement depends on pollution stock x, while polluters' emissions depend on how strictly the government is expected to respond.

This creates a feedback loop as the following:

- If pollution rises, the government increases effort $v^*(x)$
- Anticipating this, the polluters reduce their emissions $u^*(x)$
- This stabilizing mechanism prevents pollution from exploding indefinitely

However, because multiple equilibrium points are possible the final pollution path depends on the initial state and parameters $(\delta, a, \theta, \rho_1, \rho_2)$.

3.5. Multiplicity of equilibrium

Because both $u^*(x)$ and $v^*(x)$ strategies are nonlinear in the state variable x, the right–hand side of

$\frac{dx}{dt} = \dot{x}$ can be a nonlinear function, and this means:

(1) There may be one, two or three steady states x^*

(2) Some steady states are stable (convergence), while others are unstable (divergence)

This result, economically speaking, represent different pollution regimes (e.g., "clean state', "moderate state", or even "severe degradation", depending on the government interact. This alter of one state to another gives rise to bifurcation mechanism for some parameters, like θ, a, δ, of the model.

We give an economic interpretation of bifurcation as follows:

Path dependence: When multiple exist, the long – run outcome depends on initial pollution x_0

- If it starts below, it converges to the clean equilibrium
- If the system starts above the unstable threshold, it drifts toward to high pollution equilibrium

Policy sensitivity: small changes in enforcement (a, θ) or natural purification δ can suddenly eliminate bad equilibrium.

Environmental traps: With weak government enforcement, the system can be stuck in a pollution trap (stable high–pollution equilibrium). Only a strong enough policy shift (parameter change) can push the system into the clean regime.

3.6. The bifurcation occurrence.

In our model, a bifurcation happens when a parameter (e.g., taxation efficiency θ, abatement share a, natural purification δ) changes such that the number of equilibrium changes, e.g., if the government becomes slightly more effective in enforcement, θ rises, the high pollution equilibrium disappears. The latter economically means that a small policy improvement can suddenly prevent society from being trapped in permanent environmental degradation.

A wider economic interpretation of bifurcation may include the following:

- **Path dependence**: whether a region ends up clean or dirty depends not just on policy but also on the initial level of pollution
- **Tipping points**: once parameters cross critical thresholds, the system undergoes a sudden regime shift (from pollution trap to sustainable path)
- **Policy implication**: incremental improvements may look ineffective until a threshold is crossed, after which the economy naturally converges to the clean equilibrium.

In a few words, bifurcation reflects the idea that economies can get locked into high–pollution traps, but small, well–targeted changes in policy effectiveness can trigger a qualitative shift, which eliminates dirty equilibrium and pushing environment into a sustainable trajectory.
In Figure 1 we can see the bifurcation diagram.

Bifurcartion diagram: Pollution equilibrium vs taxation efficiency

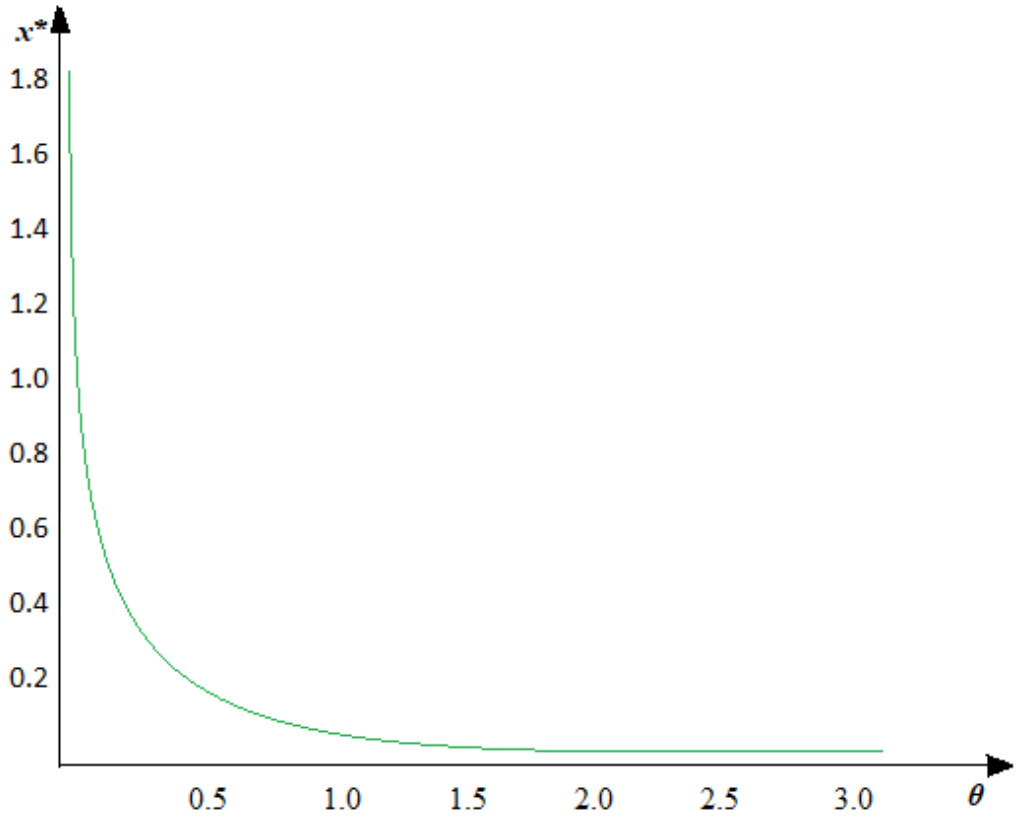


Figure 1.
As taxation efficiency θ rises, the environment shifts from multiple equilibrium world (environmental traps) to a unique sustainable regime

3.7. Check for stability

We check the stability with the given above function specifications, i.e. the emissions growth as: $G(u) = u - \frac{1}{2}u^2$, and the abatement function as $A(x) = avx$, where u is the

polluters effort, v the government effort. The next result determines the local stability condition in terms of model parameters, the controls u^*, v^* and the state variable x^*.

Proposition 2
The steady state equilibrium of the model is locally asymptotically stable if the following inequality holds:

$$\delta + a\big(v^* + x^* v_x(x^*)\big) > (1-u^*)u_x(x^*) \qquad (8)$$

Proof
We set $F(x;\theta) = G(u^*(x)) - \delta x - av^*(x)x$. A steady state x^* satisfies $F(x^*;\theta) = 0$. The steady state is locally asymptotically stable iff the linearization at x^* has negative slope, i.e.

$$F_x(x^*;\theta) = \frac{\partial F}{\partial x}|_{x^*} < 0$$

With the above function specifications

$$F_x(x^*) = (1-u^*)u_x(x^*) - \delta - a\big(v^* + x^* v_x(x^*)\big) < 0$$

Or equivalently

$$\delta + a\big(v^* + x^* v_x(x^*)\big) > (1-u^*)u_x(x^*)$$

The economic intuition of this proposition is the following.

Corollary 1
Stability occurs when damping (natural purification δ plus marginal abatement $a(v + xv_x)$ outweighs the strategic amplification from firms $(1-u)u_x$.
Proof
Follows from the stabilization condition (8).

A special case
In the feedback case the polluters increase emissions when pollution rises, $u_x > 0$, the LHS term $(1-u)u_x$ is positive and destabilizing. Therefore, in order to achieve stability required sufficiently strong natural purification δ and/or abatement strength a and a government rule that increases v with the pollutants x, it means that a positive marginal government effort ($v_x > 0$) contributes in further stabilization via the axv_x term. Conversely, if polluters reduce emissions when pollution rises, i.e. the marginal polluters effort is negative ($u_x < 0$) then it is a stabilization factor.

4. The Stackelberg game. Leader is the government

We examine the same model as a leader–follower game when leader is the government.
The dynamics is

$$\dot{x}(t) = G(u) - \delta x - avx,$$
$$G(u) = u - \frac{1}{2}u^2, \qquad \delta > 0, \quad a \in [0,1]$$

Polluters' payoff

$$J_1(u,v) = \int_0^\infty [u - \theta uv]\, e^{-\rho_1 t} dt$$

Government's payoff

$$J_2(u,v) = \left[\int_0^{\infty} -\frac{1}{2}x^2 - \frac{1}{2}v^2\right] e^{-\rho_2 t} dt$$

the discount rates are: ρ_1, ρ_2

4.1. The open loop case

Follower's problem (the polluters):
Take the government's path $v(t)$ as given and choose $u(t)$ to maximize their current – value objective (Hamiltonian) which is:

$$H_1(x,u,\lambda;t) = u - \theta u v(t) + \lambda(t)\left[u - \frac{1}{2}u^2 - \delta x - av(t)x\right]$$

Where $\lambda(t)$ is the current value costate of the follower. The necessary conditions (FOC) for an interior maximum are:

$$\frac{\partial H_1}{\partial u} = 0 \Rightarrow 1 - \theta v(t) + \lambda(t)\big(1 - u(t)\big) = 0$$

This result is recorded as:

Proposition 3.
The follower open–loop best response of the Stackelberg game between government and polluters is:

$$u(t) = 1 + \frac{1 - \theta v(t)}{\lambda(t)} \qquad (9)$$

Provided $\lambda(t) \neq 0$.

The time evolution of the costate is

$$\dot{\lambda}(t) = \rho_1\lambda(t) - \frac{\partial H_1}{\partial x} \Rightarrow \dot{\lambda}(t) = \rho_1\lambda(t) - \lambda(t)\big(-\delta - av(t)\big) \qquad (10)$$

Leader's (government's) problem:
The government chooses $v(t)$ to maximize J_2 subject to the state dynamics and the fact that the follower chooses $u(t)$ according to the best respond relation (9) and (10). Therefore, the leader's problem is the following:

$$\max_{v(.)} \left[\int_0^{\infty} -\frac{1}{2}x^2 - \frac{1}{2}v^2\right] e^{-\rho_2 t} dt$$

Subject to

$$\dot{x}(t) = G(u) - \delta x - avx$$

and the follower's costate equation $\dot{\lambda}(t) = \rho_1\lambda(t) - \lambda(t)\big(-\delta - av(t)\big)$

The current–value Hamiltonian for the leader is:

$$H_2(x,\lambda,v,p,q) = -\frac{1}{2}x^2 - \frac{1}{2}v^2 + p\left[u(t) - \frac{1}{2}u^2(t) - \delta x - avx\right] + q(\lambda(\rho_1 + \delta + av))$$

With $u = 1 + \frac{1-\theta v}{\lambda}$, and the costates $p(t), q(t)$ for the states $x(t), \lambda(t)$ respectively.

taking FOC for the Hamiltonian H_2 w.r.t. v, we have $\frac{\partial H_2}{\partial v} = 0$ and after substituting the value u from (9) yields the following explicit formula for the optimal open–loop government control $v(t)$ in terms of the current states $x(t), \lambda(t)$ and the corresponding costates $p(t), q(t)$.
This result is recorded as in the next proposition:

Proposition 4.
Consider the open–loop Stackelberg game in which the government (leader) chooses a control path $v(t)$ and the polluters (follower) take that path as given. Let the polluters' current – value costate be $\lambda(t)$, the government's costates associated to $x(t)$ and $\lambda(t)$ be $p(t), q(t)$ respectively. Assume an interior solution and $\lambda(t) \neq 0$ for all t. With

$$G(u) = u - \frac{1}{2}u^2, \qquad C(u, v) = \theta u v$$

the government's optimal open–loop control in the Stackelberg game is given by the expression:

$$v(t) = \frac{a\lambda(t)^3 q(t) - a\lambda(t)^2 p(t) x(t) + p(t)\theta}{\lambda(t)^2 + p(t)\theta^2} \qquad (11)$$

Proof
In the Appendix

Economic Interpretation of Proposition 4.
One economic interpretation of the above open–loop Stackelberg equilibrium could be the following:

- Commitment power: the government moves first, credibly committing to a long–run policy path. This is stricter than a feedback rule (in which it could re–optimize each period).
- Polluters react passively: this means that they optimize given that path. Hence, their emissions are "strategically softened" by government foresight.
- Government internalizes externality: unlike polluters, it values the stock of pollution as $-\frac{1}{2}x^2$. It sets v high enough to discipline polluters but balances that with policy cost $-\frac{1}{2}v^2$.
- Efficiency gap: because the government uses open – loop informational structure, it cannot fine–tune regulation based on the actual pollution trajectory. If the stock deviates (e.g. shocks), the policy may be inefficient compared to the feedback Stackelberg solution

Economic intuition:
Proposition 4 states: When the government acts as an open-loop Stackelberg leader, its optimal enforcement path, $v(t)$, is a complex function that depends not only on the pollution stock $x(t)$ and its own shadow price $p(t)$, but also on the polluters' shadow price $\lambda(t)$ and the government's shadow price for the polluters' shadow price, $q(t)$.
While equation (11) appears mathematically dense, its economic intuition can be broken down into three powerful strategic concepts.

(a) The government's role revised

In an open-loop game, the government doesn't just set policy for the environment; it sets policy for the entire strategic system. It must account for how its actions today will shape the polluters' future incentives and, consequently, their future emissions.

- $\boldsymbol{p(t)}$ (Shadow price of pollution): This is the standard cost the government associates with a marginal unit of pollution. A more negative $p(t)$ means pollution is very damaging, incentivizing stronger enforcement $v(t)$. This is the direct effect.
- $\boldsymbol{\lambda(t)}$ (Polluters' shadow price)**:** This represents the value polluters attach to a marginal unit of pollution stock (which, from Lemma 1, is positive). The government must monitor this. If polluters see high future value in a polluted world ($\lambda(t)$ is large and positive), they are less deterred by current policy. The government's strategy must react to this polluter morale.
- $\boldsymbol{q(t)}$ (Shadow price of the polluters' shadow price)**:** This is the most sophisticated element. $q(t)$ captures how much the government gains or loses when the polluters' incentives ($\lambda(t)$) change. It turns the polluters' shadow price into a state variable that the government actively manages.

Economic Interpretation: The government isn't just fighting pollution; it's strategically managing the *expectations and incentives* of the polluting sector over time.

(b) The government's Influence

The numerator of the equation (11) shows the three ways through which the government determines its optimal enforcement:

- **Way 1: Managing Polluter Incentives ($\boldsymbol{a\lambda(t)^3 q(t)}$)**
  (i) This term represents the government's incentive to manipulate the polluters' future behavior.
  (ii) If the government can make polluters more fearful of future pollution (i.e., influence $\lambda(t)$ to be less positive), it can reduce emissions more cheaply.
  (iii) **Intuition:** When $q(t)$ is negative, it means the government benefits from *reducing* the polluters' marginal value of pollution. This term can lead to higher initial enforcement to "break the polluters' spirit" and convince them that a high-pollution future is not profitable.
- **Way 2: The Direct Cost of Pollution ($\boldsymbol{-a\lambda(t)^2 p(t)x(t)}$)**
  (i) This is a compound term reflecting the direct damage from pollution. Since $p(t)$ is negative (pollution is bad), the term $-a\lambda(t)^2 p(t)x(t)$ becomes positive, pushing for higher $v(t)$.
  (ii) It is weighted by $\lambda(t)^2$, meaning the government's urgency is amplified when polluters are highly motivated by the existing stock ($\lambda(t)$ is large).
- **Way 3: The Immediate Deterrent Effect ($\boldsymbol{p(t)\theta}$)**
  (i) This is the most straightforward channel. It says that stronger enforcement is optimal when taxation is more efficient (θ is high) and when pollution is very costly ($p(t)$ is highly negative).
  (ii) **Intuition:** This is the classic Pigouvian logic: tax the bad thing. The higher the social cost and the more efficient the tax, the higher the tax should be.

(c) Commitment and Its Consequences

The denominator, $[\lambda(t)^2 + p(t)\theta^2]$, acts as a balancing factor, ensuring the solution is interior and finite. More importantly, the open-loop nature implies a key trade-off:

- **Strength of Commitment:** By pre-committing to an entire path of $v(t)$, the government can powerfully influence polluters' long-term investment and emission plans. It can credibly promise a tough future, which deters pollution today.
- **Inflexibility is a Weakness:** The government cannot adjust its policy if the system is hit by a shock. If pollution turns out to be higher or lower than expected, the pre-committed path $v(t)$ may be wildly inefficient compared to a feedback rule that can adapt to the actual state $x(t)$.

4.2. The feedback case

In the feedback case of the same model, we begin again with the follower's problem.When the government announces a state dependent feedback rule $v(x)$, the follower solves the HJB equation:

$$\rho_1 V_1 = \max_{u\geq 0}\{u - \theta u v(x) + w_1(x)[G(u) - \delta x - av(x)x]\} \qquad (12)$$

Where: $w_1(x) = V_1'(x)$

Taking the FOC of HJB (12) and setting $G(u) = u - \frac{1}{2}u^2$, we conclude in:

Proposition 5

The follower's best strategy in the feedback Stackelberg game, given the leader feedback $v(x)$ and marginal value $w_1(x)$, is:

$$u_S(x; v) = 1 + \frac{1 - \theta v(x)}{w_1(x)} \qquad (13)$$

Now substituting best response $w_1(x)$ into the HJB (12) yields the nonlinear ODE for the follower's value function, that depends parametrically on the leader's feedback $v(.)$

$$\rho_1 V_1 = u_S - \theta u_S v + w_1[G(u_S) - \delta x - avx] \qquad (14)$$

We turn now in the leader's side. The government as leader chooses a feedback rule $v(x)$ and its feedback HJB, anticipating the follower's response $u_S(x; v)$, is:

$$\rho_2 V_2 = \max_v \left\{-\frac{1}{2}x^2 - \frac{1}{2}v^2 + w_2(x)[G(u_S(x; v)) - \delta x - avx]\right\} \qquad (15)$$

and $w_2(x) = V_2'(x)$

Note that u_S depends on v and $w_1(x) = V_1'(x)$. The leader's maximization must therefore account for the direct effect of v (through $-\frac{1}{2}v^2$ and the $-avx$ term) and the indirect effect through the follower's change in emissions u_S. The indirect effect produces an extra term in the first order condition proportional to $\frac{\partial u_S}{\partial v}$. The leader's feedback policy is recorded as in the next proposition.

Proposition 6

Consider the feedback Stackelberg game where the government (leader of the game) announces a state–dependent enforcement rule $v(x)$ and the polluters (follower) respond with $u_S(x;v)$. Let:

- $V_1(x)$ and $V_2(x)$ be the polluters and government's value functions, with derivatives $w_1(x) = V_1'(x)$ and $w_2(x) = V_2'(x)$
- $G(u) = u - \frac{1}{2}u^2$, so $G'(u) = 1 - u$
- the follower best–response in feedback form be: $u_S(x;v) = 1 + \frac{1-\theta v(x)}{w_1(x)}$

Assuming an interior optimum, the government's feedback optimal policy satisfies the expression:

$$v_s(x) = -axw_2(x) - \frac{\theta w_2(x) G'\left(u^*(x;v_s)\right)}{w_1(x)}$$

Proof

Differentiate HJB (15) to get the FOC (we set for brevity: $u^* = u_S(x;v)$)

$$0 = -v_S - axw_2(x) + w_2(x)G'(u^*)\frac{\partial u^*}{\partial v_S} \qquad (16)$$

In order to complete the leader feedback equilibrium strategy, we need the partial derivative $\frac{\partial u^*}{\partial v_S}$. The implicit differentiation of (13), treating w_1 as a function of x only, yields:

$$\left(\frac{\partial u^*}{\partial v_S}\right)_{w_1} = -\frac{\theta}{w_1(x)} \qquad (17)$$

Substituting (17) into (16) to obtain the leader's FOC in a local form

$$0 = -v_S - axw_2 - w_2G'(u^*)\frac{\theta}{w_1}$$

and rearrange, the leader's feedback policy becomes:

$$v_S(x) = -axw_2(x) - \frac{\theta w_2(x) G'\left(u^*(x;v_S)\right)}{w_1(x)} \qquad (18)$$

It is worth to mention: The comparison of the FOC (16) of the feedback case and the corresponding FOC (6) in the open – loop (Nash) case, here in FOC (16), appears the extra term $w_2G'(u^*)u_v$ that captures how the leader leverages a marginal change of v to change the follower's emission u.

Economic intuition and comparative statics

Inspecting the two players best feedback policies can read off the key forces:

- The follower's best response $u_S^* = 1 + \frac{1-\theta v}{w_1}$ says that the polluters reduce emissions when either (i) the leader increases his intensity, i.e. larger taxation or more tight abatement, or (ii) the follower's marginal value w_1 is large, which in turn means that polluters internalize future penalties.

- The leader's feedback (18) has two terms: (i) the direct reaction to current pollution (same as in Nash case), i.e. the term $-axw_2$, and (ii) the Stackelberg leverage term (or Stackelberg advantage), i.e. the term $-\frac{\theta w_2 G'(u^*)}{w_1}$. This magnitude increases with taxation effectiveness θ and with the leader's marginal valuation w_2. The government's Stackelberg advantage has the intuition that uses taxation not just to reduce current pollution, but also to steer polluters' incentives by leveraging the best–response function. Moreover, it is divided by w_1, that means the smaller the follower's marginal value, the larger must adjust v to induce a given change in emissions.
- Policy implications:

  1. When the taxation effectiveness θ is large, the leader can credibly commit to a smaller change in his effort v and obtain a large reduction in emission effort u, that means the Stackelberg advantage is large.

  2. When polluters are very patient (large $|w_1|$), they are more responsive to future expected penalties, so the larger can use immediate enforcement.

  3. The Stackelberg leader typically chooses a stronger reaction to the state (higher taxation/abatement effort $v(x)$) than under Nash play when it allows a favorable change in polluters' behavior.

Advantages of feedback Stackelberg equilibrium

- Stronger policy than Nash: Since the government accounts for how its moves shifts the polluters' best response, the Stackelberg outcome usually features tougher enforcement (higher counter pollution effort v) and lower emissions realizations (smaller u) than in simultaneous feedback Nash equilibrium (comparing the Nash policies (4), (5) with the Stackelberg (18), (13).
- Taxation efficiency θ as leverage: if θ is high, taxes are very effective in curbing emissions, so the Stackelberg advantage is large, that means the government can credibly commit to lower actual enforcement while still inducing strong polluter compliance.
- Dynamic credibility: Because this is a feedback Stackelberg equilibrium, the policies are time – consistent, which means the government doesn't need to pre-commit to unrealistic long – term tax schedules. At every state of pollution x, the announced policy remains optimal.
- Stackelberg can eliminate exploding/trap outcomes. Under the Nash policy, the system lacked a bounded steady state for chosen parameters (pollution would grow). Under Stackelberg leadership a stable steady state exists, that means leadership prevents the environmental economy falling into an unchecked pollution path.

In short, the economic intuition is that the Stackelberg equilibrium allows the government to exploit its leadership role, credibly steering polluters' behavior through a mix of abatement and taxation. The policy implication is that credible, adaptive leadership combined with efficient monitoring technology delivers stronger and more consistent environmental protection than simultaneous (Nash) interaction.

4.3 On Stackelberg advantage

In the Nash equilibrium, the government's optimal policy is $v^*(x) = -axw_2(x)$

And in the Stackelberg case, because the government anticipates how polluters adjust emissions u when it changes enforcement v, its best policy gains an extra term, and becomes:

$$v_S(x) = -axw_2(x) - \frac{\theta w_2(x)G'(u^*)}{w_1(x)}$$

Where: $w_1 = V_1'$ and $w_2 = V_2'$.

The intuition in the Nash structure is that the government only considers the direct marginal trade–off: higher enforcement increases compliance but costs resources. It treats emissions u as if fixed when adjusting his effort v. In the Stackelberg setting, the government knows polluters will lower their emissions when enforcement rises.

The following Lemma 3 gives the formal definition of the Stackelberg advantage for the game case.

Lemma 3. (Stackelberg advantage in Environmental Enforcement).

Consider the feedback Nash equilibrium and the feedback Stackelberg equilibrium with government leadership, as defined by the strategies(7) and (18) respectively.

Assume that at a given pollution stock x, the following economically justified conditions hold:

- The government's marginal valuation of pollution is negative, $w_2(x) = V_2'(x) < 0$ (Lemma 2)
- The polluters' marginal valuation of pollution is positive, $w_1(x) = V_1'(x) > 0$ (Lemma 1)
- Emissions are below the growth–maximizing level, $G'(u^*(x)) = 1 - u^*(x) > 0$

Then, for any $x > 0$, the government's optimal enforcement effort is strictly greater under the leadership than in the simultaneous–move game

$$v_S(x) > v^*(x)$$

This difference, defined as the Stackelberg Advantage $\Delta_S(x)$, is given by:

$$\Delta_S(x) = v_S(x) - v^*(x) = -\frac{\theta w_2(x)G'(u^*(x;v_S)}{w_1(x)} > 0$$

Proof

Form the difference:

$$\Delta_S(x) = v_S(x) - v^*(x) = -axw_2(x) - \frac{\theta w_2(x)G'(u^*(x;v_S)}{w_1(x)} - \left(-axw_2(x)\right)$$

$$= -\frac{\theta w_2(x)G'(u^*(x;v_S)}{w_1(x)}$$

We examine the signs of each component:

θ is the taxation efficiency, and therefore by definition $\theta > 0$

$w_2(x)$ is the government's marginal pollution valuation and, by assumption, $w_2(x) < 0$

$G'(u^*(x;v_S)$ by assumption (c) of Lemma 3 is a positive magnitude, i.e. $G'(u^*(x;v_S) > 0$

$w_1(x)$ representing the polluter's marginal valuation of the stock is by assumption (b) positive, i.e. $w_1(x) > 0$.

Hence, numerator is negative and denominator positive and taking the overall minus sign, the final outcome is a positive magnitude for the difference, i.e. $\Delta_S(x) > 0$.

Economic remarks on the advantage

The marginal benefit of enforcement is amplified as: one extra unit of enforcement not only directly reduces current damages, but it also induces polluters to scale back emissions in

anticipation. Therefore, the first mover advantage is a strategic multiplier, because it adds the indirect effect of enforcement on emissions to the government calculus. Economically speaking, the Stackelberg advantage reflects commitment power, the latter means the government as leader, commits to a feedback enforcement policy. The polluting firms rationally anticipate this and internalize enforcement costs, choosing lower emissions. Moreover, the advantage term $\frac{\theta w_2(x)G'(u^*)}{w_1(x)}$ is proportional to $-\frac{\theta w_2}{w_1}$ which means if monitoring/tax efficiency θ is high the advantage is bigger, and when the polluters are more forward – looking (i.e. large w_2 relative to government w_1) the government gains more advantage. Concluding, without leadership (i.e. in the Nash case), this channel is absent, that means enforcement looks less effective and equilibrium pollution is higher. Therefore, the Stackelberg advantage term is the policy – maker ability to "bend" private incentives by acting first, i.e. the enforcement doesn't just punish but it reshapes expectations and behavior.

5. Stackelberg game. The polluters as leader

5.1. Open loop

We form the follower's (government's) Hamiltonian as:

$$H_2 = -\frac{1}{2}x^2 - \frac{1}{2}v^2 + \mu(t)\big[G\big(u(t)\big) - \delta x - avx\big]$$

$\mu(t)$ is the current–value costate.

Proposition 7

The optimal government's strategy in the Stackelberg game at which the polluters lead is:

$$v(t) = -ax(t)\mu(t)$$

Proof

Taking the FOC

$$\frac{\partial H_2}{\partial v} = -v + \mu(-ax) = 0 \Rightarrow$$

$$v(t) = -ax(t)\mu(t) \qquad (19)$$

The government's costate dynamics evolves according to the following equation:

$$\dot{\mu}(t) = \rho_2\mu(t) - \frac{\partial H_2}{\partial v} = \rho_2\mu(t) + x(t) + \mu(t)[\delta + av(t)] \qquad (20)$$

And the transversality condition is: $\lim_{t\to\infty} \mu(t)e^{-\rho_2 t} = 0$

In order to form the leader's Hamiltonian, we denote by $\lambda(t)$ the leader's costate associated with the state x and with $\eta(t)$ the costate associated with the state μ which is entered into the leader's optimal control problem, i.e. the differential equation (20) becomes the evolution of the second state variable.

Proposition 8

The polluters' open–loop optimal strategy in Stackelberg game at which the follower is the government is:

$$u^*(t) = 1 + \frac{1 + \theta a\mu(t)x(t)}{\lambda(t)}$$

Proof

The leader's Hamiltonian is the following:

$$H_1 = u + \theta a\mu xu + \lambda\left[G\left(u(t)\right) - \delta x - a^2\mu x^2\right] + \eta[\rho_2\mu + x + \mu(\delta - a^2\mu x)]$$

the FOC is (setting $G\left(u(t)\right) = u - \frac{1}{2}u^2$ and $G'\left(u(t)\right) = 1 - u$):

$$\frac{\partial H_1}{\partial u} = 1 + \theta a\mu x + \lambda(1 - u) = 0$$

and the optimal strategy for the leader:

$$u^*(t) = 1 + \frac{1 + \theta a\mu(t)x(t)}{\lambda(t)} \qquad (21)$$

Summary the open – loop strategies in compact form are (substituting (19) into (21)):

$$v(t) = -ax(t)\mu(t) \qquad (22)$$

$$u(t) = 1 + \frac{1 - \theta v(t)}{\lambda(t)} \qquad (23)$$

Economic intuition of the open loop equilibrium

In the open loop Stackelberg game the polluters (leader of the game), commits at time $t = 0$ to an emission path $u(t)$. The government (the follower) optimally chooses its abatement effort $v(t)$, taking the leader's path as given. Consequently, because of the commitment, the strategies depend on time and not on the current pollution stock. Thus, the polluters can exploit their first mover advantage by shaping the government's regulatory response in advance. The polluters in one hand, they don't know that higher emissions trigger more aggressive abatement from the government. In the open – loop setting, the polluters take into account how their emission choice today influences the government's costate dynamics $\mu(t)$, i.e. the shadow value of pollution in the government's problem. The optimal strategy therefore reflects to the trade–off (a) of the direct gain from higher emissions and (b) indirect cost from inducing higher regulatory effort. The government on the other, minimizes environmental damages and abatement costs. Since it moves second, it reacts passively to the emissions path already chosen by polluters, therefore, its abatement policy $v(t)$ is not chosen to shape long – run expectations but simply to best respond to the pollution dynamics given by the leader. As a policy consequence, the government loses commitment power. It cannot threaten "tough future policy" to discipline polluters, only reacts passively. Concluding, the open – loop Stackelberg equilibrium (with polluters as leader) captures the strategic disadvantage of regulators when they lack commitment. By committing early, firms lock in a high – emission trajectory, forcing governments into reactive regulation.

5.2. The feedback case

In the feedback case the polluters choose a state–dependent policy $u(x)$ and the government takes a feedback strategy $v(x)$ as its control variable when solving its HJB.

Thus, the follower's HJB is:

$$\rho_2 V_2 = \max_{v \geq 0}\left\{-\frac{1}{2}x^2 - \frac{1}{2}v^2 + V_2'(x)[G(u(x)) - \delta x - avx]\right\} \qquad (24)$$

And taking FOC we get the same as before equilibrium strategy of the government, i.e. the strategy:

$$v^*(x) = -axw_2(x) \qquad (25)$$

Where $w_2(x) = V_2'(x)$.

The polluters HJB is:

$$\rho_1 V_1(x) = \max_{u\geq 0}\{u - \theta u v^*(x) + V_1'(x)[G(u) - \delta x - a v^*(x)x]\} \qquad (26)$$

While the FOC is:

$$1 - \theta v^*(x) + V_1'(x)(1-u) = 0$$

setting $V_1'(x) = w_1(x)$

$$u^*(x) = 1 + \frac{1 - \theta v^*(x)}{w_1(x)}$$

and the final form of the polluters' strategy is (substituting (25) into the latter):

$$u^*(x) = 1 + \frac{1 + a\theta x w_2(x)}{w_1(x)} \qquad (27)$$

Thus, the pair of the feedback strategies in the Stackelberg game, at which the polluters lead, are given by (25) and (27).

6. Comparative statics

In order to make comparative statics more comprehensive we assume certain signs for the marginal values and for the model parameters as well. Thus, the assumptions are:
$w_2 = V_2'(x) < 0$ the government's value falls when pollution rises
$w_1 = V_1'(x) > 0$ the polluters marginal value of pollution is positive
$a > 0, \theta > 0, x > 0, \delta > 0$

The effect of taxation efficiency θ
The polluters is the leader of the game (feedback equilibrium, and the optimal strategies are symbolized as u_P for the polluters and v_P for the government):

Corollary 2.
A change in taxation effectiveness has no effect on the government's strategy, in the case the polluters lead.

Proof
$v_P(x) = -axw_2 \Rightarrow \frac{\partial v_P}{\partial \theta} = 0$ (indifferent – no effect)

Corollary 3
When the polluters lead in the Stackelberg game, an increment on taxation effectiveness reduces emissions.
Proof

$u_P(x) = 1 + \frac{1+a\theta x w_2}{w_1} \Rightarrow \frac{\partial u_P}{\partial \theta} = \frac{axw_2}{w_1} < 0$ (28) (since $w_2 < 0$). Higher θ reduces emissions when polluters lead.

The government is the leader of the game (feedback equilibrium, and the optimal strategies are symbolized as u_G for the polluters and v_G for the government):

Corollary 4
In the Stackelberg game in which the government is the leader, an increase at the taxation effectiveness raises the government's effort.

Proof
Taking the first derivative of government's optimal strategy $v_G(x)$ w.r.t. to θ:
$v_G(x) = -axw_2 - \frac{\theta w_2 G'(u_G)}{w_1} \Rightarrow \frac{\partial v_G}{\partial \theta} = -\frac{w_2 G'(u_G)}{w_1}$ with $w_2 < 0$ and if $G'(u_G) > 0$ (i.e. $u_G < 1$) $\frac{\partial v_G}{\partial \theta} > 0$, so increasing θ raises v_G.
This in turn implies that higher tax efficiency makes government first mover advantage more powerful, so the leader (the government) can exploit taxation more, which increases the marginal returns to enforcement.

Corollary 5
In the case the government is the leader, an increase to the taxation effectiveness θ cause the polluters' emissions u to fall. The reduction is stronger than in the case the polluters lead in the same game.

Proof
We take the first derivative of the polluters' optimal strategy: $\frac{\partial u_G}{\partial \theta} = \frac{-v_G}{w_1} < 0$ (29) means polluters emissions fall. We compare (28) with (29) and government's optimal strategy (18) to conclude the emissions' reduction is stronger in the case the government lead.

Concluding, raising taxation effectiveness θ reduces emissions in both regimes, but the reduction is larger when the government is the leader. Government leadership converts a rise in effectiveness θ into extra enforcement (the first mover advantage term) and thus stronger emission reductions.

The effect of the abatement share a
The polluters is the leader of the game (for the feedback equilibrium, and the optimal strategies are symbolized as u_P for the polluters and v_P for the government):

Corollary 6
Both leadership regimes deliver lower emissions and higher government effort when the abatement effectiveness a rises.

Proof
(a) Increasing abatement share a increase government effort.

Taking the first derivative of the government policy w.r.t a:

$v_P(x) = -axw_2 \Rightarrow \frac{\partial v_P}{\partial a} = -xw_2 > 0$ means increasing abatement share increase government effort

(b) The greater abatement share, the more the emissions reduction.

$u_P(x) = 1 + \frac{1+a\theta xw_2}{w_1} \Rightarrow \frac{\partial u_P}{\partial a} = \frac{\theta xw_2}{w_1} < 0$. So, more abatement share reduces emissions (because it raises the follower's abatement response and therefore increases expected compliance costs).

(c) When government leads:

$v_G(x) = -axw_2 - \frac{\theta w_2 G'(u_G)}{w_1}$ The first term $-axw_2$ increases in a. The first mover advantage term scales with w_2 and $G'(u_G)$ and is independent of a directly. The results are: increasing a increases v_G but reduces u_G.

The effect of current state x

Both regimes entail increasing government effort v with the increase in state x, but the slope dv/dx is larger when the government leads, because of the additional Stackelberg advantage term. That means the government leader reacts more strongly to increases in x, and this stronger v_x helps stabilization as we can see from the stabilization condition (8). Moreover, from the same condition (8) and since government leadership give larger v^* and larger v_x, one can see that both raise the LHS of the stability inequality, and therefore is less likely to allow multiple equilibrium states or pollution traps.

Welfare comparisons

The government objectives are the lower environmental damage $-\frac{1}{2}x^2$ minus the control cost $-\frac{1}{2}v^2$. A government leader can typically achieve higher welfare than it is follower, because it can credibly choose enforcement that disciplines polluters and internalizes the externality. So, the government leadership is better than the polluters' leadership for the social and environmental welfare. Concerning the polluters welfare, when they lead implies that they get the strategic advantage and therefore can often extract a higher payoff (higher emissions, lower expected future penalties. So, the polluters leadership is better for her welfare therefore favoring its private payoff. Moreover, the worser is polluter leadership weakens the stabilizing influence on the LHS of the stability condition (8). With a smaller or less responsive government effort v, the system is more likely to exhibit multiple steady states and get stuck in a high – pollution trap.

7. On the affine form of the Value Functions

As we can see the value functions (and its derivatives) appear in almost the paper as the most interesting factor of the HJB equation. In fact, the Value Function is the **"best possible performance you can achieve"** starting from a given state and time. To do this, answers the question: "If I am at time t and in state x, and I act *optimally* from now until the end of the problem, what is the maximum reward I will incur?" **Its role in the HJB Equation it is, since**

the Hamilton-Jacobi-Bellman (HJB) equation is not just an equation that the value function satisfies, a **necessary and sufficient condition for optimality** derived from the principle of optimality. Obviously, there are a lot of advantages if one knew the closed form of that value function. For the linear value functions, one of the best properties is the solution, derived from that value function, has excellent stability properties. Under mild conditions (controllability, observability), the closed-loop system is guaranteed to be globally asymptotically stable. Below, we record some results for the model under consideration concerning the affine forms of the value functions for both players of the game.

We begin with the polluters value function.

Lemma 4
Under the model assumptions:
$U(u) = u$ is strictly increasing in u
$G(u) = u - \frac{1}{2}u^2$, $C(u,v) = \theta uv$ with $\theta > 0$
$D(x) = \frac{1}{2}x^2$, $K(v) = \frac{1}{2}v^2$,
v is a given (nonnegative) government enforcement path of a feedback rule $v(x) \geq 0$
State dynamics: $\dot{x}(t) = G(u) - \delta x - avx$,
Polluters' payoff is: $R(u,v) = U(u) - C(u,v)$
Government's payoff: $\Pi(x,v) = -\frac{1}{2}x^2 - \frac{1}{2}v^2$
Assume:
parameters $a, \theta, \rho_1, \rho_2 > 0$ are fixed, the feedback strategies are smooth and equilibrium controls are interior on an open interval I containing $x = 0$, we look for $V_1 \in C^2(I)$.
Then there exist coefficients $q_1, r_1 \in \mathbb{R}$ such that the polluters' value function

$$V_1(x) = q_1 x + r_1$$

satisfies the polluter HJB on I with the interior feedback

$$u(x) = 1 - \frac{\theta v(x) - 1}{q_1}, \qquad v(x) = -axq_2$$

provided the standard nondegeneracy condition (full rank Jacobian of the coefficient matching system) hold and the interiority/sign constraints for u and V_1' are satisfied on the interval I.

Proof
In the Appendix

Economic interpretation of Lemma 4 (Polluters' Value function: $V_1(x) = q_1 x + r_1$)

(a) Constant marginal value of pollution stock
Because

$$V_1' = q_1$$

the polluter's marginal continuation payoff from the pollution state does **not depend on the level of pollution itself.**
Economic meaning:

- Increasing pollution by one unit today affects future payoffs by the same amount regardless of current pollution.

- The polluter does **not internalize increasing marginal environmental damage** — consistent with externality theory.
- Their incentives are driven not by environmental consequences, but by how x affects regulatory pressure $v(x)$.
-

(b) Decisions depend only on regulatory intensity, not on the pollution stock

The optimal polluter control is

$$u(x) = 1 - \frac{\theta v(x) - 1}{q_1}$$

Since q_1 is constant, the polluter adjusts emissions in reaction to the **current enforcement level only**, not to pollution levels directly.

This reflects a key policy insight:
"Polluters respond to enforcement, not to the environment"
Therefore, if regulators want lower emissions, enforcement must increase with x — which is what the government feedback $v(x)$ is designed to do.

(c) Higher q_1 implies weaker reaction to enforcement

$$\frac{\partial u}{\partial v} = -\frac{\theta}{q_1}$$

A larger q_1 means:
- The polluter values future payoff more
- Emissions become less sensitive to regulation
- Enforcement must be more aggressive to reduce emissions

The interpretation is: forward looking firms are harder to regulate because they discount future penalties less.

(d) Smaller **q_1 implies stronger regulatory leverage**

If q_1 is low (polluters discount the future heavily), then:
- They focus on short – run profit $U(u)$
- Enforcement measures $v(x)$ have strong impact
- Even mild penalties reduce emissions significantly

This is typical when firms face limited planning horizons or high uncertainty.

(e) r_1 captures baseline profits independent of pollution. The value of r_1 is calculated as:

$$r_1 = \frac{1}{\rho_1}\left(\frac{q_1}{2} + 1 + \frac{1}{2q_1}\right)$$

- r_1 shifts the value function vertically,
- represents base profitability even when $x \approx 0$,
- unaffected by marginal pollution cost or policy.

Interpretation: profits exist even in a clean environment — emissions are not necessary to earn revenue, only profit-enhancing up to a point.

(f) Linearity implies absence of tipping points or catastrophes

Unlike convex $V_1(x)$, which might reflect rising risk, the linear form implies:
- Polluters do not anticipate thresholds where pollution becomes dramatically costly.
- No "danger zone" — marginal damage is perceived as constant.
- They continue emitting until enforcement makes it unprofitable.

This is a strong but policy-meaningful simplification: catastrophic environmental risks are completely externalized.

Some **policy implications** drawn according to Lemma 4 are the following:

(a) If the government wants to reduce emissions, then it must raise enforcement $v(t)$ more steeply in emissions x

(b) If wants to regulate farsighted firms (i.e. high q_1) she must enforce more aggressively

(c) If she wants to reduce pollution stock faster, then it must increase the abatement share a or increase the taxation effectiveness θ.

(d) In order to internalize the externality, the policy must make the marginal valuation V_1' decreasing, and not constant.

The following Lemma 5 establishes the linear value function of the government.

Lemma 5

Under the model setup:

State dynamics: $\dot{x}(t) = G(u) - \delta x - avx,\ G(u) = u - \frac{1}{2}u^2,\ A(x) = avx,\quad C(u,v) = \theta uv$

with $\theta > 0$, $D(x) = \frac{1}{2}x^2$, $K(v) = \frac{1}{2}v^2$,

Polluters' payoff is: $R(u,v) = U(u) - C(u,v)$

Government's payoff: $\Pi(x,v) = -\frac{1}{2}x^2 - \frac{1}{2}v^2$

Government's discount rate $\rho_2 > 0$

Assume:

(a) parameters $a, \theta, \rho_1, \rho_2 > 0$ are fixed,

(b) The players use smooth feedback strategies and the equilibrium controls are interior on an open interval of states containing $x = 0$

(c) Solutions are sought in the class of twice continuously differentiable functions.

Then there exist coefficients $q_2, r_2 \in \mathbb{R}$ (at least locally in parameter space) such that the government's value function

$$V_2(x) = q_2 x + r_2$$

satisfies the government HJB with the implied interior feedback control

$$v(x) = -axV_2'(x) = -axq_2$$

with $V_2'(x) < 0$, provided a certain nondegeneracy (Jacobian) condition holds. In other words, a linear function for V_2 reduces the HJB to a finite algebraic system for (q_2, r_2) and—under a regularity/nondegeneracy condition—that algebraic system has a (local) solution.

Proof

In the Appendix

Economic intuition of Lemma 5

At its heart, Lemma 5 states that the government's marginal cost of pollution is constant. This is a powerful, albeit simplifying, assumption with profound implications for environmental policy.

Let's break down what $V_2(x) = q_2 x + r_2$, $V_2'(x) = q_2 < 0$ mean in economic terms.

(a) Constant Marginal Damage $V_2'(x) = q_2 < 0$

- **This means:** The government's value function decreases linearly with the pollution stock. An additional unit of pollution (e.g., one more ton of CO_2 in the atmosphere) causes the same amount of damage to social welfare, regardless of whether the environment is currently pristine or already heavily polluted.
- **Economic Interpretation:**
  This implies the government does **not** perceive accelerating or non-linear catastrophic risks from pollution accumulation. The damage cost is proportional and predictable.
  In reality, many environmental damages are thought to be convex (getting worse at an increasing rate), but the linear case represents a situation where the primary costs are direct, proportional impacts on public health, agricultural productivity, and infrastructure, without triggering irreversible tipping points *within the model's relevant range*.
- The negativity ($q_2 < 0$) is straightforward: more pollution is unambiguously bad for society. The government's "shadow price" of pollution is negative, meaning it would be willing to pay a certain amount to reduce the pollution stock by one unit.

(b) The Government's Feedback Rule ($v^*(x) = -axV_2'(x) = -axq_2v^*(x) = -axV_2'(x) = -axq_2$)

- **It means:** The government's optimal enforcement and abatement effort, v, is a simple, linear function of the observed pollution stock x. Since q_2 is a negative constant, $-axq_2$ is positive and increases with x.
- **Economic Interpretation:**
  "Pollution begets abatement." The government's strategy is purely reactive. It looks at the current pollution level and applies a fixed, proportional response. If pollution doubles, the government's effort also doubles.
  No Sophisticated Foresight in Execution: While the government solved a dynamic optimization problem to *find* this rule (q_2 was determined optimally), the *implementation* of the rule is myopic. The government doesn't need to constantly re-solve a complex dynamic policy; it just follows the simple rule: "See pollution level X, deploy effort level Y."
- **Transparency and Credibility:** Such a linear rule is highly transparent and easy to communicate to the public and polluters. Firms can clearly anticipate the government's response to their actions, which can have a disciplining effect. This makes the policy credible.

(c) The Absence of a "Danger Zone" or Tipping Point Mentality

- **The meaning is:** Because the marginal damage is constant, the government's urgency to act does not intensify disproportionately as pollution climbs.
- **Economic Interpretation:**
  In models with convex damage (where $V_2''(x) < 0$), the government would become increasingly desperate and aggressive as pollution approaches a critical threshold. Its

response rule $v(x)$ would be highly non-linear, "ramping up" dramatically near the danger zone.

In this linear model, the government is a "steady hand." It treats a unit of pollution the same way, whether the stock is low or high. This suggests a policy focused on steady, predictable management rather than emergency intervention to avert catastrophe.

This is both a strength (predictability, stability) and a potential weakness (it may fail to prevent actual non-linear ecological collapses that exist outside the model's assumptions).

(d) The Intercept r_2 – The Value of a Pristine Environment

- **Meaning:** r_2 is the value function when $x = 0$. It represents the present value of all future welfare when the environment is clean, accounting for the costs of keeping it that way.
- **Economic Interpretation:**
  r_2 captures the "baseline welfare" in an ideal world without pollution. It is determined by the fundamental parameters of the economy: the discount rate (ρ_2), the cost of control ($K(v)$), and the natural purification rate (δ).

A higher r_2 implies that the long-run potential of the economy, absent the pollution problem, is high.

Summary in Policy Terms

Lemma 5 paints a picture of a government that acts as a "proportional controller" for the environment.

- **It diagnoses the problem with a constant metric:** Every additional unit of pollution is judged to be equally harmful.
- **It prescribes a treatment with a fixed dosage:** The "medicine" (abatement and enforcement effort) is administered in direct proportion to the "fever" (the pollution stock).
- **The policy is simple and robust:** The government doesn't need to second-guess whether the situation is at a tipping point. It just follows its pre-committed, linear rule.

This linearity is a tractable approximation that provides a clear benchmark. It shows that even without modeling complex, accelerating damages, a state-dependent feedback rule emerges as optimal, and the strategic dynamics between the government and polluters remain rich and highly relevant for environmental policy.

8. Pollution traps

As mentioned above pollution traps appear whenever the system admits multiple steady states and the high–pollution steady state is locally stable. This is most likely when the government is follower in the Stackelberg game or in weak–enforcement Nash regime, conversely it is least likely when the government leads and uses the Stackelberg first mover advantage in a feedback rule. In our model case, once the system is trapped in high pollution, one way to recover in a clean state is to augment the taxation θ and/or abatement a efficiencies. More precise, as the planner vary the parameters under consideration the system can undergo a

saddle node bifurcation, that means two equilibrium (middle unstable and high stable) collide and annihilate as damping increases, eliminating the trap.

We begin with the stability condition (8), i.e. the condition $\delta + a(v^* + x^* v_x^*) > (1-u^*)u_x^*$ of proposition 2. The LHS of the condition is the damping, i.e. the natural purification δ plus the direct abatement av plus the incremental stabilizing effect axv_x from government increasing effort when pollution rises. The RHS is the amplification, i.e. the strategic response of polluters $(1-u)u_x$ and in words: how emissions increase when pollution rises, scaled by the marginal growth factor $(1-u)$. According to Kuznetsov (2004), a saddle node bifurcation at (x^*, p^*) occurs when two equilibrium collide and annihilate. Supposing the closed–loop scalar dynamics $\dot{x} = F(x;p)$, where p denotes the bifurcation parameter (in the model proposed $p = \theta$ or $p = a$) and $F(x;p) = G\big(u(x;p)\big) - \delta x - av(x;p)x$, the standard necessary conditions are:

$F(x^*;p^*) = 0$ (30) equilibrium condition, and

$F_x(x^*;p^*) = \frac{\partial F(x^*;p^*)}{\partial x} = 0$ (31) degeneracy (double root) condition

and together $(30)-(31)$ mean x^* is a double root of the algebraic equation $F(x^*;p^*) = 0$
In addition to $(30)-(31)$ it is needed the following conditions

$F_{xx}(x^*;p^*) \neq 0$ (32) non–degenerate fold

$\frac{\partial F(x^*;p^*)}{\partial p} \neq 0$ (33) transversality condition

If $(30)-(33)$ all hold, there is a generic saddle – node bifurcation at $(x^*;p^*)$

8.1. A case of pollution traps

In order to illustrate previous discussion about the pollution traps we consider the proposed model in the cases other than the Stackelberg game in which the government leads (since the possibility to trapped in high pollution is less, due to the Stackelberg advantage). As it is stated by Lemma 4 and Lemma 5 the value functions for both players are linear, therefore their derivatives are constants. We denote theses constants by $W_1 > 0, W_2 < 0$.
Under these value functions:

$v(x) = -axW_2$

$u(x) = 1 + \frac{1+a\theta xW_2}{W_1}$

$u_x = \frac{1+a\theta W_2}{W_1}$

$v_x = -aW_2$

$G'(u) = 1-u$

Define $A = aW_2 < 0$ and $B = W_1 > 0$
The following proposition considers the threshold of high–pollution trap.

Proposition 9.
The threshold level of taxation effectiveness that separates regimes with and without environmental traps is given by the expression:

$$\theta^* = \frac{-\delta - \sqrt{(W_1^2 - 1)(2W_2a^2 - \delta^2)}}{W_2 a} \qquad (34)$$

Provided: $0 < W_1 < 1$, i.e. the polluters' marginal value W_1 is not too large (since $W_2 < 0, W_2 \leq \frac{1}{2}\left(\frac{\delta}{a}\right)^2$ is always true).

Proof

In the appendix

Remarks on parameters

(a) **Dependence on the natural decay rate δ**

- δ appears both directly in the numerator $(-\delta)$ and inside the square root through $(2W_2a^2 - \delta^2)$. Because $W_2 < 0$ the term $(2W_2a^2 - \delta^2)$ becomes more negative as δ increases, which increases the square root magnitude. Together the numerator $-\delta - \sqrt{(W_1^2 - 1)(2W_2a^2 - \delta^2)}$ becomes more negative as δ grows, since the denominator W_2a is negative, this makes the threshold θ^* larger.
- The **implication** is: increasing the natural decay rate δ raises the critical threshold θ^*. Because traps occur for $0 < \theta < \theta^*$, raising θ^* expands the parameter interval where traps can occur.

(b) **Dependence on the abatement share**

- a appears in the denominator W_2a in linear form and inside the radicand in quadratic as $2W_2a^2$. For $W_2 < 0$ increasing a makes $2W_2a^2 - \delta^2$ more negative in magnitude, increasing the square root.
- The **implication**: increasing the abatement share a tends to reduce the critical threshold θ^*, therefore shrinking the trap interval $0 < \theta < \theta^*$, so strong abatement makes pollution traps less likely. This matches intuition: stronger direct abatement shrinks the parameter region where weak taxation would allow traps.

(c) **Dependence on polluters' marginal value W_1.**

- The radicand contains the factor $(W_1^2 - 1)$. For $0 < W_1 < 1$ that factor becomes negative but approaches zero as $W_1 \to 1$. As W_1 increases towards unity the discriminant shrinks and the algebraic structure can permit multiple equilibrium. If W_1 becomes larger than one the square root becomes negative therefore is rejected.
- **Implication**: a higher polluters' marginal value W_1 pushes the system into parameter ranges with more complex equilibrium structure, which intuitively means that makes traps more likely or makes the distinction between regimes sharper.

(d) **Dependence on government's marginal value W_2**

- W_2 appears on the denominator and inside the square root. Since $W_2 < 0$, making W_2 more negative (government more averse to pollution) tends to reduce θ^* (because the denominator magnitude increases and the radicand changes sign) shrinking the trap interval.
- The **implication** is: stronger government aversion to pollution (more negative W_2) helps prevent pollution traps.

Economic summary:

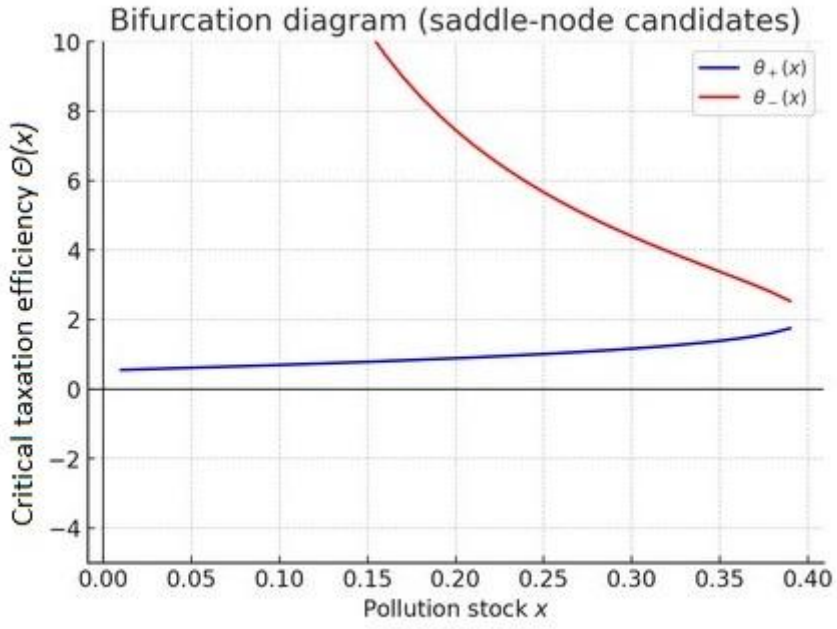
- Pollution traps exist when $0 < \theta < \theta^*$. In that interval taxation is too weak (relative to system dynamics and abatement) and the high pollution steady state survives.

- No trap when $\theta > \theta^*$. Effective taxation (large θ), higher abatement share a, or stronger government aversion (more negative W_2) reduce or remove the high – pollution steady state.

Economic implications of Proposition 9

Proposition 9 demonstrates that environmental dynamics are characterized by a critical threshold of taxation effectiveness, θ^*, which divides the economy into two distinct long-run regimes. When taxation efficiency is weak ($0 < \theta < \theta^*$), the system remains vulnerable to a high-pollution trap, as policy intervention is insufficient to counteract the self-reinforcing accumulation of pollution. In contrast, when taxation exceeds the threshold ($\theta > \theta^*$), the high-pollution equilibrium disappears and the economy converges to the clean steady state, indicating that effective environmental policy is not gradual but instead operates through a threshold mechanism. The parameters shaping this threshold further highlight the structural fragility of the system: stronger abatement efforts and greater governmental aversion to pollution lower $\theta^*$and reduce the likelihood of environmental traps, whereas a higher marginal value of pollution for firms raises the risk of multiple equilibria. Interestingly, although natural decay reduces pollution intrinsically, it raises the critical threshold, implying that natural resilience alone does not guarantee recovery and may even delay policy-induced escape from a trap. Overall, Proposition 9 emphasizes that pollution traps arise only when policy remains below a critical intensity, and decisive intervention—rather than incremental adjustment—is required to shift the economy onto a sustainable low-pollution path.

Figure 2



Bifurcation diagram:

The blue branch $\theta_+(x)$ and the red branch $\theta_-(x)$ represent the two possible critical thresholds $\theta^*(x)$ at which steady states collide and vanish. Where both branches exist (for some range of x), the system admits multiple equilibria: a low pollution and a high pollution steady state. Beyond the turning points, only one equilibrium remains. For $\theta < \theta^*$, the system can be stuck

in a high – pollution equilibrium. When θ crosses the critical value, the high – pollution state disappears, and the system naturally converges to the clean equilibrium.

8.2. General Economic Implications of Pollution Traps

The existence of pollution traps fundamentally changes the economic narrative of environmental regulation from a simple, continuous trade-off to a problem of dynamic instability and regime shifts. This has critical implications for policy design, investment, and long-term economic planning

- **Implications for Environmental Policy Design**

(a) **The Importance of Policy Credibility and Commitment:** A pollution trap is a self-reinforcing equilibrium sustained by expectations. If polluters believe the government will relent on enforcement when costs rise (a lack of commitment), they will anticipate that high pollution will eventually become the tolerated norm. Credible, long-term commitment to a policy path (like a rising carbon tax schedule) is not just beneficial but essential to convince firms that the high-pollution regime is permanently closed off, steering expectations toward the clean equilibrium.

(b) **Targeting Critical Policy Levers:** The model identifies that traps are most likely when taxation efficiency (θ) is low and the government is in a follower or Nash position. Therefore, the most effective policies are those that directly boost these critical parameters. This means:
Investing in monitoring and enforcement capacity (raising θ) is not a secondary administrative task but a primary strategic investment to eliminate the trap.
Asserting policy leadership (e.g., setting long-term, state-contingent targets) is a powerful tool to change the strategic game itself.

- **Implications for Economic Development**

(c) **Poverty-Environment Traps:** The model provides a formal structure for the classic "poverty-environment trap" narrative. A developing country may start with a moderately polluted state (x_0) and, due to weak institutions (low θ, a), find itself in the follower role to powerful polluting industries. This can lead to a trap where environmental degradation undermines public health and agricultural productivity, which in turn reduces the state's capacity to fund effective environmental regulation, perpetuating poverty and pollution.

(d) **The High Cost of Delayed Action:** Because the trap is a stable equilibrium, small, early interventions when the pollution stock is low (and the system is in the basin of attraction of the clean state) are cheap and effective. Once the system has crossed the unstable threshold into the trap's basin, the policy effort required to escape is discontinuous and vastly more expensive. This creates a powerful economic argument for precautionary and early intervention.

(e) **Intergenerational Inequity:** Falling into a pollution trap represents a profound failure of intergenerational equity. The current generation reaps the benefits of high emissions, while future generations inherit a degraded environment and are faced with the colossal cost of either living in a polluted world or engineering a costly escape from the trap. The dynamic inefficiency of the trap is also an intergenerational injustice.

- **Implications for the Role of Government**

(f) **Government as a "System Steerer" not a "Market Fixer":** The trap phenomenon elevates the role of government from merely correcting a static market failure (Pigouvian taxes) to managing the stability of a complex dynamical system. The government's key function is to ensure the economy operates within the "safe" basin of attraction leading to the sustainable equilibrium. This is a more profound and demanding role.

(g) **The Strategic Value of Leadership:** The analysis shows that the government's ability to act as a Stackelberg leader is a critical tool to eliminate traps. Leadership, in this context, is the ability to credibly commit to a future policy path, thereby shaping the expectations and investments of private actors to align with the clean equilibrium. It is a form of expectations management that is as important as the policies themselves.

- **Conclusions on Pollution traps**

The economic implications of pollution traps move the discourse beyond marginal analysis. They frame environmental policy as a problem of managing systemic risk and avoiding catastrophic regime shifts. The key takeaways for economists and policymakers are:

(a) **Focus on Thresholds, Not Just Trends:** Identify the critical levels of policy effectiveness (θ^*, a) and pollution stocks.

(b) **Prioritize Credibility:** Long-term, predictable, and state-contingent policies are essential to guide expectations.

(c) **Invest in Foundational Capacity:** Building monitoring, enforcement, and abatement capacity is a strategic investment to shift the system's dynamics.

(d) **Act Early and Decisively:** The cost of prevention is dwarfed by the cost of escaping a trap.

9. Discussion

The analytical results of the model are highlights in the economic policy design. The interplay between capital accumulation, environmental quality, and strategic behavior yields a set of robust insights.

The first of core economic insights concerns about the dynamic interdependence of capital and the environment. It is in common sense that capital accumulation and environmental quality evolve jointly and influence one another. Higher production boosts current consumption but accelerates environmental degradation, which reduces future productivity through climate damages. This mutual dependence creates intertemporal externalities that decentralized agents fail to internalize.

The second economic insight is the role of the shadow value of environmental quality that drives the optimal policy. Since the costate associated with environmental quality captures its long–run environmental value, this variable reflects the effect of environmental conditions on productivity, climate damages and future welfare. When climate feedback intensifies, the shadow value rises sharply, increasing optimal mitigation and altering the trajectory of capital and consumption.

Another important economic insight arises from the inefficiencies in decentralized equilibrium. In the Nash equilibrium, the agents internalize only private benefits of environmental quality while bearing the full private cost of mitigation. This leads to systematic under – mitigation, overuse of fossil capital, and faster economic deterioration. The resulting trajectory lies well below the socially optimal environmental and welfare outcomes. Additionally, a Stackelberg leader anticipates follower's responses, internalizing a larger share of the environmental externality. As a result, mitigation increases relative to Nash play. However, because global spillovers are not fully internalized, the Stackelberg outcome remains strictly between the decentralized and planner solutions.

Finally, the analysis concerns about the environmental stability and the threshold effects. The coupled system may produce stable or unstable steady states depending on the strength of climate feedback relative to regeneration and mitigation. Strong feedback or insufficient mitigation can produce instability, implying the presence of threshold dynamics and the possibility of irreversible environmental declines.

The policy implications drawn from the analytical results are:

(a) Need for coordinated mitigation to achieve global optimality: Because environmental quality is a global public stock, decentralized mitigation remains insufficient even with strong leadership. Achieving the social optimum requires coordinated climate policy—through binding agreements, harmonized carbon pricing, or cooperative burden-sharing arrangements.

(b) Leadership is a complement not a substitute for global cooperation: While leadership increases global mitigation, it cannot fully internalize worldwide spillovers. Climate leadership by major economies should therefore be complemented by cooperative institutions capable of enforcing broad participation and ensuring reciprocal commitments.

(c) Importance for early mitigation to avoid instability: that means, Unstable steady states indicate that delays in mitigation may push the system beyond recoverable thresholds. Policymakers should prioritize early action and credible long-term commitments to keep the system within stable, sustainable regions of the state space.

(d) Long–run gains from environmental restoration: Because environmental quality enhances productivity through reduced climate damages, investments in restoration—reforestation, pollution control, ecosystem regeneration—yield dual benefits: direct environmental improvements and long-run economic gains. These policies complement mitigation and reduce the required burden on emissions reduction.

(e) Role of international institutions: Effective governance of shared environmental stocks requires institutions that facilitate monitoring, information sharing, enforcement, and transfers. Without institutional support, equilibrium behavior will remain inefficient, and the system may drift toward unstable environmental trajectories.

In summary, the model highlights the importance of viewing climate and environmental policy through the lens of dynamic strategic interaction. Optimal policy requires internalizing the shadow value of environmental quality, coordinating mitigation across agents, and acting proactively to avoid destabilizing climate dynamics. Leadership helps, but lasting sustainability ultimately hinges on robust international cooperation supported by credible institutions.

Some thoughts of future research are drawn below:

The framework developed in this paper opens up several promising avenues for future research, which could further enhance the model's realism and policy relevance.

(a) **Empirical Calibration and Testing:** A primary next step is to calibrate the model using real-world data—for instance, from regional air pollution management or international carbon emissions. Estimating the key parameters (e.g., θ, a, the damage function, and the shadow values W_1, W_2) for specific industries or countries would allow for a test of the model's predictions and a quantification of the potential welfare gains from strategic leadership.

(b) **Incorporating Technological Change:** The current model treats technology as static. A critical extension would be to endogenize technological innovation, allowing firms to invest in green technology and the government to subsidize R&D. This would create a dynamic link between policy, market structure, and the cost of abatement over time.

(c) **Multi-Agent and Asymmetric Firm Models:** Extending the model to an oligopoly with heterogeneous firms (e.g., differing in abatement costs or market power) would yield richer insights. This could explore how strategic interactions among firms, combined with government policy, affect the industry's overall emission path and the potential for "green" firms to dominate.

(d) **International and Transboundary Pollution Context:** Scaling the model to an international setting with multiple governments (e.g., a coalition of committed "leader" countries versus "follower" countries) would be highly relevant for global challenges like climate change. This could analyze the conditions under which a subgroup of leading nations can trigger a global shift away from a high-pollution equilibrium.

10. Conclusion

This paper analyzed a dynamic differential game between polluters and the government under Nash and Stackelberg competition. The analysis of the dynamic game yields several critical conclusions regarding environmental policy, strategic interaction, and the potential for sustainable outcomes.

First of all, detected the Inherent Risk of Pollution Traps. The model demonstrates that an economy can become locked in a stable, high-pollution equilibrium—an "environmental trap." This path dependence means that the long-run environmental state depends not only on current policy but also on the initial level of pollution. This highlights the urgency of early and decisive intervention, as a deteriorating environment can become progressively harder to reverse.

Another result obtained is that strategic leadership is decisive. The distribution of strategic power significantly impacts environmental outcomes. **The analysis in the paper reveals the optimality of the government leadership.** When the government acts as a Stackelberg leader, it gains a crucial **first-mover advantage**. By committing to a state-

dependent policy, it can strategically influence polluters' expectations and behavior, leading to lower emissions and higher social welfare than in a Nash equilibrium. This leadership role is the most effective in preventing pollution traps. **Conversely the polluter Leadership is detrimental.** That means when polluters lead, they can exploit their commitment power to force the government into a reactive role, resulting in higher emissions and a greater risk of being trapped in a high-pollution state.

Concerning the policy parameters these can trigger tipping points as: The model identifies a **bifurcation mechanism**, where small continuous improvements in policy effectiveness can lead to a sudden, qualitative shift in the system. Incrementally increasing the efficiency of taxation (θ) or the share of the budget allocated to abatement (a) may have limited apparent effect until a critical threshold is crossed. Beyond this threshold, the high-pollution equilibrium vanishes, and the economy naturally converges to a clean state. This underscores that persistent, targeted policy improvements can yield disproportionate, transformative benefits.

In the model analysis is revealed the dual role of the government enforcement (v) which serves two purposes:

A direct effect that is, it directly reduces the pollution stock through abatement, and **an indirect strategic effect which** shapes polluters' future expectations and emission decisions. The **Stackelberg advantage** term quantifies this strategic benefit, showing that effective enforcement is not merely about punishment but about credibly altering the incentive structure for polluters.

Concerning environmental robustness, the model demonstrates that stability requires overcoming strategic amplification: The local stability of a clean equilibrium is not guaranteed. It requires that the combined forces of natural purification and proactive government policy (the **damping** effect) be stronger than the polluters' tendency to increase emissions as pollution rises (the **amplification** effect). Government leadership, by making enforcement more responsive to pollution levels ($v(x) > 0$), directly strengthens this damping effect and promotes stability.

Finally pointed out the key policy levers for success. The analysis points to two powerful instruments for successful environmental regulation, i.e.:

Invest in Taxation Efficiency (θ): Improving monitoring and collection to make taxes and surcharges more certain and costly for polluters is a highly effective deterrent, especially when the government acts as a leader, and
Commit to State-Contingent Rules ($v(x)$): Adopting clear, predictable policies that automatically intensify enforcement as pollution rises provides a credible commitment mechanism. This enhances the government's strategic position, whether in a Nash or Stackelberg setting, and is key to unlocking the first-mover advantage.
In summary, the model provides a rigorous foundation for the argument that overcoming environmental challenges requires more than just spending on abatement. It demands **strategic, forward-looking policy** that leverages the power of commitment, targets key efficiency

parameters, and understands the non-linear dynamics of the economic-environmental system to avoid traps and steer the economy toward a sustainable, clean equilibrium.

Appendix
Proof of Proposition 9

The equilibrium equation (30) $F(x) = 0$ becomes:
$u - \frac{1}{2}u^2 - \delta x + a^2 W_2 x^2 = 0$
with $u = 1 + \frac{1+A\theta x}{B}$
and the degeneracy condition (31) $F_x(x) = 0$ reduces into:
$(1-u)u_x - \delta + 2a^2 W_2 x = 0 \qquad (A.1)$
Substituting $u_x = \frac{A\theta}{B}$ and $1 - u = -\frac{1+A\theta x}{B}$
$(A.1)$ becomes the quadratic equation in θ:
$-\frac{1+A\theta x}{B}.\frac{A\theta}{B} - \delta + 2a^2 W_2 x = 0$
$\left(\frac{A}{B}\right)^2 x\theta^2 + \frac{A}{B^2}\theta + \delta - 2a^2 W_2 x = 0 \qquad (A.2)$

Which gives the solution:

$$\theta = \frac{-\frac{A}{B^2} \pm \sqrt{\frac{A^2}{B^4} - 4\frac{A^2 x}{B^2}(\delta - 2a^2 W_2 x)}}{2\frac{A^2 x}{B^2}} \qquad (A.3)$$

Setting: $A = aW_2$ and $B = W_1$
$(A.3)$ simplifies into:

$$\theta = \frac{-1 \pm \sqrt{1 - 4B^2\delta x + 8B^2 a^2 W_2 x^2}}{2W_2 a x} \qquad (A.4)$$

Using the equation $F(x) = G\big(u(x)\big) - \delta x - av(x)x = 0$ and under the constant W approximation we have $v(x) = -axW_2$, $u(x) = 1 + \frac{1+A\theta x}{B}$
Substituting and eliminating x algebraically leads to a polynomial condition in θ alone, after clearing denominators and factoring, the resultant factorizes cleanly; discarding degenerate algebraic factors, the nontrivial factor gives a quadratic for θ. Solving that quadratic yields the explicit critical values θ^*

$$\theta^* = \frac{-\delta \pm \sqrt{(W_1^2 - 1)(2W_2 a^2 - \delta^2)}}{W_2 a}$$

Setting $s := \sqrt{(W_1^2 - 1)(2W_2 a^2 - \delta^2)} > 0, \qquad d := W_2 a < 0$
The two algebraic solutions are:

$$\theta_+ = \frac{-\delta + s}{d}, \qquad \theta_- = \frac{-\delta - s}{d}$$

Concerning signs, the final sign of θ_- is always positive.
The sign of root θ_+ is ambiguous, since it maybe either positive or negative, depending on whether s is larger than δ. If $-\delta + s > 0$ then $\theta_+ < 0$, so is not economically relevant; If $-\delta +$

$s < 0$ then $\theta_+ > 0$ and is another admissible positive threshold. In short, θ_- is the always positive root and therefore the natural candidate for the threshold θ^* separating regimes with/without traps.

So for the clear statement of Proposition 9 we write the threshold:

$$\theta^* = \frac{-\delta - \sqrt{(W_1^2 - 1)(2W_2a^2 - \delta^2)}}{W_2 a}$$

Proof of Lemma 1

Fix a (measurable) government enforcement path $v(.)$ or a feedback map $v(x)$ (both cases are similar). For any admissible polluter control $u(.)$ and initial state x, let $x^u(t;x)$ denote the solution of

$$\dot{x}(t) = G(u(t)) - \delta x(t) - av(t)x(t), \qquad x(0) = x_0$$

Where $v(t)$ is the realized government path (if the government uses a feedback rule, write $v(t) = v(x^u(t;x))$). The polluter's payoff with control $u(.)$ is

$$J_1(u(.);x) = \int_0^\infty [u(t) - \theta u(t)v(t)]e^{-\rho_1 t}dt$$

The value function is the supremum over admissible $u(.)$

$$V_1(x) = \sup_{u(.)} J(u(.);x)$$

Fix any admissible control path $u(.)$ And two initial states x and $x + \varepsilon$ with $\varepsilon > 0$. Consider the two state trajectories $x^u(t;x)$ and $x^u(t;x+\varepsilon)$ under the same control $u(.)$ And the same government path $v(.)$. Define the difference

$$\Delta(t) := x^u(t;x+\varepsilon) - x^u(t;x)$$

Then $\Delta(0) = \varepsilon > 0$ and $\Delta(t)$ satisfies the linear ODE (by subtracting the two state equations)

$$\dot{\Delta}(t) = -(\delta + av(t)\Delta(t), \qquad \Delta(0) = \varepsilon$$

Thus

$$\Delta(t) = \varepsilon e^{-\int_0^t (\delta + av(s))ds} > 0$$

In words: for the same controls, the trajectory starting from $x + \varepsilon$ remains strictly above the one starting from x at all future times.

Because the instantaneous payoff integrand $u(t) - \theta u(t)v(t)$ does not depend on the state x directly, the payoff stream generated by the same control $u(.)$ Is identical whether it is evaluated starting from x or from $x + \varepsilon$. Therefore, for any admissible $u(.)$

$$J_1(u(.);x+\varepsilon) = J_1(u(.);x)$$

Consequently, if $u(.;x)$ is an optimal control achieving $V_1(x)$, then using the same control from the higher initial state is feasible, so

$$V_1(x+\varepsilon) \geq J_1(u(.,x);x+\varepsilon) = J_1(u(.,x);x) = V_1(x)$$

Hence, V_1 is nondecreasing: for all $\varepsilon > 0, V_1(x+\varepsilon) \geq V_1(x)$ and passing into limits:

$$V_1' = \lim_{\varepsilon \to 0} \frac{V_1(x+\varepsilon) - V_1(x)}{\varepsilon} \geq 0$$

We now show strict positivity $V_1'(x) > 0$ at states where are polluter's optimal control is interior (i.e., $u^*(t;x)$ and not constrained at the boundary).

Let $u^*(.;x)$ be an optimal control starting from state x. Because the control is interior we can construct a nearby admissible control that strictly increases the objective from the slightly higher initial state $x+\varepsilon$. We fix small $\varepsilon > 0$ and consider the following feasible perturbation $\tilde{u}(.)$for the initial state $x+\varepsilon$:

$$\tilde{u}(.) = \begin{cases} u^*(t;x)+\eta, & 0 \le t \le \tau \\ u^*(t;x), & t > \tau \end{cases}$$

Where $\eta > 0$ and $\tau > 0$ are small parameters to be chosen. Because $u^*(.;x)$ is interior, for sufficiently small η the perturbed control $\tilde{u}(.)$ remains a admissible and near-optimal. Let $x^{\tilde{u}}(t;x+\varepsilon)$ be the state path under the control $\tilde{u}$ from initial $x+\varepsilon$. Because the initial state is larger and the perturbed control increases emissions slightly on $[0,\tau]$, the corresponding payoff difference compared to $J(u^*(.;x);x)$ is:

$$J(\tilde{u}(.;x+\varepsilon);x) - J(u^*(.;x);x) = \int_0^{\tau} \eta\big(1-\theta v(t)\big)e^{-\rho_1 t}dt + o(\eta,\varepsilon,\tau)$$

choose $\tau > 0$ small but fixed so that $1-\theta v(t)$ does not change sign on $[0,\tau]$ (this is possible because $v(t)$ is bounded and continuous on finite horizon segments). If $1-\theta v(t)$ is nonnegative on $[0,\tau]$, the integral above is strictly positive for $\eta > 0$; if it is negative, we can instead use a small delayed increase in control (a different perturbation) that increases payoff due to future effects. Thus, we can choose η, τ so that perturbed control from the higher initial state strictly outperforms the original control $u^*(.;x)$ from the lower state.

Therefore, for sufficiently small $\varepsilon > 0$,

$$V_1(x+\varepsilon) \ge J(\tilde{u};x+\varepsilon) > J(u^*(.;x);x) = V_1(x)$$

Establishing $V_1(x+\varepsilon) > V_1(x)$, and passing to the limit $(\varepsilon \to 0)$

$$V_1' = \lim_{\varepsilon \to 0} \frac{V_1(x+\varepsilon) - V_1(x)}{\varepsilon} > 0$$

Proof of Lemma 2

Fix any admissible control path $v(.)$ (and the realized polluter path $u(.)$). For two initial states x and $x+\varepsilon$ with $\varepsilon > 0$, let $x^{v,u}(t;x)$ and $x^{v,u}(t;x+\varepsilon)$ denote the two solutions of the state equation under the same control $u(.), v(.)$. Subtracting the two equations gives

$$\Delta(t) \coloneqq x^{v,u}(t;x+\varepsilon) - x^{v,u}(t;x)$$

With

$$\dot{\Delta}(t) = -(\delta + av(t)\Delta(t), \qquad \Delta(0) = \varepsilon > 0$$

Hence,

$$\Delta(t) = \varepsilon e^{-\int_0^t (\delta + av(s))ds} > 0$$

For all $t \ge 0$. Thus, for any fixed control path, the trajectory started at the larger initial state stays strictly above the one started at the lower initial state for every future time.

The government instantaneous payoff is strictly decreasing in the state x; for any fixed v,

$$R\big(x^{v,u}(t;x+\varepsilon), v(t)\big) = -\frac{1}{2}\big(x^{v,u}(t;x+\varepsilon)\big)^2 - \frac{1}{2}v(t)^2 < -\frac{1}{2}\big(x^{v,u}(t;x)\big)^2 - \frac{1}{2}v(t)^2$$
$$= R\big(x^{v,u}(t;x), v(t)\big)$$

Because $x^{v,u}(t;x+\varepsilon) > x^{v,u}(t;x)$

Integrating and discounting yields, for the same fixed control path,

$$J_2(v(.);x+\varepsilon)=\int_0^{\infty} e^{-\rho_2 t}R\left(x^{v,u}(t;x+\varepsilon),v(t)\right)dt<\int_0^{\infty} e^{-\rho_2 t}R\left(x^{v,u}(t;x),v(t)\right)dt$$
$$=J_2(v(.);x)$$

So, for every admissible control $v(.)$

$$J_2(v(.);x+\varepsilon)<J_2(v(.);x)$$

The strict inequality for value functions is obtained as:

Let $v^*(.;x)$ be an optimal control (or an ε −optimal control) for the initial state x. Using the same control path at higher initial state yields

$$V_2(x+\varepsilon)=J_2(v^*(.;x);x+\varepsilon)<J_2(v^*(.;x);x)=V_2(x)$$

Hence $V_2(x+\varepsilon)<V_2(x)$, thus V_2 is strictly decreasing.

Since, V_2 is differentiable at the considered state, passing into limits

$$V_2'(x)=\lim_{\varepsilon\to 0}\frac{V_2(x+\varepsilon)-V_2(x)}{\varepsilon}<0$$

Proof of Proposition 4

The polluters (follower of the game) take the government path $v(t)$ as given. Their Hamiltonian is

$$H_1=u-\theta uv(t)+\lambda(t)(G(u)-\delta x-av(t)x),$$

$\lambda(t)$ is the costate variable.

The FOC w.r.t. u is

$$\frac{\partial H_1}{\partial u}=1-\theta v+\lambda(1-u)=0$$

Therefore,

$$\lambda(1-u)=\theta v-1\Rightarrow u(t)=1+\frac{1-\theta v(t)}{\lambda(t)} \qquad (A.5)$$

Moreover,

$$\frac{\partial u}{\partial v}=-\frac{\theta}{\lambda} \qquad (A.6)$$

The costate dynamics is also

$$\dot{\lambda}=\rho_1\lambda-\frac{\partial H_1}{\partial x}=\rho_1\lambda-\lambda(-\delta-av)=\lambda(\rho_1+\delta+av) \qquad (A.7)$$

The government's (leader) Hamiltonian is:

$H_2(x,\lambda,v,p,q)$

$$=-\frac{1}{2}x^2-\frac{1}{2}v^2+p(G(u)-\delta x-avx)+q\left(\lambda(\rho_1+\delta+av)\right) \qquad (A.8)$$

p,q are the leader's costate variables for the states x,λ.

The equations for the costate variables are:

$$\dot{p}=\rho_2 p-\frac{\partial H_2}{\partial x}=\rho_2 p+p(av+\delta)+x$$

$$\dot{q}=\rho_2 q-\frac{\partial H_2}{\partial \lambda}=\rho_2 q-\frac{\lambda^3 q(av+\delta+\rho_1)+p(\lambda(-\lambda+2\theta v-2)+(\lambda-\theta v+1)^2}{\lambda^3}$$

And the boundary conditions:

$$\lim_{t\to\infty}p(t)e^{-\rho_2 t}=0,\qquad \lim_{t\to\infty}q(t)e^{-\rho_2 t}=0$$

It is worth noting that the leader's maximization problem is subject of two state variables, i.e. the pollutants evolution equation $\dot{x} = G(u) - \delta x - av(t)x$ and the new state arisen from the follower's costate $\dot{\lambda} = \lambda(\rho_1 + \delta + av)$.
Differentiate H_2 wrt v to obtain the FOC

$$\frac{\partial H_2}{\partial v} = -v + p\left(G'(u)\frac{\partial u}{\partial v} - ax\right) + aq\lambda \qquad (A.9)$$

Setting $\frac{\partial H_2}{\partial v} = 0$ and substituting into $(A.9)$ the equation $(A.6)$ we obtain the FOC

$$0 = -v + p\left(-\frac{\theta(1-u)}{\lambda} - ax\right) + aq\lambda \qquad (A.10)$$

Rearrange the terms in $(A.5)$ and neglect the time variable we have

$$1 - u = -\frac{1-\theta v}{\lambda}$$

Plugging the latter into $(A.10)$ the FOC after simplifications becomes:

$$0 = -v + p\left(\frac{\theta(1-\theta v)}{\lambda^2} - ax\right) + aq\lambda \qquad (A.11)$$

Multiplying both sides by λ^2 and solve for v, we obtain

$$v(t) = \frac{a\lambda^3 q - a\lambda^2 px + p\theta}{\lambda^2 + p\theta^2}$$

Which is exactly the equation (11) in the main text.
Remarks on the proof of Proposition 4.
The derivation assumed an interior optimum (so the FOC holds) and $\lambda \neq 0$. The denominator $\lambda^2 + p\theta^2$ is strictly positive if p is nonnegative; more generally the admissibility of the solution requires that the right–hand side be nonnegative (because $v \geq 0$). When boundary solutions occur $v = 0$, the same FOC analysis must be augmented with complementary slackness.

Proof of Lemma 4
The polluters' HJB is

$$\rho_1 V_1(x) = \max_{u \geq 0}\left\{u - u\theta v + V_1'(x)\left(u - \frac{1}{2}u^2 - \delta x - avx\right)\right\}$$

We guess the value function

$$V_1(x) = q_1 x + r_1, \qquad V_1'(x) = q_1$$

Substitute into the HJB

$$\Phi = u - u\theta v + q_1\left(u - \frac{1}{2}u^2 - \delta x - avx\right)$$

The FOC:

$$\frac{\partial \Phi}{\partial u} = 1 - \theta v + q_1(1-u) = 0$$

And the feedback control law is:

$$u(x) = \frac{q_1 + 1 - \theta v(x)}{q_1} = 1 - \frac{\theta v(x) - 1}{q_1} \qquad (A.12)$$

This is admissible only when $u(x) > 0$, fixing the required sign region of q_1.
Substituting $(A.12)$ into the HJB and simplify:
Let $v(x) = kx,\ k > 0$ (since $v(x) = -axq_2$ and for a linear value function V_2 of the government $q_2 = V_2' < 0$ according to lemma 2),

Then $u(x) = 1 - \frac{\theta k x - 1}{q_1}$
Plug into HJB and expand.

With the requirement $p_1 x + q_1 \neq 0$ on I so $(A.8)$ is well defined.
Define

$$u(x) = 1 - \frac{\theta v(x) - 1}{p_1 x + q_1}, \qquad G(u) = u - \frac{1}{2}u^2$$

and

$$\Phi(x) = G\big(u(x)\big) - \delta x - a v(x)$$

The polluter HJB is

$$\rho_1 V_1(x) = u(x) - \theta u(x) v(x) + V_1'(x)\Phi(x) \qquad (A.13)$$

Substitute the expressions for V_1, V_1', u, v, Φ. After substitution into $(A.13)$, simplifications and grouped by powers, we have:

$$x^2\left(-akq_1 + \frac{k^2\theta^2}{2q_1}\right) + x(-(\delta + \rho_1)q_1 - k\theta - \frac{k\theta}{q_1}) + \frac{q_1}{2} + 1 + \frac{1}{2q_1} - \rho_1 r_1 = 0 \qquad (A.14)$$

In $(A.14)$ every factor of $x-$ power and the constant must equal to 0, therefore:

$$-akq_1 + \frac{k^2\theta^2}{2q_1} = 0 \qquad (A.15)$$

$$-(\delta + \rho_1)q_1 - k\theta - \frac{k\theta}{q_1} = 0 \qquad (A.16)$$

$$\frac{q_1}{2} + 1 + \frac{1}{2q_1} - \rho_1 r_1 = 0 \qquad (A.17)$$

Solving $(A.15)$ $q_1 = \pm\theta\sqrt{\frac{k}{2a}}$ and since it is required $u(x) > 0$, we choose $q_1 > 0$, and

$$q_1 = \theta\sqrt{\frac{k}{2a}} \qquad (A.18)$$

Similarly, from $(A.17)$ $\qquad r_1 = \frac{1}{\rho_1}\left(\frac{1}{2}q_1 + 1 + \frac{1}{2q_1}\right) \qquad (A.19)$

The Jacobian of system $(A.15) - (A.17)$ w.r.t. (q_1, r_1) must be full rank, ensuring a unique solution in the neighborhood of equilibrium.
Interiority conditions require:

$$u(x) > 0, \;\; V_1' = q_1 > 0$$

which restrict parameters and determine the valid branch of q_1.
A linear function

$$V_1(x) = q_1 x + r_1$$

solves HJB and yields the interior optimal feedback

$$u(x) = 1 - \frac{\theta k x - 1}{q_1}, \qquad (x) = -axq_2$$

and the proof is completed.

Proof of Lemma 5

The stationary HJB equation for the government value function $V_2(x)$ is given by (24):

$$\rho_2 V_2 = \max_{v\geq 0}\left\{-\frac{1}{2}x^2 - \frac{1}{2}v^2 + V_2'(x)\left[u - \frac{1}{2}u^2 - \delta x - avx\right]\right\}$$

The regulator takes u as given (strategic interaction), but under Markov perfect equilibrium (that we later construct) both strategies depend on x. Here we focus solely on solving the government's optimization problem for a given $V_2 \in C^2$ and search for a linear solution.

$$V_2(x) = q_2 x + r_2, \quad V_2'(x) = q_2 < 0, \quad V_2''(x) = 0 \qquad (A.20)$$

The FOC of the HJB equation gives:

$$\frac{\partial}{\partial v}\left(-\frac{1}{2}v^2 + V_2'(x)(avx)\right) = 0 \Rightarrow v = -axV_2' \Rightarrow v(x) = -aq_2 x \qquad (A.21)$$

The second order condition yields:

$$\frac{\partial^2}{\partial v^2}\left(-\frac{1}{2}v^2 - avq_2 x\right) = -1 < 0$$

Therefore $(A.21)$ is an interior maximum. If $q_2 < 0$, then $v(x) \geq 0$ for $x \geq 0$.

Plug $(A.20)$ and $(A.21)$ into HJB:

$$\rho_2(q_2 x + r_2) = -\frac{1}{2}x^2 - \frac{1}{2}a^2x^2q_2^2 + q_2\left[u - \frac{1}{2}u^2 - \delta x + a^2x^2q_2\right] \qquad (A.22)$$

Rearrange $(A.22)$ collecting the powers of x

$$\rho_2 q_2 x + \rho_2 r_2 = \left(-\frac{1}{2} - \frac{1}{2}a^2q_2^2 + a^2q_2^2\right)x^2 - q_2\delta x + q_2\left(u - \frac{1}{2}u^2\right) \qquad (A.23)$$

Since the LHS is affine in x and the RHS contains x^2 term:

$$-\frac{1}{2} - \frac{1}{2}a^2q_2^2 + a^2q_2^2 = 0 \Rightarrow a^2q_2^2 = 1 \qquad (A.24)$$

Thus (choosing the negative root):

$$q_2 = -\frac{1}{a} < 0 \qquad (A.25)$$

Plug $q_2 = -\frac{1}{a}$ into $(A.23)$ and collect the constant term (independent of x)

$$\rho_2 r_2 = q_2\left(u - \frac{1}{2}u^2\right) \Rightarrow r_2 = \frac{-1}{a\rho_2}\left(u - \frac{1}{2}u^2\right) \qquad (A.26)$$

This constant is determined uniquely once the equilibrium $u(x)$ is substituted.

Since the above derivation requires to solve a polynomial system (q_2, r_2) we check the Jacobian to ensure the admissibility. The crucial condition is:

$$\frac{\partial}{\partial q_2}(a^2q_2^2 - 1) \neq 0 \Rightarrow 2a^2q_2 \neq 0 \Rightarrow q_2 \neq 0$$

Since we choose $q_2 = -\frac{1}{a} \neq 0$ the condition holds locally. Thus, the linear solution exists and is admissible.

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Urban centers, Traffic, Atmospheric Pollution and Associated Health Risks: Evidence from Africa

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Abstract

African cities are experiencing a rapid urbanization and sustained economic growth. The increasing demand for transportation and mobility is bringing forth significant challenges: undeveloped transport and mobility infrastructure, low roads density, reduced car fleet, non-integrated transport modes, lack of regulation and emissions control. In urban centers, traffic emits substances harmful to human health which should be controlled and monitored. Mixtures of gases (NOx, CO, SO_2…) and particles are emitted from different sources (engine combustion, fuel evaporation, tires, clutch, and wear degradation, etc.). Exposure to high pollutants concentration can be detrimental to human health. In recent years, it has been demonstrated that air pollution is associated with many diseases such as diabetes, stroke, cancer, hypertension, respiratory and pulmonary diseases such as asthma, etc. Short-term exposure can irritate eyes, nose, and throat, while long-term exposure is more serious, causing heart and lung diseases, reduced lung function, low birth outcome, and premature death. This paper is a comprehensive overview of traffic-related air pollution in African urban centers, key driving factors and associated health risks. Emissions concentrations are higher than in developed countries and well above threshold values. Fine particulate matter concentration varies across cites but remains high: 32-79 $\mu g.m^{-3}$ in Thiès (Senegal), 82-113 in Douala (Cameroon), 100-500 in Cotonou (Benin), 33-328 in Addis Ababa (Ethiopia). Health quotient (HQ) derived from these values, are high (>1), demonstrating high risks of developing non-carcinogenic diseases. Potential solutions and strategies to address this pressing issue (focusing on sustainable transportation practices, emission control technologies, and urban planning initiatives) are highlighted. The complex nature of the traffic-induced air pollution calls for more research and synergized actions by stakeholders.

Keywords: *African cities; air pollution; clean fuels; health risks.*

JEL Codes: I15; O29; R00

A Marxist analysis of the Relation Between CO_2 Emissions Growth and Sectoral Profitability

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Abstract

The relationship between ecological degradation and capitalist accumulation has been a longstanding focus within critical political economy. In this paper, we examine this dynamic through a panel analysis of 35 countries and 24 economic sectors over the period 2000–2014. Employing a Marxist analytical framework, our findings indicate a positive association between greenhouse gas emissions and sectoral profitability, particularly within industries characterized by low technological complexity. These sectors—predominantly located in the Global South—tend to be labour-intensive, exhibit low labour productivity, possess a low organic composition of capital, and generate limited value added. Moreover, our analysis suggests that the structural asymmetries between the Global North and the Global South, or between the core and the periphery, are not only reproduced but further deepened, both in ecological and economic terms.

Keywords: *Ecological degradation; capitalism; global south; sectoral analysis*

JEL Codes: P18, L6

The Pollution levels in Athens and Salonica: An Environmental Analysis Approach

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Abstract

The target of this paper is to describe briefly the existed statistical analysis on the existed main pollutants in Athens and Salonica, developed under two different lines of thought; (i) Probability oriented Data Analysis and (ii) Statistical Models comparing the pollution. Our target is to improve the study on the pollution between the two main cities, [1]. [2], in Greece were almost the 70% of the population is living and propose the appropriate methods and strategies, under the uncertainty principle developed in [3].

Keywords: *pollution; statistical analysis; probability-oriented data analysis*

JEL Codes: Q53; Q58; Q52

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Session 8.

Novelties in Environmental Valuation under Uncertainty

Environmental Uncertainty Effects on Money Investments: Strengthening or Weakening Resilience to Inflation?

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Abstract
This study investigates how key kinds of money, such as metallic (commodity) money and international fiat currencies, interact with environmental uncertainty across market regimes. We generate extended joint connectedness (EJC), averaged dynamic connectedness, and network connectedness at lower (bear), middle (normal), and upper (bull) quantiles using daily data from January 22, 2020, to January 31, 2025, using a Quantile-VAR (QVAR) methodology. In general, fiat currencies have a stronger correlation with environmental uncertainty than do metals used for monetary reasons, and systemwide connectivity increases in tail regimes (bull and bear). Under current conditions, U.S. climate policy and environmental risk are the main exceptions to the rule that climate risks normally operate as net absorbers of systemic risk. The U.S. dollar is the primary net shock contributor in fiat markets. Iron ore is the most potent net stabilizer among base metals, while gold, silver, and platinum act as safe havens (net absorbers) in bear markets and change to net transmitters in bull markets. These findings emphasize the strategic significance of inflation-resilient liquidity for investors and policymakers facing climate-related financial stress, as well as the dual role of precious metals—as channels for risk transmission during periods of optimism and as inflation shields during downturns.

Keywords: *Environmental Uncertainty; Fiat Currencies; Precious Metals; Quantile-VAR (QVAR); Dynamic Interplay; Market Risk.*

JEL Codes: E52, E58, G15, O44, Q54, Q58.

Conflict of interest: There is no conflict of interest for the authors
Data availability statement: All data are available upon request

Reinstatement of Rail Transport Between Strymon and Alexandroupolis – an Environmental, Financial, and Economic Evaluation

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Abstract

The rail line Strymon – Alexandroupolis has been out of circulation since the mid-2010s due to poor maintenance, which led to a severe degradation of its quality. The Greek Railways had a study conducted to reinstate traffic through heavy maintenance and targeted construction works. These works aimed to replace or upgrade specific structures (culverts, bridges, tunnels) and stations to meet the requirements for interoperability through a public-private partnership (PPP), a scheme which did not go forward. Other options for the reinstatement of traffic include alignment changes and different funding schemes, such as public financing or a concession. The present study examines different engineering and financing options, using advanced Machine Learning forecasting models for passenger and freight traffic, the recently published Greek Finance Ministry's guide to transport project feasibility studies, and relevant European Union guidelines to produce environmental, financial, and economic evaluation metrics.

Keywords: *Rail Transport, Electrification, Forecasting, Machine Learning*

JEL Codes: R41, R48, Q41, Q42

Digital Self-Assessment of Accommodation Vulnerability to Climate Change Using Artificial Intelligence Tools

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Abstract

This paper explores the need for the development and implementation of an innovative digital self-assessment tool that evaluates the vulnerability of tourism enterprises to climate change by utilizing Artificial Intelligence (AI). The climate crisis exerts increasing pressure on the tourism sector, particularly in coastal and island regions where tourism establishments are exposed to risks such as rising sea levels, extreme weather events, and shifts in tourism demand. Despite the severity of these impacts, small and medium-sized tourism enterprises (SMEs) still lack access to affordable, flexible, and customized risk management tools. The use of AI can accelerate the creation of such solutions, providing tailored vulnerability assessments and adaptation scenarios. Moreover, the adoption of a dynamic vulnerability framework allows for a deeper understanding of the ever-changing nature of climate risks and their effects on tourism. The ClimaSafe project addresses this challenge by developing a web-based tool that enables the self-assessment of climate vulnerability while simultaneously offering personalized adaptation recommendations. The methodological approach includes: (a) a systematic literature review of international tools, (b) pilot implementation in at least 15 accommodation units with different characteristics, and (c) analysis of existing systems such as Climate ADAPT and CRiSTAL. The tool combines the power of AI with a participatory design approach and dynamic micro-level risk assessment. Such tools can serve not only as risk management mechanisms but also as educational platforms that strengthen strategic adaptive capacity and promote a culture of sustainability in the tourism sector. The adoption of these solutions contributes to the development of organizational skills related to adaptation, while simultaneously fostering the active engagement of employees and managers in knowledge creation and the implementation of sustainable strategies. ClimaSafe is proposed as a preventive solution, strategically aligned with the principles of the green transition, resilience, and operational sustainability, offering a competitive advantage to tourism enterprises that adopt it.

Keywords: *Climate change, vulnerability self-assessment tool, climate adaptation, sustainable tourism, climate resilience, risk management, operational sustainability*

JEL Codes: Q54, Q56, L83, Q01

Impact of Artificial Intelligence Implementation on Sustainability in Colombo's Business Process Outsourcing Sector in Sri Lanka

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Abstract

The processes of Artificial Intelligence integration are evolving at a fast pace and are rapidly changing business models across industries and organizational functions. This study investigates the impact of Artificial Intelligence (AI) implementation on sustainability in Colombo's Business Process Outsourcing (BPO) sector. The research investigates the following four dimensions: energy efficiency, adaptability of workforce and compliance with the sustainability standards, operational efficiency. The study uses a mixed methods approach including survey, a statistical analysis and shows that AI implementation has a huge impact on energy efficiency and operational efficiency that will positively influence one's overall sustainability. Although adaptation of the workforce has a negative relationship with sustainability, this demonstrates the need for comprehensive reskilling and changing management. There is no significant difference in overall sustainability outcome due to compliance with sustainability standards. There are several key contributions that the study makes to the field. First, it offers empirical proof of how multifaceted the impacts AI has on sustainability in an emerging market BPO environment, which contributes to that literature. It is also an illustration of opportunities and challenges associated with the use of AI for sustainable development and is a view of the use of AI. It finally presents practical insights for the implementation of AI in BPO firms, policymakers, and other stakeholders design to counteract the negative aspects of AI use. What these findings imply is that by using AI, both the economic, social and environmental sustainability of the BPO sector could be boosted, if there is a balanced approach towards technological impact and those of human factors in achieving such results.

Keywords: Artificial Intelligence, Business Process Outsourcing, Sustainability, Energy Efficiency, Workforce Adaptability, Operational Efficiency

JEL Codes: O33, L86, Q01, Q41, J24, D24

Session 9.

Climate Anxiety & Ecological Awareness

The influence of motivational goal frames and coping strategies on climate anxiety

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Abstract

Crossing critical planetary boundaries underscores the urgent need to accelerate global action toward carbon neutrality, climate adaptation, and implementation of SDGs. As individuals serve as micro-level agents of change, understanding their cognitive, behavioral and emotional responses to climate-related threats is essential for addressing climate crisis. In response, the present research explores how diverse goal frames that motivate environmental decision-making relate to climate change coping strategies and climate anxiety. Using a cross-sectional design, a convenience sample of 802 participants completed online self-reported questionnaires. Data analysis relied on PLS-SEM methodology, including validity and reliability assessments of the proposed model, test for common method bias, evaluation of structural parameters, and robustness checks for linearity assumptions, endogeneity, and unobserved heterogeneity. Bootstrapping results confirmed the construct validity and reliability of the measurement model, with path coefficients supporting all research hypotheses. Robustness checks revealed endogeneity concerns which were addressed by estimating a Gaussian-copula adjusted model. Findings indicate that de-emphasizing coping strategies are positively influenced by gain goal frame but negatively associated with hedonic motivation. Normative goal frame strongly affects both meaning and problem-focused coping. De-emphasizing and problem-oriented coping strategies are significant predictors of climate anxiety, whereas meaning-focused coping mechanisms inversely impact it. The results offer practical implications for policymakers to integrate psychological mechanisms into environmental policy design, promoting adaptive responses to climate change and strengthening societal resilience.

Keywords: *Goal Framing Theory; Climate change; Coping; Climate Anxiety; PLS-SEM.*

JEL Codes: A14; Q00; Q51; Q56; Q5; Q58, Q59.

The Role of Environmental Education in Promoting Sustainable Development and Ecological Awareness: An Economic & Social Approach

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Abstract

Achieving sustainable development requires profound social transformations based on environmental education and the strengthening of ecological awareness and sensitivity. This paper examines the role of environmental education as a catalyst for the transition to a sustainable economic and social model, focusing on the interactions between citizens' knowledge, values, and behavior. Through a qualitative and conceptual analysis of policy frameworks and environmental education programs in Greece and internationally, the study explores the mechanisms through which education enhances social and environmental resilience. Particular emphasis is placed on its contribution to the rational management of natural resources and the integration of the Sustainable Development Goals (SDGs) into the educational process. The findings highlight that the institutional strengthening of environmental education can serve as a lever of ecological responsibility and social cohesion, significantly contributing to the shaping of a long-term sustainable development trajectory.

Keywords: *Environmental Education, Sustainable Development, Ecological Awareness, Social Resilience, Natural Resource Policy Management*

JEL Codes: I2

The Contribution of the Psychology of Religion to the Formation of Ecological Consciousness

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Abstract

The present paper systematically examines the contribution of the Psychology of Religion to the formation of ecological consciousness, focusing on the psychological, ethical, and emotional factors that decisively influence human attitudes toward the natural environment. Initially, the concept of the Psychology of Religion is analyzed as a scientific field that studies religious experience and the ways in which it affects an individual's thought, emotion, and behavior. Subsequently, ecological consciousness is presented as a complex psychological attitude that is not limited to awareness of environmental problems, but also encompasses emotional, ethical, and behavioral dimensions. Particular emphasis is placed on the relationship between religion and nature, as well as on the concept of human responsibility toward the environment, as expressed through fundamental religious values such as respect, self-restraint, and care for life. At the same time, the role of religious emotions—such as awe and gratitude—is highlighted in fostering a deeper connection with nature. Finally, the paper demonstrates that the Psychology of Religion provides a substantial theoretical framework for understanding and strengthening ecological consciousness at both the individual and collective levels.

Keywords: *Psychology of Religion, ecological consciousness, spirituality, environmental ethics, stewardship.*

JEL Codes: O44; O47; O52; Q43; Q56.

1. Introduction

The contemporary era is strongly characterized by acute environmental challenges that threaten the sustainability of natural ecosystems and the quality of human life. The ecological crisis is not merely a technical or scientific issue; rather, it is inextricably linked to modes of thinking, values, and attitudes that shape the relationship between humans and nature. For this reason, ecological consciousness emerges as a decisive factor in addressing environmental problems, as it involves not only knowledge but also the ethical, emotional, and behavioral dimensions of human existence. Within this context, religion and spirituality have historically played a significant role in shaping human worldview and attitudes toward the world and the natural environment.

The Psychology of Religion, as a scientific field that studies religious experience and its psychological effects, offers a particularly fruitful and interdisciplinary theoretical framework for understanding ecological consciousness (Fountoulakis,2023). Through the exploration of meaning, values, emotions, and moral identity associated with religious belief, it becomes possible to interpret the deeper motivations that lead individuals to responsible or irresponsible attitudes toward nature.

The purpose of the present study is to highlight the contribution of the Psychology of Religion to the formation of ecological consciousness, examining how religious experience and spirituality can substantially enhance environmental sensitivity and responsible ecological behavior. The study seeks to demonstrate that ecological attitudes are not merely the result of information or knowledge, but are directly connected to internalized values and meaning-making processes.

Regarding its structure, the study first presents an analytical overview of the concept and subject matter of the Psychology of Religion. It then examines ecological consciousness and its basic psychological dimensions. This is followed by an exploration of the relationship between religion, nature, and human responsibility. In the final section, the contribution of the Psychology of Religion to the formation of ecological consciousness is analyzed in depth, prior to the presentation of the concluding remarks.

2. The Concept of the Psychology of Religion

The Psychology of Religion constitutes an autonomous and recognized branch of psychological science that studies religious experience, religious belief, and their effects on human thought, emotion, and behavior (Tsisigkos, 2017). Its central concern is not the evaluation of the truth of religious doctrines, but rather the understanding of how individuals experience religion and integrate it into their everyday lives. Religion is approached as a psychological and social phenomenon that contributes significantly to the formation of personality and worldview (Paloutzian & Park, 2013, pp. 3–4).

Religious experience functions as a fundamental mechanism of meaning-making in human existence. Through it, individuals seek to interpret the world, understand their place within it, and address fundamental existential questions related to the meaning of life, suffering, death, and responsibility. The Psychology of Religion systematically examines how the search for meaning through faith influences human attitudes toward life, other people, and the natural environment, fostering values such as respect, humility, and responsibility (Hood, Hill & Spilka, 2018, p. 6).

Particular emphasis is placed on the concept of the internalization of religious values. When these values are not experienced as external rules or imposed norms but as personal convictions, they acquire increased psychological potency. The internalization of faith is directly associated with the development of moral consciousness and influences the way individuals make decisions and shape their behavior. Thus, religiosity can function as an internal motivation for responsible life attitudes and behaviors that respect both humanity and the surrounding world (Emmons, 2005, pp. 738–739).

The Psychology of Religion also examines the role of emotions associated with religious experience, such as awe, gratitude, and a sense of the sacred. These emotions enhance the individual's sense of connection to something greater than the self and contribute to the formation of a more holistic perception of life. Emotions generated by spirituality and religion are associated with increased empathy, moral sensitivity, and responsibility toward the world—elements that can positively influence attitudes toward nature as well (Pargament, 2007).

Within this framework, the Psychology of Religion provides an important theoretical foundation for understanding ecological consciousness. The relationship between humans and nature is not approached solely as a matter of knowledge or information, but as a deeper psychological and moral stance. Through religious experience, values of care, respect, and responsibility are cultivated, which can serve as the basis for the development of ecological sensitivity and sustainable ways of living.

3. Ecological Consciousness and Its Psychological Dimensions

Ecological consciousness constitutes a complex and multidimensional psychological attitude that concerns the way individuals perceive their relationship with the natural environment and their place within it. It is not limited exclusively to knowledge of environmental problems, but includes emotional, moral, and behavioral dimensions that decisively influence an individual's overall stance toward nature. Contemporary psychological research emphasizes that ecological consciousness is directly linked to values, identity, and lifestyles, rendering it a critical factor in addressing the environmental crisis (Kollmuss & Agyeman, 2002, pp. 239–241).

At the cognitive level, ecological consciousness is associated with an understanding of environmental issues such as climate change, pollution, and ecosystem degradation. However, research clearly demonstrates that knowledge alone is insufficient to bring about behavioral change. The phenomenon of the "cognitive–behavioral gap" is frequently observed, whereby individuals are aware of environmental problems but fail to act accordingly. This indicates that ecological behavior depends on deeper psychological mechanisms rather than information alone (Steg & Vlek, 2009, pp. 309–310).

Particular importance is attributed to the emotional dimension of ecological consciousness. Emotions such as love for nature, concern about environmental destruction, and guilt over human interventions function as fundamental motivators for pro-environmental action. Emotional connection to the natural environment strengthens the perception that nature constitutes an integral element of both personal and collective human identity, rather than an impersonal external space (Schultz, 2000, pp. 6–9).

At the same time, ecological consciousness possesses a strong moral dimension. Individuals are called upon to recognize their responsibility toward nature and future generations by adopting attitudes grounded in justice, respect, and the protection of life. Environmental ethics approaches nature not as an object of exploitation, but as a value in itself, a perspective that directly influences moral choices and individual behavior (Jensen & Schnack, 2006, pp. 163–164).

On a psychological level, ecological consciousness ultimately finds expression through behavior. Pro-environmental practices, such as conserving natural resources, recycling, and adopting sustainable habits, represent external manifestations of internalized values. When these values are integrated into an individual's personal identity, environmental behavior is not experienced as coercive, but as an obvious and natural way of life (Clayton, 2003).

4. Religion, Nature, and Human Responsibility

The relationship between religion and nature constitutes a fundamental element of many religious traditions and profoundly influences the way humans perceive the natural world. Nature is not presented merely as a neutral environment or as a collection of natural resources, but as a space of meaning, life, and relationship. Within this framework, religious worldview contributes to the formation of an attitude toward nature that transcends utilitarianism and incorporates ethical and spiritual dimensions (Grim et al., 2013, pp. 1–2).

Central to the religious understanding of nature is the concept of human responsibility. Humans are not conceived as absolute rulers of the natural world, but as stewards and caretakers of it. This responsibility is not confined to preserving nature for practical reasons, but is directly linked to the perception that environmental destruction constitutes a moral problem. From a psychological perspective, the sense of responsibility strengthens individual commitment and

functions as a powerful internal motivation for environmentally responsible attitudes (Gifford, 2014, pp. 547–548).

Religion also contributes to the formation of values that decisively influence ecological attitudes. Values such as respect for life, temperance, self-restraint, and solidarity act as counterweights to contemporary consumer culture, which often promotes the overexploitation of nature. Temperance, in particular, may be understood not only as a moral virtue but also as a psychological mechanism of self-regulation, enabling individuals to limit behaviors that are harmful to the environment (Ives et al., 2024).

Furthermore, religious experience is associated with emotions that enhance ecological sensitivity. Awe toward nature, a sense of the sacred, and gratitude for life cultivate a deeper emotional connection with the natural environment. Research indicates that such emotions can strengthen intentions to protect nature, as individuals experience the environment as part of a broader moral and spiritual relationship rather than as a mere object of use (Keltner & Haidt, 2003, pp. 303–305).

The concept of repentance and self-criticism, present in many religious traditions, may also acquire an ecological dimension. The recognition of human responsibility for environmental degradation and the need for a change in lifestyle constitute core elements of an ecological ethic grounded in religious thought. From a psychological standpoint, this process is linked to the re-evaluation of attitudes and the potential for genuine behavioral change (Rajabi et al., 2015).

In the contemporary context of ecological crisis, the connection between religion, nature, and human responsibility acquires particular significance. Environmental degradation is not solely a technical or scientific problem, but also a crisis of values and meaning. Religion, through its role in shaping worldviews and moral orientations, can function as a framework for strengthening ecological consciousness. In combination with the Psychology of Religion, it offers tools for understanding and reinforcing internal human commitment toward nature and future generations (Abumoghli, 2023, p. 490).

5. The Contribution of the Psychology of Religion to the Formation of Ecological Consciousness

The Psychology of Religion, particularly in its contemporary development, contributes substantially to understanding the internal motivations that shape human attitudes toward the environment. Modern psychological approaches recognize that ecological behavior is not formed exclusively by external factors such as information or social norms, but primarily by deeper systems of values, meaning, and identity. Within this framework, religiosity and spirituality may function as internal motivational mechanisms that promote a more responsible way of life (Saroglou, 2013).

A central element of the contribution of the Psychology of Religion is the concept of moral identity. When religious faith is experienced as an internal conviction rather than as external conformity, it contributes to the formation of a stable moral self-concept. Contemporary research indicates that individuals with internalized religiosity demonstrate greater consistency between values and behavior, thereby strengthening long-term ecological commitment. In this case, ecological responsibility becomes integrated into the individual's broader moral identity (Vitell, Paolillo & Singh, 2006).

The Psychology of Religion also highlights the role of meaning and existential understanding in the formation of ecological consciousness. Religion and spirituality provide coherent interpretive frameworks that help individuals understand their place in the world and their relationship with nature. When nature is integrated into a broader system of meaning that transcends the individual and narrow utilitarianism, its protection acquires clear existential and moral significance. Research demonstrates that the search for meaning is directly associated with increased environmental sensitivity and willingness to engage in responsible action (Park, 2016).

The emotional dimension of religious experience is likewise of particular importance. Contemporary studies in the psychology of emotions document that experiences such as awe, gratitude, and a sense of the sacred can reduce egocentrism and enhance feelings of connectedness with the world. The Psychology of Religion interprets these emotions as a bridge between inner experience and moral action, thereby contributing to the formation of an ecological consciousness grounded in relationship, care, and respect rather than exploitation (Van Cappellen & Saroglou, 2012).

Finally, the Psychology of Religion provides essential theoretical and interpretive tools for understanding the collective dimension of ecological consciousness. Religious communities can function as dynamic contexts for reinforcing ecological values by offering behavioral models, shared meanings, and a sense of collective responsibility. Contemporary studies indicate that religious communities that integrate ecological messages into worship and public engagement are capable of strengthening sustainable behavior among their members. In this way, the Psychology of Religion contributes not only to the individual but also to the collective formation of ecological consciousness (Veldman et al., 2014, pp. 4–5).

6. Conclusion

The present study has systematically highlighted the decisive role of the Psychology of Religion in shaping ecological consciousness, illuminating the deeper psychological, moral, and emotional processes that influence human attitudes toward the natural environment. As demonstrated by the theoretical analysis, the ecological crisis cannot be addressed solely through scientific knowledge or technological solutions, but requires a substantive transformation of values, meaning, and ways of life.

The Psychology of Religion makes a substantial contribution to this process by examining how religious experience and spirituality are internalized by individuals and how they influence thought, emotion, and behavior. When religious faith is experienced as a personal and internal reality, it can function as a powerful intrinsic motivation for cultivating responsibility, respect, and care toward nature. Values such as humility, temperance, solidarity, and human responsibility emerge as essential counterbalances to contemporary consumerism and the instrumental view of the natural world.

At the same time, the emotional dimension of religious experience—through experiences of awe, gratitude, and a sense of the sacred—strengthens the human connection with nature and reduces egocentrism. Within this framework, ecological consciousness is not perceived as an external obligation, but as a natural extension of the individual's moral and spiritual identity.

In summary, the collective dimension of religious life emerges as a significant factor in reinforcing ecological attitudes and practices. The Psychology of Religion thus offers a fertile theoretical and interpretive framework for understanding and strengthening a sustainable and meaningful relationship between humans and nature, contributing to the formation of an ecological consciousness with deep moral and existential roots.

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Socioeconomic status and pro-environmental behaviours in the EU

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Abstract

The study examines demographic, socioeconomic, occupational, trust, and political determinants of individuals' pro-environmental behaviours—specifically whether they believe they fall short of desired engagement—and their willingness to pay higher environmental taxes, using the 2022 Eurobarometer survey for multiple European countries. Empirical models are estimated for the full sample and for country groups disaggregated by economic development levels. The dataset contains detailed information on respondents' economic status and their economic capacity to engage in energy-saving behaviours. We estimate logistic regression models with heteroskedasticity-robust standard errors for each country group. The results indicate that socioeconomic inequalities are significant drivers of both the likelihood of undertaking environmentally friendly actions (for example, household investments in energy saving) and the willingness and ability to pay higher taxes for environmental protection.

Keywords: *pro-environmentalism; willingness to pay; socioeconomic inequalities; logistic models.*

JEL Codes: D10; H31; I24; Z13.

Session 10.

Sustainable Development: Degrowth & Inclusive Wealth

The role of institutional and socio-economic factors in shaping environmental performance: A cross-country analysis in fluctuating times

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Abstract
This study examines the impact of formal institutions and socio-economic variables—including the Human Development Index (HDI), Consumer Price Index (CPI), renewable energy, technological innovation, and trade openness—on environmental performance across 56 countries (31 developed and 25 developing). The analysis spans two periods: 2011–2019 (a period of stability) and 2011–2020 (encompassing the COVID-19 pandemic). A novel Bayesian Data Envelopment Analysis (DEA) is employed to estimate environmental performance, while a two-step iterative Generalized Method of Moments (GMM) framework assesses the effects of these variables on environmental performance. Key findings highlight the critical role of HDI in enhancing environmental performance during global crises, especially in developing countries. The CPI shows mixed effects when combined with the control of corruption in developed (negative effect) and developing (positive effect) countries on environmental performance. The most significant drivers of environmental performance are lagged environmental performance, country classification (developed or developing), and control of corruption, particularly in developing countries.

Keywords: *Environmental efficiency; Corruption; Human Development Index; Data envelopment analysis; Bayesian methods*

JEL Codes: Q56, Q58, C33

The Economic Geography of Inclusive Wealth: Convergence Clubs Across Nations

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Abstract
Gross Domestic Product (GDP) alone is insufficient to capture the prerequisites of sustainable development. In the Beyond-GDP context, this study advances the Inclusive Wealth Index (IWI), which tracks the evolution of produced, human, and natural capital worldwide from 1990 to 2020. The present analysis focuses on wealth stocks rather than flow-based output, the IWI offers a more comprehensive lens on long-term prosperity and sustainability. Empirically, we identify three convergence "clubs" for both the IWI and its adjusted variant (IWI adj.), indicating heterogeneous development paths across countries. These patterns are corroborated through ordered-logit estimations and slope-homogeneity robustness checks, strengthening confidence in the clustering results. The analysis underscores that countries' sustainable trajectories diverge when natural and human capital are explicitly considered, even when GDP trends appear similar. Policy implications emphasize investing in human capabilities, maintaining and restoring natural assets, and aligning fiscal and regulatory frameworks to safeguard intergenerational well-being and ensure the responsible use of natural resources.

Keywords: *imergeclub; logtreg; log t regression test; inequality, well-being; sustainable development*

JEL Codes: Q01, C23, O44

1. Introduction

In recent decades, the inadequacy of Gross Domestic Product (GDP) as a measure of national progress has stimulated the development of alternative sustainability metrics (Aitken, 2019; Dasgupta, 2014). Among these, the Inclusive Wealth Index (IWI), introduced in the 2012 Inclusive Wealth Report by the United Nations Environment Programme (UNEP), has emerged as a theoretically grounded and comprehensive indicator of long-term well-being and sustainability (UNEP, 2023).

Building on the work of Dasgupta and Mäler (2000) and Arrow et al. (2003a, 2003b), the IWI conceptualizes social welfare in terms of changes in total wealth, encompassing produced, human, and natural capital. This multidimensional framework distinguishes it from other indicators, such as the Human Development Index (HDI), which omits environmental dimensions (Suganthi, 2020), and the Genuine Progress Indicator (GPI), which primarily adjusts economic accounts while also incorporating selected social and environmental concerns (Hamilton, 1999; Kubiszewski et al., 2013).

The principal strength of the IWI lies in its ability to capture the intertemporal interdependence of capital stocks and to assess development beyond output-based measures. By assigning value to natural, human, and produced capital, and, in its adjusted form, accounting for exogenous factors such as carbon damages (Halkos et al., 2018; Managi et al., 2024), the IWI provides a more policy-relevant benchmark for evaluating sustainability, intergenerational equity, and progress toward the SDGs (Halkos et al., 2025b). Nevertheless, aggregate global trends may obscure substantial cross-country heterogeneity. To address this gap, the present study applies the Phillips and Sul (2009, 2007) club convergence methodology to IWI and adjusted IWI data in order to identify convergence patterns, reveal distributional disparities, and assess their implications for sustainability transitions.

The current paper seeks to shed light on three research questions (RQs):

RQ1: Do countries show convergence or divergence in IWI over time, and does this differ between IWI and adjusted IWI?

RQ2: How does GDP per capita affect countries' classification into wealth-based clubs, and are IWI and adjusted IWI equally sensitive to GDP-related changes?

RQ3: How do components of adjusted IWI, such as carbon damages, oil capital gains, and total factor productivity, shape cross-country heterogeneity in the relationship between GDP per capita and inclusive wealth?

The paper has two main objectives: to examine cross-country convergence in IWI by identifying global clubs using the Phillips and Sul (2007) methodology, and to derive policy-relevant implications for global wealth inequality and sustainable development. Its main contribution lies in applying club convergence analysis to the IWI, thereby addressing a notable gap in the literature and offering a novel framework for examining its dynamic, non-linear

evolution across countries. The study is organized as follows: Section 2 reviews the IWI literature and its role as an alternative to GDP, Section 3 outlines the data and methodology, Section 4 presents and discusses the empirical results, and Section 5 concludes with policy implications.

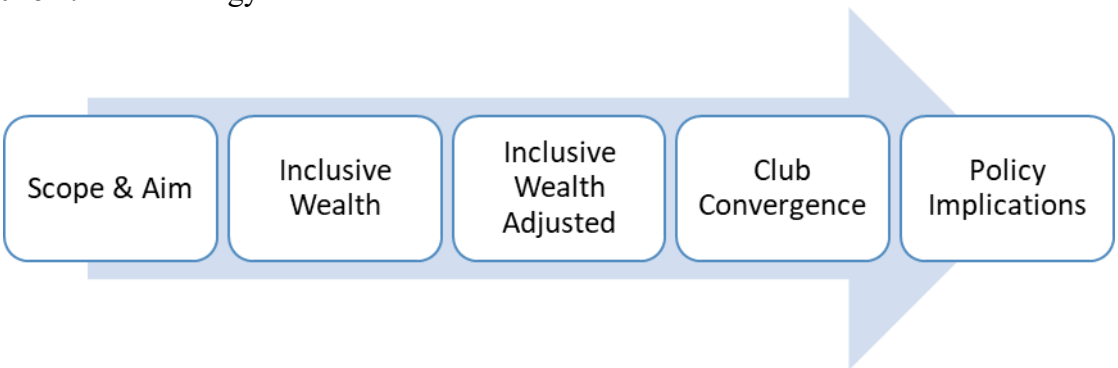
2. Materials & Methods

The paper investigates global trends in IWI per capita and adjusted IWI per capita for 163 countries over the period 1990–2020 using UNEP (2023) data, within the framework of club convergence. Countries are also classified by income group based on GNI per capita following the Atlas methodology (World Bank, 2025).

2.1.1. Methodological insights of the inclusive wealth index

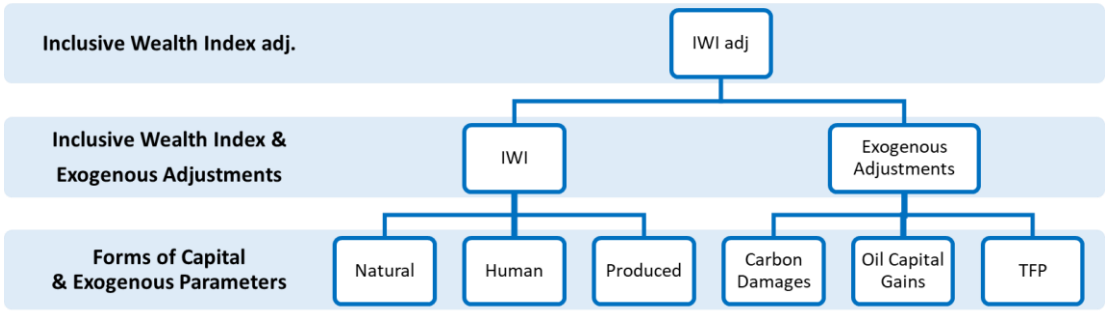
The descriptive statistics reveal marked cross-country disparities in inclusive wealth and income. In particular, both IWI per capita and adjusted IWI per capita display means substantially higher than medians, indicating highly skewed distributions driven by a small number of very wealthy countries. High skewness and kurtosis further suggest heavy-tailed distributions with numerous outliers, while GDP per capita shows similar but less pronounced inequality. In this sense, **Figure 1** illustrates the methodology flow of the paper.

Figure 1: Methodology flow



Methodologically, the IWI is grounded in the inclusive wealth approach, which expands conventional assessments of human well-being and sustainability by incorporating produced, human, and natural capital (Agliardi et al., 2012; Arrow et al., 2003a, 2003b; Dasgupta, 2014, 2001; Dasgupta and Mäler, 2000; Irwin et al., 2016) as in Figure 2. The index is linked to intergenerational welfare and dynamic resource allocation, with each capital stock weighted by its social or shadow price UNEP (2023, pp. 87–90). Although the IWI is expressed in linear form, this does not imply perfect substitutability among capital types, as their shadow prices depend on stock levels and only limited substitution is feasible (Gravelle and Rees, 2004; UNEP, 2023).

Figure 2: The parameters of the Inclusive Wealth Index and the Adjusted Inclusive Wealth Index



Finally, the adjusted IWI extends the standard framework by incorporating exogenous factors that affect sustainability outcomes, including cross-border environmental externalities such as GHG emissions, total factor productivity, and trade-related effects such as oil capital gains (UNEP, 2023). In this way, the adjusted IWI offers a broader and more policy-relevant measure of sustainable development than traditional GDP-based indicators (Halkos et al., 2025a).

2.2. Club Convergence Methodology

The study employs the Phillips and Sul (2007) "log t" club convergence methodology, a nonlinear and time-varying factor approach widely used to test convergence and identify clusters of units with similar developmental paths (Du, 2017). This method is applied to examine whether countries from different income groups exhibit convergence in IWI per capita and adjusted IWI per capita over 1990–2020. Within this framework, inclusive wealth is decomposed into a common systematic component and a transitory component, while a time-varying idiosyncratic coefficient captures each country's distance from the common path.

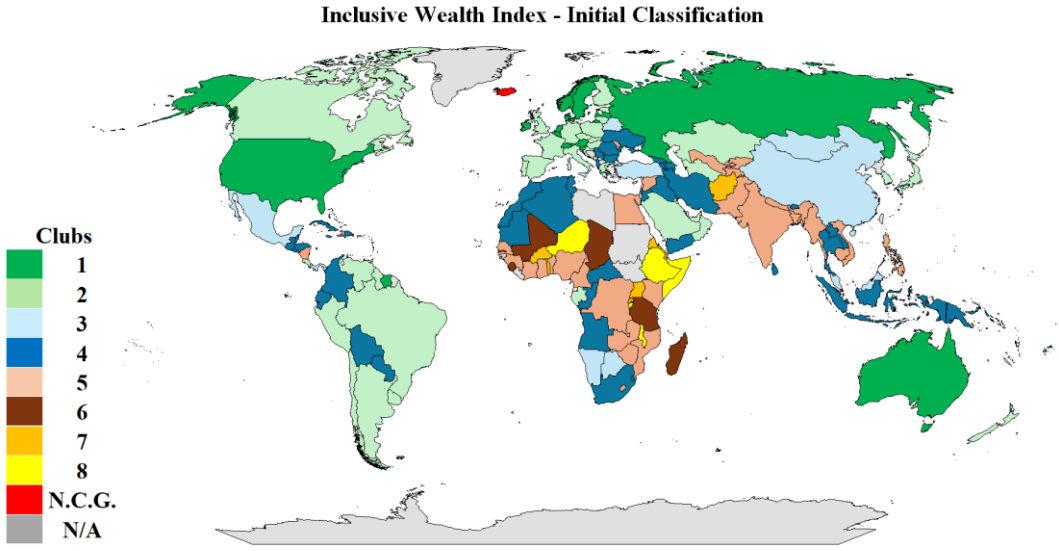
The methodology tests the null hypothesis of convergence against divergence by analyzing relative transition paths, which measure each country's position relative to the cross-sectional average. Convergence is supported when these transition parameters approach unity over time and cross-sectional variation tends toward zero (Phillips and Sul, 2007). The empirical test is based on the "log t" regression, where the key coefficient indicates the speed of convergence. The null hypothesis is rejected when the corresponding t-statistic falls below –1.65 at the 5% significance level.

To identify convergence clubs, the Phillips and Sul (2007) algorithm follows four steps: countries are first sorted, an initial core group is formed, additional countries are tested for membership, and final convergence clubs are then determined. This procedure provides a flexible framework for detecting heterogeneous convergence patterns across countries.

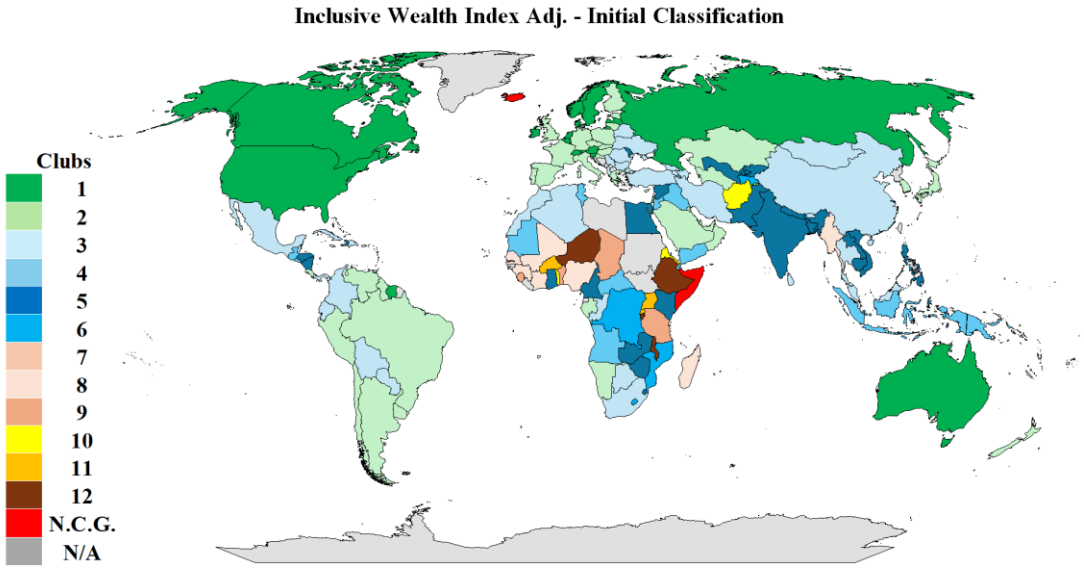
2. Results and Discussion

The results strongly reject full-sample convergence for both IWI per capita and adjusted IWI per capita, as the log t test statistics are far below the critical threshold of –1.65, indicating overall divergence across countries. Given this result, the Phillips and Sul club convergence algorithm identifies distinct subgroups of countries that converge toward different steady states rather than a single global path. Specifically, Map 1 shows that the initial club classification for the IWI and IWI adj. have 8 and 12 convergence clubs, respectively.

Map 1. Initial club classification of (a) inclusive wealth index and (b) adjusted inclusive wealth index



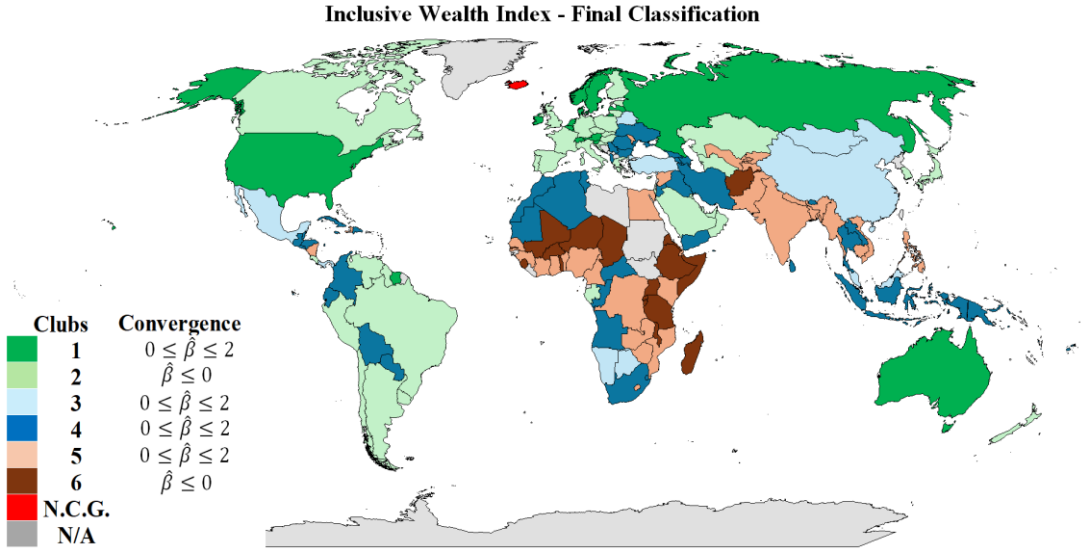
(a)



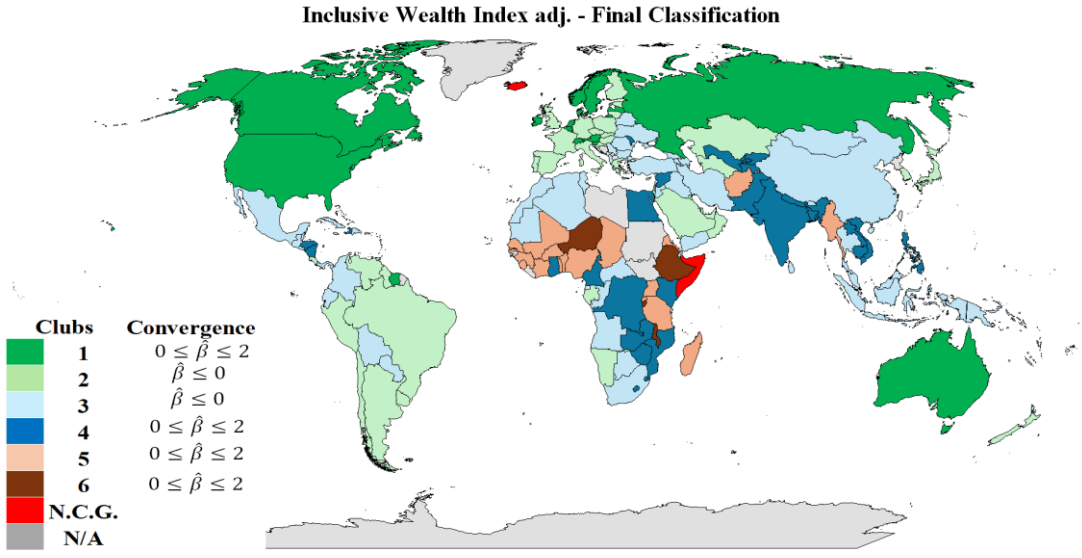
(b)

Note: NCG: Not-convergent group, N/A: no availability of data.

Map 2. Final club classification of (a) inclusive wealth index and (b) adjusted inclusive wealth index.



(a)



(b)

Note: NCG: Not-convergent group, N/A: no availability of data.

For both indices, as shown in Map 2, the final clustering structure consists of six convergence clubs and one non-convergent group. In both the IWI and adjusted IWI, two clubs correspond to high inclusive wealth levels, three to moderate levels, and one to low levels. The adjusted IWI initially produces a more fragmented structure than the standard IWI, suggesting that the inclusion of exogenous factors reveals greater heterogeneity across countries.

In terms of convergence levels, countries in Clubs 1 and 2 maintain the highest steady-state wealth values, while Clubs 5 and 6 represent the lowest levels. High-wealth countries, including the United States, Canada, Australia, Norway, and most Western European countries,

remain in the top clubs under both measures, indicating stability in their relative positions. By contrast, many African countries are concentrated in the lowest clubs, particularly after adjustment, pointing to persistent disadvantage and in some cases divergence.

The adjusted IWI also changes the relative positions of several middle-income economies. Some Latin American countries, such as Brazil, Argentina, Mexico, and South Africa, tend to move downward after adjustment, implying that exogenous factors reduce their relative inclusive wealth. In contrast, countries such as India, China, and Indonesia tend to shift upward, especially within Asia, suggesting improved relative performance once these factors are taken into account. Eastern Europe and Central Asia generally move slightly downward, while Southeast Asia displays greater internal divergence.

Regarding convergence dynamics, some clubs exhibit relatively fast convergence, especially Club 3 in the IWI and Club 6 in the adjusted IWI, whereas other clubs show weak or negative convergence coefficients, indicating limited internal cohesion. Overall, the findings suggest that inclusive wealth follows multiple differentiated development paths across countries, and that the adjusted IWI captures cross-country disparities more sharply than the unadjusted index.

3. Conclusions & Policy Implications

The study concludes that, although both IWI and adjusted IWI produce six final convergence clubs for 163 countries over 1990–2020, countries follow distinct development trajectories, especially once exogenous factors are incorporated. The findings show that GDP per capita alone is insufficient to reflect human development and environmental sustainability, since it overlooks key dimensions of produced, human, and natural capital. In addition, the structural adjustments included in the adjusted IWI, such as carbon damages and related exogenous factors, significantly shape cross-country heterogeneity.

From a policy perspective, the results suggest that development strategies should be tailored to each convergence club rather than based on uniform approaches. For high-wealth clubs, the priority is to preserve and diversify natural capital while strengthening inclusive social policies. For middle clubs, policies should focus on improving health, education, and environmental governance in order to support more balanced wealth accumulation. For the lowest clubs, where countries often face institutional fragility, conflict, poverty, and environmental vulnerability, priorities include strengthening human capital, rebuilding infrastructure and governance capacity, protecting natural capital, and expanding international support, particularly for African countries through debt relief and climate adaptation finance. Overall, the paper argues that club-specific inclusive wealth strategies provide a more effective framework than GDP-based approaches for promoting long-term well-being, intergenerational equity, resilience, and progress toward the SDGs.

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Degrowth and Planetary Boundaries: Economic Dimensions of an Alternative Paradigm for Sustainable Transition

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Abstract

Degrowth is defined as a deliberate social and political process of reducing energy and material consumption to achieve social equity within sustainable ecological limits. It represents a conscious shift away from the capitalist model of perpetual economic growth, proposing instead a framework for a fair and sustainable socioeconomic system. Despite its growing academic prominence, degrowth remains insufficiently explored regarding its economic implications and political feasibility. This study investigates the relationship between the conceptual framework of planetary boundaries and the theory of degrowth, focusing on their economic dimensions. A systematic literature review was conducted following the PRISMA 2020 guidelines, categorizing the identified economic impacts into three main axes: macroeconomic, microeconomic, and socioeconomic. The results reveal a relatively limited but expanding body of research, suggesting that this alternative economic paradigm may substantially contribute to addressing the global environmental crisis. Nevertheless, its practical implementation requires social legitimization, institutional reforms, and the development of new welfare indicators that can more accurately reflect the multidimensional nature of sustainable progress.

Keywords: *Degrowth; planetary boundaries; sustainability; GDP; economic implications;*

JEL Codes: P41; P43; P44; P48.

1. Introduction

Planetary boundaries, as a set of biophysical limits within which human activity can remain safe, are a central tool for assessing environmental risk (Rockström et al., 2009). The fact that six of the nine boundaries have been exceeded and another is on the verge of being exceeded (ocean acidification) demonstrates that humanity is already operating beyond the "safe operating space" (Steffen et al., 2015; Sobkowiak et al., 2023).

Although green growth seeks to reconcile economic growth with environmental sustainability, the empirical literature shows that the desired absolute decoupling of GDP from environmental pressures has not been achieved at the global level (Hickel & Kallis, 2020). In this context, degrowth is proposed as an alternative economic and social approach that challenges growth as an end and prioritizes well-being, social justice, and environmental protection (Demeria et al., 2013; Sekulova et al., 2013). However, despite growing research interest, a coherent framework that systematically focuses on the economic implications of degrowth in relation to the planet's biophysical limits has not yet been established.

This paper aims to contribute to an understanding of the relationship between the theory of degrowth and the planetary boundaries framework from an economic perspective, by examining: (a) how the relevant literature links the concept of degrowth to planetary boundaries, (b) what economic impacts are attributed to the transition toward low- or zero-growth models per planetary boundary, (c) in what ways degrowth is proposed in the literature as a potential strategy for addressing the key environmental pressures associated with exceeding planetary boundaries.

2. Theoretical Framework

2.1. The Theory of Degrowth

Degrowth is defined as "the deliberate social and political process of reducing energy and material use, with the aim of achieving social equality within sustainable ecological limits" (Kallis, 2018). Its main principles include the redistribution of wealth and the reduction of inequalities, the decoupling of well-being from economic growth (Trainer, 2021), the prioritization of environmental sustainability, strengthening local and solidarity-based economies, scaling back overconsumption patterns (Hickel, 2020), and democratic governance (Martínez-Alier, 2009).

Advocates of degrowth question the use of GDP as an indicator of well-being and argue for the need to reorient policy goals toward quality of life, social cohesion, and ecological balance (van den Bergh & Kallis, 2012). In particular, they argue that developed countries can maintain high levels of human well-being through a deliberate reduction in energy and resource use, without relying on continuous economic growth (Hickel, 2020). However, despite the

benefits highlighted, it has been criticized regarding the feasibility of implementing it without causing a rise in unemployment, recession, and widening social inequalities, particularly if it is not accompanied by appropriate redistribution policies and robust social protection systems (Trainer, 2021).

2.2. Planetary Boundaries and Degrowth

The planetary boundaries framework was developed by Rockström et al. (2009) and identifies nine key biophysical processes that regulate the stability of the Earth system, such as climate change, biodiversity loss, the biogeochemical cycles of nitrogen and phosphorus, land-use change, and ocean acidification. Keeping human activity within these boundaries is considered essential to avoid irreversible environmental changes and ensure the sustainability of ecosystems and human societies (Rockström et al., 2009). However, recent studies indicate that six of the nine planetary boundaries have already been exceeded, a fact that calls into question the compatibility of the dominant model of continuous economic growth with the planet's ecological capacity (Sobkowiak et al., 2023).

In this context, the theory of degrowth proposes reducing overall production and consumption, particularly in high-income countries, so that human activities can return within ecological limits (Hickel, 2020; Farley et al., 2013). At the same time, Kate Raworth's (2017) Doughnut model combines planetary boundaries with a social foundation of basic needs, defining a "safe and just space for humanity" where economic activity can support human well-being without exceeding ecological limits (Raworth, 2017; O'Neill et al., 2018).

3. Methodology

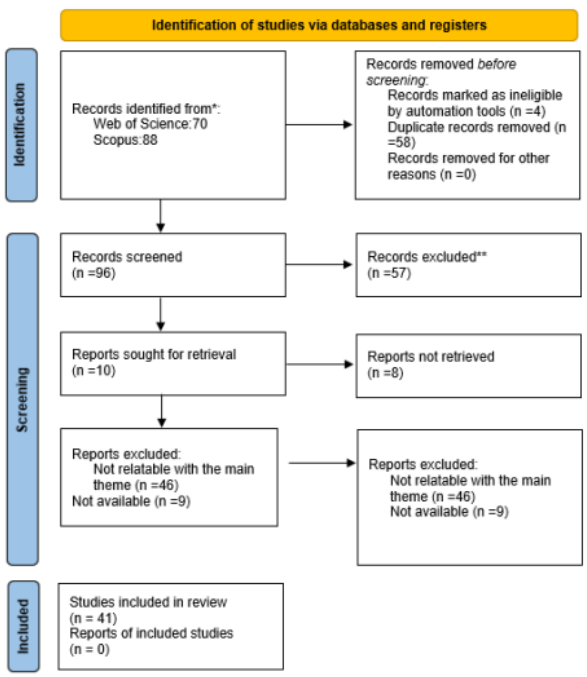
This study is a systematic literature review conducted in accordance with the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Page et al., 2021), with the aim of systematically identifying and analyzing the existing literature on the relationship between degrowth and planetary boundaries from an economic perspective.

The search for relevant literature was conducted in the Web of Science and Scopus databases, which provide extensive coverage of reputable scientific publications (Visser et al., 2021). The search was limited to the fields of title, abstract, and author keywords to ensure the relevance of the results to the research topic. The search was conducted on May 2, 2025. After testing different combinations of keywords and applying Boolean operators, the following search query was used:

("degrowth" OR "postgrowth" OR "steady-state economy") AND ("planetary boundar" OR "planetary limit*" OR "ecological threshold*" OR "environmental limit*" OR "ecological limit*") AND ("econom*" OR "macroecom*" OR "socioeconomic*")*

The initial search identified 70 results in the Web of Science database and 88 in Scopus. Restrictions were then applied regarding the language of publication (English) and the publication period (2012–2025). After removing 58 duplicate records, a total of 96 articles remained for evaluation. The articles were screened based on their titles and abstracts for relevance to the research topic. This process excluded 57 articles that were not related to the economic dimension of the relationship between degrowth and planetary boundaries. Ultimately, 41 articles were included in the analysis. The study selection process is illustrated in the PRISMA flow diagram presented in Figure 1.

Figure 1: PRISMA 2022 flowchart.



4. Results

The literature review increasingly links degrowth to the planetary boundaries framework, treating planetary boundaries as a fundamental constraint on future economic activity. This section presents the findings of the literature regarding the economic implications of degrowth in relation to planetary boundaries.

4.1. Climate Change

According to Kallis et al. (2024), traditional economic models, such as the Environmental Kuznets Curve (EKC), tend to underestimate the costs of climate change, as the expected reduction in carbon emissions has not been empirically confirmed, even in high-income countries. Furthermore, climate change is expected to cause significant income losses: a 19% reduction in per capita income is projected over the coming decades, and an additional loss of approximately 12% of global GDP for every additional degree of temperature rise (Kallis et al.,

2024). The current global economy is based on increasing use of materials and energy (approximately 100 Gt per year), with high-income countries consuming an average of 28 tons of resources per capita, a level many times higher than the sustainable limit (Hickel & Hallegatte, 2022).

Victor (2012), using the LowGrow macroeconomic model for Canada, shows that scenarios of low or zero growth allow for a 22% reduction in emissions without increasing unemployment or poverty. More specifically, in a degrowth scenario, per capita GDP falls to levels compatible with the global ecological space, emissions are reduced by nearly 80%, while indicators such as unemployment, the poverty rate, and public debt as a percentage of GDP remain stable (Victor, 2012).

Finally, the debate over the extent to which economic growth can be decoupled from environmental impacts directly links development trajectories to planetary boundaries. Therefore, for growth to be compatible with the <2°C temperature rise target, "carbon productivity" must increase by at least 5% annually; 1.5°C targets require a 7–9% annual increase (Stoknes & Rockström, 2018). The higher the GDP growth rate, the greater the improvement in efficiency must be (Stoknes & Rockström, 2018), a fact that makes degrowth more compatible with climate limits.

4.2. Biosphere Integrity

The breach of the biosphere integrity threshold is directly linked to the rise of overconsumption patterns, deforestation, species loss, and urban expansion. Santika et al. (2023) argue that the primary approach to managing the risk of deforestation at the producer level fails to yield the desired results; demand continues to rise in countries through exports. Therefore, they propose policies consistent with the principles of degrowth, such as curbing overconsumption, debt cancellation or restructuring in producer countries, as well as the imposition of targeted taxation on agricultural commodity companies, so that they internalize ecological and social costs into product prices (Santika et al., 2023).

At the urban level, modern cities act as engines of economic growth and exacerbate the logic of expansion: urbanization, urban sprawl, and the overconsumption of energy and materials (Kronenberg et al., 2024). In this way, available space for other species is reduced and vital ecosystems are disrupted (Kronenberg et al., 2024). Consequently, degrowth policies could potentially offer solutions by consciously slowing down economic activities, particularly urban expansion.

4.3. Land-use change

Land-use change refers to the conversion of natural areas into agricultural and urban areas, which reduces the planet's natural capacity to regulate the climate and maintain

biodiversity (Kreinin & Aigner, 2022). Fanning and O'Neill (2016) use the "land footprint/biocapacity" index to compare the scale of land use with biocapacity in Canada and Spain. Their findings indicate that Spain, and Andalusia in particular, already exceed available limits due to urbanization and an export-oriented agricultural model, while Canada remains within limits thanks to its extensive forest cover, although deforestation is on the rise (Fanning & O'Neill, 2016). They argue that a transition to a steady-state economy could help reduce the land footprint in developed regions as well as shift economic resources from energy-intensive sectors—such as intensive industrial agriculture, to more sustainable options.

In the Swedish low growth/degrowth framework proposed by Fauré et al. (2016), a target is suggested whereby the amount of land used for final consumption per capita would not exceed the global per capita share of biocapacity. Given that Swedish land consumption exceeds this share by approximately 50%, achieving the target requires a significant reduction in demand for land-intensive products (meat, animal feed, biofuels) and a restructuring of agriculture and imports (Fauré et al., 2016). This approach is characteristic of degrowth, as it sets direct biophysical targets, regardless of whether GDP will increase, stabilize, or decrease.

4.4. Decline in Freshwater Reserves

The increasing consumption of freshwater for agriculture, industry, and urban use is depleting natural reserves and threatening the sustainability of water resources (Farley et al., 2013). According to a study by Fanning & O'Neill (2016), freshwater consumption in Canada exceeds availability by approximately 1.5 months per year, mainly due to seasonal river ice cover, while in Spain the shortfall lasts more than four months annually, and in Andalusia up to six months (Fanning & O'Neill, 2016). In Spain, for water use to remain within safe limits, consumption during the summer months must be reduced by 30–65%, while in Andalusia the required reduction is 20–70% during several months of the year (Fanning & O'Neill, 2016). The primary economic activity behind these exceedances is the irrigation of agricultural crops, which often relies on water-saving technologies.

From the perspective of degrowth, this suggests that technological progress alone, without restrictions on the overall scale of production, is not sufficient on its own to return within biophysical limits. However, a combined approach is proposed that includes reducing the area under cultivation in water-vulnerable regions, a shift from extensive cropping to multifunctional, local systems, and a reduction in demand for water-intensive products in affluent countries (Santika et al., 2023; Fanning & O'Neill, 2016).

4.5. Disruption of Biogeochemical Cycles (Nitrogen & Phosphorus)

The use of nitrogen and phosphorus fertilizers significantly exceeds the soil-based biogeochemical limits in the study areas of Canada and Spain (Fanning & O'Neill, 2016). The economy must therefore be restructured in such a way as to strengthen local, less intensive

production systems, particularly in food production, so that human needs can be met within planetary boundaries (Hinton, 2022). The economic consequences of adhering to these limits are linked to the need to curb intensive agriculture, industrial livestock farming, and certain industrial sectors (e.g., chemical fertilizer production), as well as the reorganization of food systems toward diets with lower nitrogen and phosphorus intensity (e.g., reduced consumption of red meat).

4.6. Ocean Acidification

Ocean acidification does not appear in the literature as a distinct category linking planetary boundaries to degrowth; it is primarily treated as a consequence of CO_2 accumulation in the atmosphere. In a broader context, degrowth argues that the voluntary downsizing of the economy substantially increases the likelihood of achieving climate goals compared to business-as-usual scenarios (van den Bergh & Kallis, 2012).

4.7. Stratospheric Ozone Depletion

The case of stratospheric ozone depletion serves as an example where targeted regulation of the Chlorofluorocarbons (CFC) production and use made it possible to halt the depletion without causing widespread economic collapse (Kronenberg et al., 2024). The relevant literature on degrowth uses this example to demonstrate that timely, politically coordinated phase-out of environmentally harmful activities can limit transition costs, in contrast to piecemeal interventions that lead to larger, uncontrolled disruptions (Kronenberg et al., 2024). From an economic perspective, the planned contraction of specific polluting industries is compatible with maintaining prosperity when accompanied by a reallocation of resources to less harmful sectors (Rockström et al., 2009; Kallis et al., 2024). The experience of the Montreal Protocol also shows that adaptation costs for businesses can be recouped relatively quickly through technological innovation and product substitution, provided that regulatory signals are clear and stable (Steffen et al., 2015; Stoknes & Rockström, 2018).

4.8. Pollution from Chemicals and Toxic Waste

The threshold for new entities (chemicals, plastics, and other toxic waste) is already considered exceeded, with research showing that high-income countries exhibit the greatest exceedances without a corresponding improvement in social indicators (Kallis et al., 2024; Fanning et al., 2022). This suggests that further economic growth in these economies is accompanied by worsening chemical pollution with low or zero marginal social benefits, reinforcing the case for selective degrowth (Hickel et al., 2021). Degrowth policies propose a combination of restrictions, divestment, and substitution with low-resource-intensity activities (e.g., reuse, repair, care services) as a strategy to reduce toxic burdens without compromising overall well-being (Steinberger et al., 2020). Furthermore, exceeding the threshold for new entities suggests that the spatially and socially unequal impacts of pollution (e.g., the sitting of

polluting facilities and waste in poorer areas) constitute a form of ecological debt owed by the Global North to the Global South (Fanning et al., 2022; Hickel et al., 2022).

4.9. Aerosol Concentrations in the Atmosphere

Atmospheric aerosol pollution is primarily linked to the combustion of fossil fuels and heavy industry, with indications that we may already be approaching the relevant planetary boundary (Zink, 2019). Since aerosols are linked to serious impacts on health and agricultural production, continued expansion in energy-intensive sectors entails rising economic costs through productivity losses and healthcare expenditures (Zink, 2019; Rammelt & Gupta, 2021). A degrowth policy aimed at reducing overall energy consumption and heavy industrial production could limit both the overshoot of the aerosol threshold and the associated socioeconomic inequalities (Rammelt & Gupta, 2021; Farley, 2013). Globally, this means that continued growth in energy-intensive sectors in wealthy nations limits the available "atmospheric space" for low-income countries, which have contributed little to the problem (Hickel, 2020; Hickel et al., 2021). Planned reduction of energy demand in the North, combined with investments in low-emission public infrastructure, could simultaneously achieve a reduction in air pollution, improve public health, and expand development space for the Global South within global limits (O'Neill et al., 2018; Kallis et al., 2024).

5. Discussion

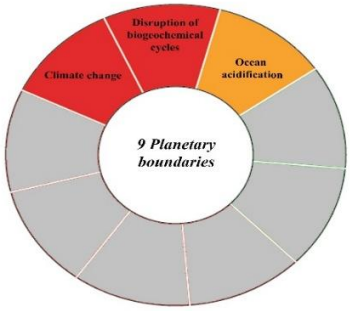
The above findings are summarized in three tables illustrating the nine planetary boundaries, which define the safe operating space for the sustainability of the Earth system and human societies. For each planetary boundary, the main environmental risks resulting from exceeding it are listed, as well as the potential impacts of the transition toward degrowth. Additionally, the level of economic impact reflects the economic dimension in relation to the characteristics of each limit.

5.1. Climate and Biogeochemical Cycles

Figure 2 illustrates three critical planetary boundaries: climate change, disruption of biogeochemical cycles (nitrogen and phosphorus), and ocean acidification, which, according to the planetary boundaries framework, have already been exceeded or are close to being transgressed (Rockström et al., 2009). Exceeding these boundaries is linked to rising temperatures, increased CO_2/CH_4 emissions, soil and water pollution, and reduced ecosystem productivity, with serious expected losses in global GDP and per capita income (Kallis et al., 2024). At the macroeconomic level, degrowth is proposed as a strategy to reduce energy consumption and emissions through a transition to renewable energy and targeted green investments, with existing analyses indicating that low- or zero-growth scenarios can drastically reduce emissions without increasing unemployment or poverty (Victor, 2012; Farley et al., 2013).

Figure 2: Climate and biogeochemical system

1. Climate & Biogeochemical System	
Planetary boundaries	**Climate change • Disruption of biogeochemical cycles • Ocean acidification**
Environmental risks	Rising temperatures • CO_2 & CH_4 emissions • soil and water pollution • loss of ecosystem productivity
Economic effects of degrowth	Reducing energy consumption and emissions • transitioning to clean energy and renewable energy sources • redirecting investments toward green technologies
Level of impact	Macroeconomic – affects production GDP, employment, fiscal policy



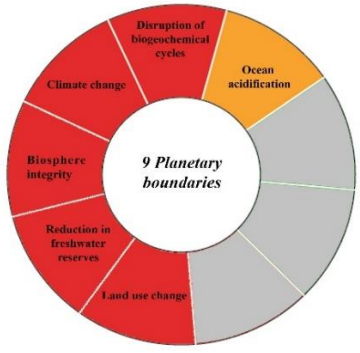
Visualization of the status of biophysical limits. Red (outside safe limits), green (within safe limits), orange (imminent exceedance)

5.2. Biodiversity and Ecosystems

The second table focuses on the integrity of the biosphere, land-use change, and the depletion of freshwater reserves—planetary boundaries that recent analyses indicate have already been exceeded (Steffen et al., 2015). Exceeding these limits manifests itself in species loss, ecosystem destabilization, desertification, and water scarcity, with direct impacts on agriculture, raw material markets, and access to drinking water. At the same time, many developed regions are already exceeding available biocapacity, which necessitates curbing intensive agriculture and export-oriented production to return within these limits (Fanning & O'Neill, 2016). From an economic perspective, degrowth is linked to policies aimed at protecting and restoring natural resources, strengthening sustainable agriculture, and restructuring food and land-use systems so that human needs are met within biophysical limits at both the macro- and microeconomic levels (Fauré et al., 2016; Hickel & Hallegatte, 2022).

Figure 3: Biodiversity and ecosystems

2. Biodiversity & Ecosystems	
Planetary boundaries	**Biosphere integrity • Land use change • Reduction in freshwater reserves**
Environmental risks	Loss of species • destabilization of ecosystems • desertification • water scarcity • reduced availability of drinking water
Economic effects of degrowth	Conservation of natural resources • land restoration • sustainable agriculture and water management • reduction of intensive farming
Level of impact	Macroeconomic & microeconomic affects agriculture, raw material markets, and production sustainability.



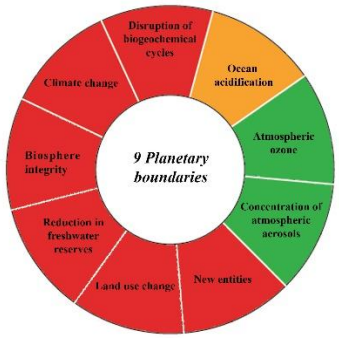
Visualization of the status of biophysical limits. Red (outside safe limits), green (within safe limits), orange (imminent exceedance)

5.3. *Pollution and the Atmosphere*

The final table addresses planetary boundaries related to new entities, atmospheric aerosol concentrations, and the ozone layer. Environmental risks such as air, water, and soil pollution, increased UV-B radiation, climate imbalances, and serious impacts on public health and agricultural production are highlighted (Steffen et al., 2015; Zink, 2019). Degrowth perspectives propose a reduction in chemical processes, cleaner production, energy conservation, and divestment from petrochemical and related industries to reduce the economic costs of pollution and improve quality of life at the socioeconomic and microeconomic levels (Farley et al., 2013; Kronenberg et al., 2024).

Figure 4: Pollution and atmosphere

3. Pollution & Atmosphere	
Planetary boundaries	New entities (chemicals, toxic waste) • Concentration of atmospheric aerosols • Atmospheric ozone
Environmental risks	Air, water and soil pollution • increased UV-B radiation • climate imbalances • impacts on public health
Economic effects of degrowth	Reduction of chemical processes • cleaner production • health protection • reduction of pollution costs and energy waste
Level of impact	Socioeconomic & microeconomic improvement in quality of life, health, and social well-being



Visualization of the status of biophysical limits. Red (outside safe limits), green (within safe limits), orange (imminent exceedance)

6. Conclusions

This study has provided evidence obtained from relevant reliable literature that the prevailing economic model is incompatible with planetary boundaries, since most the biophysical boundaries have been exceeded on a global scale. Degrowth is presented in the same literature that it can serve as a pathway toward an economy that contributes to the protection of biodiversity, the reduction of pollutants, and respect for natural limits, especially in high-income countries that currently exceed planetary boundaries disproportionately. Proposed degrowth policies, such as the redistribution of the tax burden, the promotion of public goods and infrastructure, and the strengthening of democratic decision-making, offer a positive outlook for the future.

However, serious challenges that accompany this transition should not be overlooked. Social acceptance of degrowth policies along with a shift in long-standing consumer habits and economic perceptions are key factors for the success of such a reform process. At the same time, strong institutions of transparency and environmental accountability are necessary for the implementation of such sustainable reforms, while the formation of new values, such as

sufficiency and self-reliance, constitutes the foundation of social progress. Addressing potential negative phenomena such as unemployment and economic uncertainty clearly requires decisive policies, which are often absent from existing degrowth strategies. Finally, the development and adoption of innovative well-being indicators that take into account the ecological and social footprint alongside economic metrics is a fundamental prerequisite for reliably measuring progress toward a sustainable degrowth model.

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Transitional Dynamics and Policy Spillovers. Are Market-Based Instruments and Technology Autarky Structural Drivers in the European Green Transition?

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Abstract
We investigate whether market-based instruments and technology autarky act as structural drivers of the European green transition. We focus on two pillars of structural transformation, EU climate policy, captured by the Emissions Trading System (carbon pricing) and renewable feed-in tariffs, and green technology sovereignty, measured by technological independence. Using panel data for the EU-28 during 2010-2019 and an instrumental variables panel quantile estimator on the Green Growth Index, we analyse both contemporaneous and lagged effects to capture transitional dynamics and diffusion channels. Results show that policy and technology changes exert strong and consistent effects on green growth progress. While contemporaneous levels have immediate effects, reinforcing mechanisms operate through diffusion. Technology autarky emerges as a balancing factor, mitigating adverse effects of green policy. Findings underscore the need for integrated policy frameworks aligning market incentives with domestic technological capabilities to drive European green transition. This study contributes to SDGs 7,8,9,12,13, and 16.

Keywords: *EU ETS; Green Technology Independence; Green Transition; Instrumental Variables Panel Quantile Estimator; Environmental Policy Effectiveness; Europe*

JEL Codes: O38; Q54; Q58

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Session 11.

CSR - ESG

The role of internal CSR as driver of sustainable innovation through intrapreneurship

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Abstract

This paper investigates the role of internal corporate social responsibility (CSR) in fostering a culture conducive to sustainable innovation within established organizations. Internal CSR is conceptualized as a fundamental organizational dimension that cultivates employee motivation, commitment, and empowerment toward innovation practices aligned with sustainability principles. The primary aim of this study is to develop a conceptual framework that elucidates the interconnections among internal CSR, intrapreneurship, and sustainable innovation. Intrapreneurship is approached as the mediating mechanism through which internal CSR values and practices are transmitted to employees, enabling the translation of responsible organizational culture into sustainability-oriented innovative outcomes. The paper adopts an exploratory and conceptual methodology, grounded in an extensive review of the relevant literature. Through this approach, it seeks to identify theoretical linkages, underlying mechanisms, and critical research questions that can inform future empirical investigations of the triadic relationship among the three constructs. By integrating insights from the domains of CSR, intrapreneurship, and sustainable innovation, this study aspires to contribute to the theoretical advancement of how internal CSR practices may underpin and strengthen organizational capacities for sustainable innovation through the promotion of a culture of sustainable intrapreneurship.

Keywords: *CSR and Corporate Culture, intrapreneurship / corporate entrepreneurship, innovation processes, sustainability context, knowledge sharing and learning mechanisms*

JEL Codes: M14, L26, O31, Q01, D83

1. Introduction

The accelerating global emphasis on sustainability has transformed the strategic priorities of contemporary organizations. Firms are increasingly expected to generate economic value while simultaneously addressing environmental challenges and social responsibilities. This shift has elevated sustainable innovation as a critical mechanism through which organizations seek long-term competitiveness and legitimacy (Schaltegger and Wagner, 2011; Lehman et al., 2005).

Sustainable innovation extends beyond traditional innovation by incorporating the principles of the triple bottom line, which integrates economic, environmental, and social performance objectives (Lehman et al., 2005). Achieving such integration requires not only technological capabilities but also internal organizational conditions that support creativity, risk-taking, and ethical decision-making.

Internal Corporate Social Responsibility (CSR) has emerged as a central organizational mechanism in this context. Internal CSR refers to policies and practices that promote employee well-being, fairness, empowerment, and participation within the organization (Turker, 2009; Mory et al., 2015). By shaping organizational culture and employee attitudes, internal CSR may play a critical role in fostering innovation-oriented behaviour.

In parallel, intrapreneurship—defined as entrepreneurial behaviour within established organizations—has been identified as a key driver of innovation and organizational renewal (Pinchot, 1985; Antoncic and Hisrich, 2001). When intrapreneurial behaviour is aligned with sustainability values, it can function as a catalyst for sustainable innovation.

Despite increasing scholarly attention to these constructs, the literature remains fragmented, with limited conceptual integration examining how internal CSR, intrapreneurship, and sustainable innovation interact within a unified framework (Andreassi, 2003; Smith et al., 2005). This paper seeks to address this gap by developing a conceptual model that explains how internal CSR fosters intrapreneurship and how intrapreneurial drivers contribute to sustainable innovation outcomes.

2. Literature Review

2.1. Internal Corporate Social Responsibility

Internal CSR encompasses organizational practices aimed at enhancing employee well-being, development opportunities, ethical treatment, and participatory decision-making (Turker, 2009; Mory et al., 2015). Grounded in stakeholder theory, internal CSR recognizes employees as primary stakeholders whose engagement and satisfaction are critical for organizational sustainability (Dmytriyev et al., 2021).

Empirical and conceptual studies suggest that internal CSR strengthens perceived organizational support, trust, and psychological safety (Eisenberger et al., 1986; Glavas, 2016). These conditions reduce fear of failure and encourage employees to engage in creative and innovative behaviour (Aguinis and Glavas, 2012). Ethical leadership and transparent communication further reinforce employees' perception of fairness and organizational integrity (Brammer et al., 2007).

Employee empowerment and well-being initiatives embedded in internal CSR frameworks enhance intrinsic motivation and organizational commitment, increasing employees' willingness to engage in discretionary, innovation-oriented activities (Turker, 2009; Brieger et al., 2021). Consequently, internal CSR can be conceptualized as an enabling infrastructure that supports entrepreneurial behaviour within organizations.

2.2. Intrapreneurship as Entrepreneurial Behaviour

Intrapreneurship refers to entrepreneurial behaviour exhibited by employees within existing organizations, including opportunity recognition, innovation, autonomy, proactiveness, and risk-taking (Pinchot, 1985; Antoncic and Hisrich, 2003). Such behaviour contributes to organizational renewal and competitiveness by transforming internal knowledge into marketable innovations (Ireland et al., 2009).

The literature emphasizes that intrapreneurship is highly context-dependent and shaped by organizational culture, leadership, and resource availability (Kuratko et al., 2015). Supportive internal environments that tolerate experimentation and failure are essential for intrapreneurial initiatives to flourish (Antoncic and Hisrich, 2001).

Internal CSR directly contributes to these enabling conditions by reinforcing empowerment, autonomy, and perceived fairness (Mory et al., 2015). Organizational support theory further explains why employees operating in socially responsible internal environments are more likely to engage in intrapreneurial behaviour that extends beyond formal job roles (Eisenberger et al., 1986; Ghani et al., 2023).

2.3. Sustainable Innovation

Sustainable innovation involves the development of products, services, processes, or business models that simultaneously generate economic value, minimize environmental impact, and promote social well-being (Hall and Wagner, 2011). It is central to sustainability transitions that aim to shift organizations and industries toward more responsible modes of production and consumption (Kemp et al., 1998).

Innovation plays a critical role in enabling such transitions, particularly when driven from within organizations by empowered employees (Linnanen, 2002; Larson, 2000).

Intrapreneurship enables organizations to mobilize internal creativity and knowledge toward sustainability-oriented goals (Schaltegger and Wagner, 2011).

Research suggests that sustainable innovation is more likely to emerge in organizations that embed ethical commitment, stakeholder awareness, and long-term orientation into internal governance structures (Khan et al., 2021). Internal CSR contributes to this embedding process by institutionalizing sustainability-related values at the employee level.

2.4. Integrating Internal CSR, Intrapreneurship, and Sustainable Innovation

Although positive relationships have been identified between internal CSR and intrapreneurship, intrapreneurship and innovation, and CSR and sustainability outcomes, comprehensive triadic models remain limited (Andreassi, 2003; Smith et al., 2005).

This study positions intrapreneurship as both an outcome of internal CSR and a driver of sustainable innovation. Internal CSR provides the enabling conditions—such as empowerment, ethical leadership, and employee well-being—that foster intrapreneurial behaviour, which in turn translates into sustainability-oriented innovation outcomes. This logic supports the proposition that thinking and acting like an entrepreneur within a responsible organizational context can lead to sustainable innovation initiatives.

3. Hypotheses Development

H1: Effective internal CSR outcomes positively influence intrapreneurial behaviour within organizations.
Internal CSR practices foster autonomy, initiative-taking, and risk tolerance by creating supportive and ethical internal environments (Brammer et al., 2007; Glavas, 2016).

H2: Drivers of intrapreneurship positively influence sustainable innovation outcomes. Intrapreneurial characteristics such as proactiveness, problem-solving capability, and risk-taking enable employees to develop innovative solutions addressing economic, environmental, and social challenges (Kyro, 2001; Larson, 2000).

H3: Effective internal CSR outcomes directly contribute to sustainable innovation. Internal CSR embeds ethical values, stakeholder awareness, and long-term orientation into organizational decision-making, directly shaping sustainability-oriented innovation (Khan et al., 2021; Fay and Flöther, 2024).

4. Methodology

4.1. Research Design

This study adopts a conceptual and exploratory research design based exclusively on a structured literature review. The literature review is used as an analytical tool to academically examine the proposed hypotheses and conceptual relationships.

In order to achieve this result, an extended list of outcomes and drivers has been created, where the three models provide proof of multilateral links.

4.2. Analytical Framework and Variable Mapping

Variables are categorized and linked across the three constructs.

Table 1. Core elements of effective Internal CSR

VARIABLES			
Training & Development	Self-efficacy	Job Security	Health & Safety
Recognition	Internal communication	Fair Rewards Risk / initiative-taking	Equal Opportunity
'Practical' Empowerment Autonomy Decision authority Participation Ownership	Enabling Resources Skills Autonomy	Wellbeing Perceived fit Self-verification Self-enhancement	Psychological Empowerment Creativity Psychological ownership
Work-life balance	Ethical leadership		

Keywords: Employee empowerment; employee well-being; fair reward systems; ethical leadership; internal communication and training.

The suggested literature presented at the end of this paper, has allowed to identify the different elements of effective internal CSR in order to be able at second stage to link these outcomes as potential drivers for intrapreneurship and sustainable innovation.

Table 2. Key drivers fostering Intrapreneurship

VARIABLES			
Perceived competence and control	Visionary Leadership Management Support	Strategic Renewal	Participation Decision-making
Resources	Initiative / Autonomy / Proactiveness	Risk-tolerance	Opportunity Recognition
Knowledge / Awareness	Capabilities	Problem-solving	Reward / Recognition
Intrapreneurial Climate / Culture	Sustainability integration	Cross-functional collaboration	Intrinsic motivation

Keywords: Autonomy; proactiveness; problem-solving capability; risk-taking; participation; decision authority.

Using different colours, this paper categorises the different elements that connect the outcomes of internal CSR and are becoming drivers of effective intrapreneurship.

Table 3. Drivers of Sustainable Innovation

VARIABLES			
Purpose-driven mindset Intrinsic motivation	Opportunity recognition	Ethical commitment	Autonomy / Initiatives
Empowerment	Participation Decision-making	Knowledge Development Orientation	Leadership Vision and Commitment
Organisational Support	Reward System Institutional Incentives	CSR and Values	Corporate Culture
Strategic Alignment / transformation	Resources	Stakeholder engagement Ethical requirements	Customer demand
Cost savings	Innovation capability		

Keywords: Economic value creation; environmental responsibility; social impact.

As in the previous two tables, Table '3', aims to identify through literature the main drivers of effective sustainable innovation and by linking them to the outcomes or internal CSR and drivers of intrapreneurship, creates a causal linkage in different categories.

Table 4. Variables connecting Internal CSR and Intrapreneurship

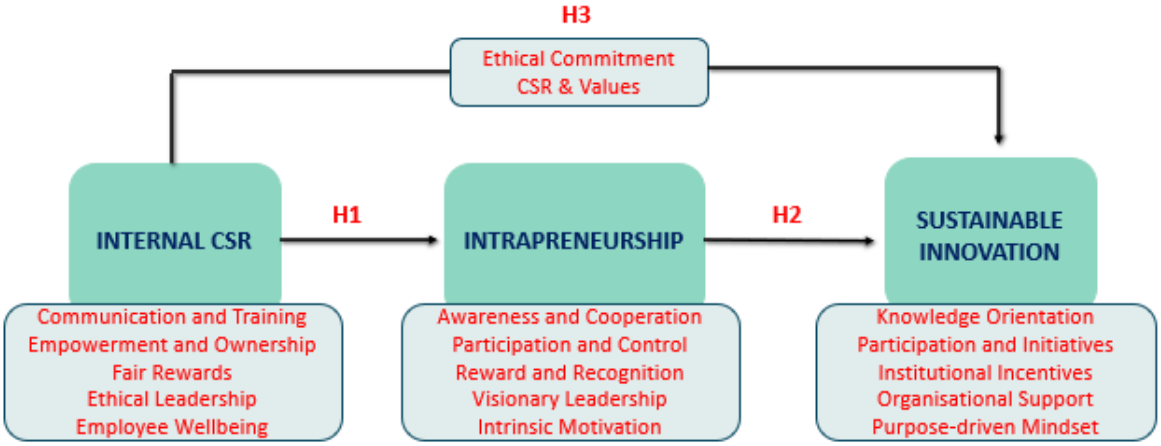
Internal CSR	Intrapreneurship	Sustainable Innovation
Knowledge Training & Development Internal Communication Skills Development	**Knowledge / Awareness** Cross-functional cooperation Capabilities	**Knowledge Development & Orientation**
Empowerment Autonomy Decision authority Participation Ownership	**Empowerment** Perceived competence & control Initiative / autonomy Participation Decision-making	**Empowerment** Autonomy / Initiatives Participation Decision-making
Rewards / Recognition Fair Rewards Recognition Risk-tolerance	**Rewards / Recognition** Risk tolerance Rewards Recognition	**Reward System Institutional Incentives**
Ethical Leadership Psychological empowerment Equal Opportunities	**Visionary Leadership** Management Support Intrapreneurial culture Sustainability integration	**Organisational Support** Leadership Vision Leadership Commitment CSR and Values
Employee Wellbeing Perceived fit Self-verification Self-enhancement Self-efficacy	**Intrinsic Motivation**	**Purpose-driven mindset Intrinsic Motivation**

Keywords: Empowerment; ethical leadership; reward and recognition; employee well-being. Knowledge orientation; intrinsic motivation; organizational support; purpose-driven mindset.

In the table '4' above, there is a 'recreation' of a list of the main constructs under unified categories across the three disciplines. Even though in current literature the way concepts are used changes across disciplines, there is a definite connection between the three disciplines (e.g. 'Knowledge' in iCSR is identical for 'Knowledge / Awareness' in intrapreneurship and 'Knowledge Development & Orientation' in sustainable innovation).

4.3. Literature Review as Hypothesis Testing

The hypotheses are examined through thematic and comparative analysis of the reviewed literature. Recurring theoretical arguments, constructs, and mechanisms supporting each relationship are identified and synthesized, enabling academic hypothesis testing appropriate for conceptual research.



In an effort to unify and group better the outcomes and drivers for each Hypotheses, an extensive 'gpouping' of keywords / concepts has been created as shown above. When taking into account all the constructs, we can see that the meaning of each keyword and concept changes under each discipline, without at any point, changing the direct links that exist between concepts. The direct link between Internal CSR and Sustainable Innovation passes through the 'Ethical Cimmitment' as well as 'CSR and Values' of the company that shape the orientation of the employees of any organisation regarding the structure, value and nature of their innovative practices and development initiatives.

5. Discussion

The analysis supports the proposed conceptual framework, highlighting internal CSR as a foundational organizational capability that fosters through its outcomes the intrapreneurial

behaviour. Intrapreneurship operates as a key mechanism translating internal CSR values into sustainable innovation outcomes.

The findings also emphasize that not all intrapreneurial initiatives inherently lead to sustainability-oriented outcomes, underscoring the importance of aligning intrapreneurial drivers with sustainability values through internal CSR practices.

6. Conclusions

This paper advances theoretical understanding of how internal CSR can act as a driver of sustainable innovation through intrapreneurship. By integrating CSR, intrapreneurship, and sustainable innovation literature, the study develops a coherent conceptual framework that supports the proposition that entrepreneurial thinking within organizations can lead to sustainability-oriented innovation.

While limited by its conceptual nature, the study provides a robust theoretical foundation for future empirical research aimed at validating and extending the proposed model.

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Disability and Social Economy: Corporate Responsibility for Equal Employment Opportunities in NGOs

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Abstract

This study explores the extent to which Non-Governmental and Non-Profit Organizations (NGOs) demonstrate corporate and social responsibility toward employees and volunteers with special needs. The theoretical framework analyzes key disability models, the relevant regulatory context, and the principles of corporate social responsibility within the sphere of the social economy. The empirical part adopts a quantitative methodology through a structured questionnaire focusing on individuals who self-identify as persons with disabilities, aiming to capture existing inclusion policies, organizational culture, and diversity management practices. The study seeks to highlight the role of NGOs as agents of equality and social inclusion, as well as to formulate recommendations for enhancing accessibility, non-discrimination, and the professional empowerment of people with disabilities in the workplace. The contribution of this research lies in understanding the factors that influence the implementation of social responsibility principles and in providing policy directions for more inclusive and equitable organizations.

Keywords: *NGOs; disability; corporate social responsibility; social inclusion; accessibility; non-discrimination.*

JEL Codes: Q53; Q56; Q58.

1. Introduction

The inclusion of persons with disabilities in the labour market constitutes a central dimension of social sustainability and equitable development. Despite the increasing recognition of disability rights within international frameworks and policy agendas, individuals with disabilities continue to face structural barriers that limit their equal participation in employment. These barriers often arise not solely from individual impairments but from environmental, institutional, and attitudinal factors that restrict access and participation. In this context, the social model of disability emphasizes that disability is produced through the interaction between individuals and societal structures that fail to accommodate human diversity (Morris & Oliver, 1990; Shakespeare, 2017).

Within contemporary discussions of sustainability and organizational responsibility, Corporate Social Responsibility (CSR) has emerged as a key framework through which organizations are expected to address social inequalities and promote inclusive practices. Traditionally associated with the private sector, CSR refers to the voluntary integration of social, ethical, and environmental concerns into organizational strategies and operations (Carroll, 1991; Dahlsrud, 2008). Increasingly, however, the concept has also been applied to organizations of the third sector, including Non-Governmental and Non-Profit Organizations (NGOs).

NGOs occupy a distinctive position within the social economy as actors that frequently promote human rights, social inclusion, and the empowerment of vulnerable groups. Their legitimacy and credibility depend not only on the initiatives they implement externally but also on the extent to which they embody the values they promote within their own organizational structures. In this sense, the internal implementation of social responsibility—particularly in relation to employment practices—represents an important dimension of organizational integrity and accountability (Ebrahim, 2020). While NGOs often advocate for disability rights and accessibility through their programs, the extent to which these principles are reflected in their internal policies and organizational culture remains relatively underexplored in academic research. Existing studies tend to focus primarily on disability inclusion within corporate or public sector settings, leaving a significant gap in understanding how organizations within the social economy manage diversity and inclusion within their own workforce (Williams & Moser, 2019).

Disability inclusion in organizational contexts extends beyond formal employment policies. It involves a broader set of practices related to accessibility, workplace adjustments, organizational culture, and the recognition of both visible and “invisible” forms of disability. These dimensions require not only institutional policies but also awareness, training, and supportive leadership capable of fostering inclusive environments where individuals feel respected and able to participate fully in organizational life.

Against this background, the present study examines the extent to which NGOs demonstrate corporate and social responsibility toward employees and volunteers with disabilities. Specifically, the research investigates how inclusion is perceived and implemented within NGO environments, exploring both organizational practices and the lived experiences of individuals with and without disabilities working within these organizations. By combining quantitative and qualitative methods, the study aims to capture both measurable patterns of inclusion and the deeper narratives that shape everyday organizational realities.

Research Questions

The study addresses the following research questions:

- How do NGOs perceive their social responsibility toward employees with disabilities?
- To what extent are inclusion policies and equal opportunity practices implemented within NGO workplaces?
- How do employees with disabilities experience participation and inclusion within NGO environments?
- Are there differences in perceptions between employees with and without disabilities regarding inclusion and accessibility?

By addressing these questions, the study contributes to the growing literature on disability inclusion and organizational responsibility within the social economy. More specifically, it provides empirical insight into the potential gap between the normative commitment of NGOs to social justice and the practical implementation of inclusive practices within their internal structures. In doing so, the research also seeks to inform policy and organizational strategies aimed at strengthening accessibility, reducing discrimination, and enhancing the professional empowerment of people with disabilities within NGO environments.

2. Literature Review

2.1. Disability and the Social Model

The concept of disability has evolved significantly over the past decades, moving from a predominantly medical interpretation toward more socially oriented approaches. Traditional medical models framed disability primarily as an individual impairment or functional limitation requiring treatment or rehabilitation. In contrast, contemporary disability studies emphasize that disability arises not solely from physical or cognitive differences but from the interaction between individuals and societal structures that fail to accommodate diversity (Morris & Oliver, 1990; Shakespeare, 2017). This perspective, widely known as the social model of disability, highlights the role of environmental barriers, institutional arrangements, and social attitudes in shaping the lived experiences of persons with disabilities.

According to the social model, barriers such as inaccessible infrastructure, inflexible work arrangements, and discriminatory attitudes are central factors that limit participation in

social and economic life (Barnes & Mercer, 2010). From this viewpoint, inclusion requires not only physical accessibility but also organizational and cultural changes that enable equal participation. In the workplace context, these changes may include reasonable accommodations, flexible organizational practices, and a broader commitment to diversity and equality.

The shift toward a social understanding of disability has been reinforced by international policy frameworks. The United Nations Convention on the Rights of Persons with Disabilities (CRPD) emphasizes the right of persons with disabilities to participate fully in society, including equal access to employment and professional opportunities (United Nations, 2006). Such frameworks highlight the responsibility of organizations to create inclusive environments that enable individuals with disabilities to contribute meaningfully to economic and social life.

2.2. Corporate Social Responsibility and Internal Organizational Practices

Corporate Social Responsibility (CSR) has become a key concept in discussions of ethical organizational conduct and sustainable development. CSR generally refers to the voluntary integration of social and environmental considerations into organizational decision-making and operations (Carroll, 1991; Dahlsrud, 2008). Although originally associated with corporate actors, the concept has increasingly been applied to organizations across different sectors, including public institutions and non-profit organizations.

Carroll's (1991) widely cited framework conceptualizes CSR as a multi-dimensional responsibility encompassing economic, legal, ethical, and philanthropic obligations. Within this framework, organizations are expected not only to comply with legal requirements but also to actively contribute to social well-being. In recent years, attention has shifted toward the internal dimension of CSR, which concerns how organizations treat their employees, manage diversity, and promote inclusive work environments.

Workplace inclusion of persons with disabilities represents a critical aspect of internal CSR practices. Inclusive employment policies contribute to social equity while also enhancing organizational diversity and innovation (Shore et al., 2018). Research has shown that organizations that adopt inclusive practices—such as accessibility measures, diversity training, and supportive leadership—can foster more positive organizational cultures and improve employee well-being (Dobusch, 2017).

However, the implementation of disability-inclusive policies remains uneven across sectors and organizational contexts. While many organizations publicly endorse diversity and inclusion principles, the translation of these commitments into formal policies and everyday practices is often inconsistent. This discrepancy highlights the importance of examining how CSR principles are operationalized within organizations rather than simply articulated at a rhetorical level.

2.3. *NGOs and the Social Economy*

Non-Governmental Organizations (NGOs) constitute a significant component of the social economy, operating in areas such as social services, humanitarian assistance, environmental protection, and advocacy for marginalized groups. Their missions frequently emphasize values such as solidarity, equality, and social justice, positioning them as important actors in promoting inclusive societies (Defourny & Nyssens, 2010).

Because NGOs often work directly with vulnerable populations, they are commonly perceived as agents of social transformation. Their activities may include advocacy for disability rights, programs aimed at social integration, and initiatives promoting equal access to employment opportunities. As such, NGOs play an important role in shaping public discourse and policy related to social inclusion.

Nevertheless, scholars have noted that the internal organizational practices of NGOs do not always fully reflect the values they promote externally. Questions of accountability, transparency, and organizational coherence have become increasingly central to discussions of NGO governance (Ebrahim, 2020). In particular, the extent to which NGOs implement inclusive practices within their own organizational structures has attracted growing academic attention.

From a legitimacy perspective, organizations that advocate for equality and social justice are expected to demonstrate consistency between their external missions and their internal policies. Failure to do so may undermine their credibility and moral authority (Brown, 2020). Consequently, examining how NGOs manage diversity and inclusion within their workforce becomes an important area of inquiry.

2.4. *Disability Inclusion in Organizational Contexts*

Research on disability inclusion in workplaces has expanded considerably in recent years, reflecting broader societal attention to diversity and equality. Studies suggest that inclusive organizational environments are shaped not only by formal policies but also by informal practices, leadership attitudes, and workplace culture (Schur, Kruse, & Blasi, 2013).

One of the central challenges in disability inclusion relates to the recognition of different types of disabilities. While physical disabilities are often more visible and therefore more easily accommodated through structural adjustments, other forms—such as psychosocial or cognitive disabilities—may remain less visible and less understood within organizational contexts (Santuzzi et al., 2014). This invisibility can create barriers to disclosure and support, as employees may hesitate to reveal their condition due to concerns about stigma or discrimination.

Another key dimension concerns accessibility and reasonable accommodations. Research indicates that relatively small adjustments—such as flexible schedules, assistive technologies, or adapted workspaces—can significantly improve the participation and productivity of employees with disabilities (Schur et al., 2013). However, the successful implementation of such measures often depends on organizational awareness, training, and leadership commitment.

Education and training also play an important role in fostering inclusive organizational cultures. Diversity training programs and awareness initiatives can help reduce stereotypes and promote more supportive attitudes among employees and managers (Dobusch, 2017). In organizations where inclusion is integrated into strategic planning and leadership practices, employees with disabilities are more likely to experience a sense of belonging and equal participation.

2.5. Research Gap and Study Contribution

Despite the growing body of literature on disability inclusion and corporate social responsibility, relatively limited research has examined these issues within the context of NGOs. Much of the existing scholarship focuses on private-sector organizations or public institutions, leaving the internal employment practices of NGOs comparatively understudied.

Given the prominent role of NGOs in promoting social inclusion and human rights, understanding how these organizations address disability inclusion within their own workforce is particularly important. Investigating this issue can reveal potential gaps between normative commitments to equality and the practical implementation of inclusive policies.

The present study contributes to this area of research by examining how NGOs perceive and implement corporate social responsibility toward employees and volunteers with disabilities. By combining quantitative and qualitative approaches, the research seeks to provide a more comprehensive understanding of organizational practices, employee experiences, and the challenges associated with implementing inclusive policies in the NGO sector.

3. Methodology

3.1. Research Design

This study adopts a mixed-methods research design, combining quantitative and qualitative approaches in order to provide a comprehensive understanding of how Non-Governmental Organizations (NGOs) address issues of inclusion and corporate social responsibility toward employees and volunteers with disabilities. Mixed-methods approaches allow researchers to integrate numerical data with in-depth qualitative insights, enabling a more holistic exploration of complex social phenomena. In the present research, quantitative data

were used to identify patterns related to experiences of discrimination and perceptions of institutional support, while qualitative data provided deeper insight into personal experiences, organizational practices, and perceived challenges within NGO environments.

The methodological choice to combine both approaches was motivated by the need to capture not only the extent of inclusion practices but also the lived experiences and interpretations of individuals working within NGOs. The two strands of data were subsequently interpreted together in order to produce a more integrated understanding of organizational responsibility and inclusion practices.

3.2. *Quantitative Component*

Data Collection Instrument

The quantitative component of the study was conducted through a structured questionnaire designed to examine perceptions and experiences related to disability inclusion within NGOs. The questionnaire included Likert-scale items ranging from 1 to 5, allowing respondents to express their level of agreement with statements related to organizational practices, funding incentives, and experiences of workplace discrimination.

Two key variables were examined through these items:

- Perception of funding incentives, referring to whether respondents believed that funding mechanisms or policies exist that encourage organizations to employ persons with disabilities.
- Experience of workplace discrimination, referring to whether respondents had experienced discrimination within their working environment due to their disability.

The questionnaire also collected demographic and professional information, including gender, age, years of experience within NGOs, and organizational role.

Sample

From the total questionnaire responses, the analysis focused on individuals who self-identified as persons with disabilities. The final quantitative sample consisted of 18 participants (N = 18). The demographic characteristics of the sample were as follows:

- Gender: 12 men (66.7%) and 6 women (33.3%)
- Mean age: 43.4 years (SD = 15.5)
- Average years of work within NGOs: 6.6 years (SD = 6.8)

Participants occupied different organizational roles within NGOs, including:

- Volunteers (n = 9)
- Employees (n = 6)
- Administrative or managerial staff (n = 3)

The sample included individuals with different types of disabilities, allowing the study to explore whether experiences of inclusion or discrimination differed across disability categories.

Data Analysis

The quantitative data were analyzed using descriptive statistics and non-parametric statistical tests, appropriate for small sample sizes and ordinal data derived from Likert scales.

The analysis included:

- Descriptive statistics, used to summarize key characteristics of the sample and provide an overview of responses related to the examined variables.
- Spearman's rank correlation coefficient, applied to examine potential relationships between variables.
- Kruskal–Wallis tests, used to explore possible differences in perceived discrimination across categories of disability.
- Mann–Whitney tests, used to examine differences between organizational roles, particularly between volunteers and employees.
- Fisher's Exact Test, used to investigate potential associations between organizational position and reported levels of discrimination.

These statistical techniques allowed the study to examine whether meaningful differences or associations existed within the dataset while accounting for the limited sample size and the non-normal distribution of the variables.

3.3. Qualitative Component

Data Collection

The qualitative component of the research consisted of semi-structured interviews, conducted using a predefined interview guide designed to explore experiences of inclusion, accessibility, and organizational culture within NGOs.

Each interview lasted approximately 30 to 45 minutes. Interviews were audio-recorded and subsequently transcribed to facilitate systematic analysis. The interview questions aimed to encourage participants to reflect on their personal experiences within NGOs, focusing on issues such as workplace support, accessibility, organizational attitudes toward disability, and perceived gaps between organizational values and internal practices.

Sample

The qualitative sample included 12 participants (N = 12) representing different roles within NGO environments.

The sample consisted of:
10 individuals with disabilities
2 individuals without disabilities, who participated as collaborators or organizational staff members.

Participants represented a variety of roles, including volunteers, employees, coordinators, managerial staff, and individuals working in human resources or administrative positions. This diversity of roles allowed the study to capture perspectives from multiple levels of organizational structure.

The participants also represented a range of disability types, including:

- Mobility impairments
- Sensory disabilities (visual or hearing impairments)
- Chronic health conditions
- Psychosocial or neurodiversity-related conditions

For the purposes of confidentiality and anonymity, participants were presented through coded profiles (Personas A–L) rather than identifiable information.

Data Analysis

The qualitative data were analyzed using thematic analysis, following a systematic process aimed at identifying recurring patterns and themes within participants' narratives. The analysis involved multiple stages, including familiarization with the data, coding of key statements, identification of emerging categories, and the development of broader thematic patterns.

Through this process, several central thematic axes were identified, including:

- Organizational acceptance without formal institutional structures
- Accessibility and practical workplace adjustments
- Challenges related to "invisible" disabilities and mental health
- The role of education and organizational learning
- The concept of internal social responsibility within NGOs

The thematic analysis allowed the research to explore how inclusion is experienced in everyday organizational settings and how individuals interpret the gap between organizational values and institutional practices.

Integration of Quantitative and Qualitative Findings

Following the separate analysis of the quantitative and qualitative datasets, the findings were interpreted in an integrated manner. This approach enabled the comparison of statistical patterns with personal narratives and organizational experiences.

The combination of both methods allowed the study to examine the issue of disability inclusion from complementary perspectives. While the quantitative analysis provided an overview of patterns related to discrimination and organizational support, the qualitative interviews offered deeper insights into the mechanisms, perceptions, and challenges underlying these patterns.

By synthesizing both strands of evidence, the study aimed to generate a more comprehensive understanding of how NGOs approach corporate social responsibility and inclusion in practice.

Ethical Considerations

The research followed standard ethical procedures for social science research involving human participants. All participants were informed about the purpose of the study and provided informed consent prior to their participation.

To ensure confidentiality and data protection, personal identifiers were removed from the dataset and participants were represented through anonymized profiles. All recorded material and transcripts were stored securely and used exclusively for research purposes.

These procedures aimed to protect participant privacy while ensuring the integrity and credibility of the research process.

4. Results

4.1. Sample Characteristics

The quantitative analysis focuses on respondents who self-identified as persons with disabilities. From the total questionnaire responses, a subset of 18 participants (N = 18) was selected for further analysis.

The demographic characteristics of the sample reveal a predominance of male participants, with 12 men (66.7%) and 6 women (33.3%). The mean age of respondents was 43.4 years (SD = 15.5), while the average length of employment or collaboration within NGOs was 6.6 years (SD = 6.8).

Participants represented different organizational roles, including volunteers (n = 9), employees (n = 6), and administrative or managerial staff (n = 3). This diversity of roles provides a broader understanding of how inclusion is experienced across different organizational positions within NGOs.

Figure 1. Sample characteristics and professional roles of participants

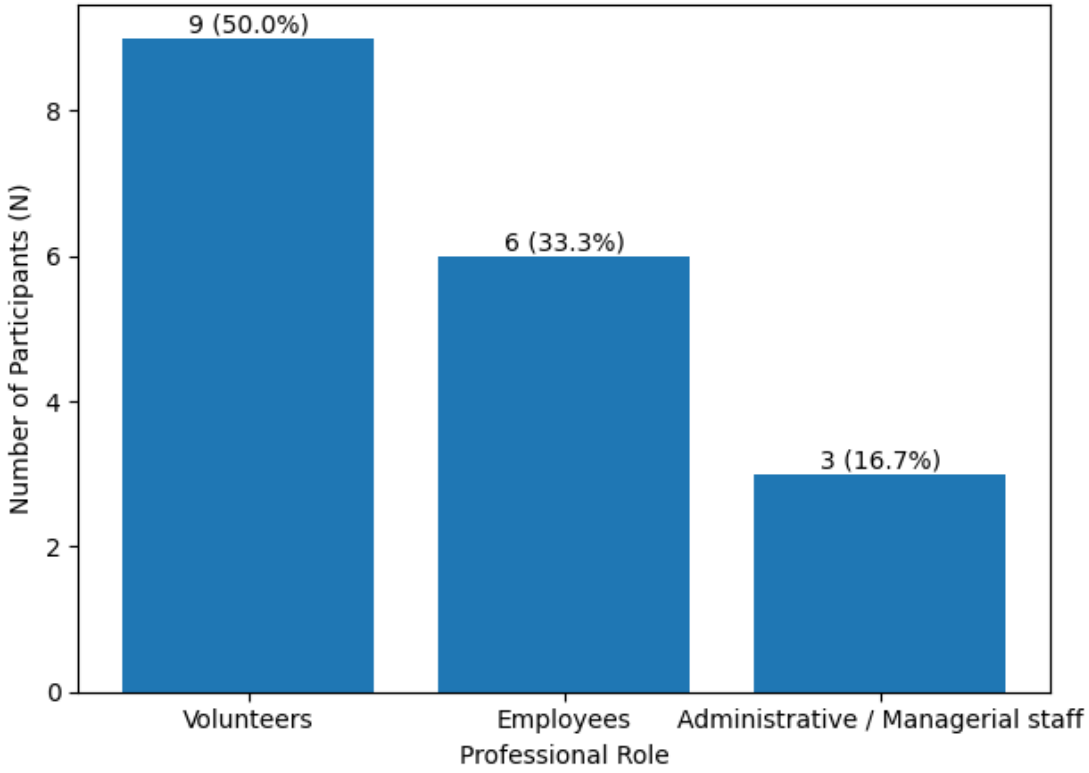


Table 1. Demographic characteristics of respondents

Variable	Category	N	Percentage (%)
Gender	Male	12	66.7
	Female	6	33.3
Organizational Role	Volunteers	9	50.0
	Employees	6	33.3
	Administrative / Managerial staff	3	16.7
Age (years)	Mean	43.4	
	Standard Deviation (SD)	15.5	
Years working in NGOs	Mean	6.6	
	Standard Deviation (SD)	6.8	

4.2. Perceptions of Funding Incentives and Experiences of Workplace Discrimination

The questionnaire examined two key variables related to the organizational environment of NGOs: the perception of funding incentives for employing persons with disabilities and personal experiences of workplace discrimination.

Responses indicate that participants reported relatively low levels of experienced discrimination within NGO environments, suggesting that respondents generally perceived their workplaces as supportive or inclusive. However, perceptions regarding the existence of institutional or financial incentives for hiring persons with disabilities were more moderate.

This finding suggests that while interpersonal attitudes and organizational culture may be relatively positive, formal institutional mechanisms supporting disability inclusion appear to be less visible or less clearly communicated within NGOs.

Table 2. Descriptive statistics of the main survey variables related to funding incentives and workplace discrimination.

Variable	N	Mean	Standard Deviation (SD)	Median
Funding Incentives	18	2.89	1.13	3
Workplace Discrimination	18	1.39	0.92	1

4.3. Statistical Associations and Group Differences

To explore potential relationships between variables, several non-parametric statistical tests were conducted. First, Spearman's rank correlation analysis was applied in order to examine possible associations between key variables. The analysis did not reveal statistically significant relationships, suggesting that respondents' perceptions of discrimination and institutional incentives were not strongly correlated within the dataset.

Table 3. Results of correlation and non-parametric statistical tests examining relationships between workplace discrimination and organizational variables.

Test	Variables / Comparison	Statistic	p-value	N	Interpretation
Spearman correlation	Years in NGOs ↔ Workplace Discrimination	ρ = 0.09	0.75	16	Not significant
Spearman correlation	Funding Incentives ↔ Workplace Discrimination	ρ = -0.01	0.96	18	Not significant
Kruskal–Wallis test	Discrimination across disability categories	H test	0.795	18	No significant differences
Mann–Whitney test	Volunteers vs Employees (discrimination levels)	U test	0.54	18	No significant differences
Fisher's Exact test	Organizational position ↔ High discrimination levels	Fisher test	1.00	18	No significant association

Second, group differences were examined through Kruskal–Wallis tests, which assessed whether experiences of discrimination differed across categories of disability. The results indicated no statistically significant differences (p = 0.795) between disability categories.

Additionally, Mann–Whitney tests were conducted to examine differences between organizational roles, particularly between volunteers and employees. The results showed no statistically significant differences ($p = 0.54$) between these groups.

Finally, Fisher's Exact Test was applied to explore the association between organizational position and reported high levels of discrimination. The results again indicated no statistically significant association ($p = 1.00$).

Qualitative Results

Profile of Interview Participants

The qualitative component of the study included 12 participants, representing different roles within NGOs, such as volunteers, employees, coordinators, and managerial staff.

Among these participants:

- 10 individuals identified as persons with disabilities
- participants did not report disabilities but were involved in NGO activities as staff members or collaborators

Participants represented a range of disability types, including mobility impairments, sensory disabilities, chronic health conditions, and psychosocial conditions. To protect confidentiality, participants were presented using coded personas (A–L) rather than personal identifiers.

Table 4. Profile of interview participants (Personas A–L)

Participant	Role / Position	Type of Disability
A	Employee	Mobility impairment
B	Volunteer	Sensory disability (hearing)
C	Coordinator	Chronic condition (Type 1 diabetes)
D	Volunteer	Mental health condition (anxiety disorder)
E	HR Manager	Partial visual impairment
F	New volunteer	Mobility impairment (myopathy)
G	Technical support	Hearing impairment
H	Coordinator	Dyslexia
I	Volunteer coordinator	Mobility impairment (amputation)
J	Communication / PR	Bipolar disorder type II
K	Team supervisor	No disability
L	Volunteer / Coordinator	No disability

Thematic Analysis of Interviews

The thematic analysis of the interview data revealed several recurring patterns regarding disability inclusion within NGOs. Five central thematic axes emerged from the analysis.

Acceptance Without Institutional Structure

Participants frequently described a generally positive and respectful organizational climate. However, this acceptance was often informal and based on individual attitudes rather than institutionalized procedures.

Several respondents indicated that although colleagues and managers were supportive, formal policies or structured procedures for disability inclusion were often absent.

Accessibility and Workplace Adjustments

Another recurring theme concerned accessibility and practical accommodations. Participants mentioned examples of flexible working arrangements, adapted tasks, and technological or physical accessibility measures.

However, these adjustments were often described as inconsistently applied across different projects or departments, indicating a lack of systematic implementation.

Invisible Disabilities and Mental Health

Participants also highlighted challenges related to "invisible" disabilities, particularly mental health conditions or cognitive differences. In such cases, individuals often expressed hesitation about disclosing their condition due to concerns about misunderstanding or stigma.

Education and Organizational Learning

Many interviewees emphasized the importance of training and awareness initiatives for staff and managers. Participants suggested that inclusive workplaces do not necessarily require prior experience with disability but rather structured learning opportunities that promote understanding and inclusive practices.

The findings indicate that leadership and human resource management can play a critical role in institutionalizing inclusive practices through training and policy development.

Internal Social Responsibility

A final theme concerned the concept of internal corporate social responsibility. Several participants observed a discrepancy between NGOs' external advocacy for equality and their internal organizational practices.

While NGOs often promote social inclusion through their public programs, internal policies addressing disability inclusion are not always systematically implemented.

These findings suggest that organizational awareness of non-visible disabilities remains limited, even in environments that generally promote inclusion.

Figure 2. Word Cloud



Illustrative Interview Excerpts

To further illustrate these themes, selected excerpts from participant interviews highlight key perceptions and experiences.

For example, one participant described the organizational climate as supportive but lacking formal guidance:"There is respect and a positive attitude, but no one really knows what exactly they should do."

Another participant highlighted the absence of formal procedures for accommodations:

"When I needed to adjust my working hours for health reasons, the response was 'of course', but there was no formal process."

These narratives reinforce the broader finding that inclusive attitudes exist but are not always supported by structured institutional frameworks.

5. Discussion

The aim of this study was to examine how Non-Governmental Organizations (NGOs) perceive and implement corporate social responsibility toward employees and volunteers with disabilities, as well as to explore how individuals with and without disabilities experience inclusion within NGO environments. By combining quantitative and qualitative data, the research sought to capture both measurable patterns and deeper experiential dimensions of disability inclusion within organizations of the social economy.

Overall, the findings suggest that NGOs demonstrate a generally positive organizational culture toward individuals with disabilities, yet the institutionalization of inclusive practices remains limited. This pattern reflects a broader transition from informal support toward more structured forms of organizational responsibility.

The quantitative findings indicate relatively low reported levels of workplace discrimination among participants. This result suggests that, at the interpersonal level, individuals with disabilities often experience supportive attitudes within NGO environments. Such findings are consistent with the normative values commonly associated with NGOs, which typically emphasize equality, solidarity, and social inclusion as central organizational principles.

However, while the absence of reported discrimination may reflect a positive organizational climate, it does not necessarily imply the presence of systematic inclusion policies. The qualitative findings of the study provide a deeper understanding of this dynamic. Participants frequently described environments characterized by goodwill and informal support rather than by formalized procedures or structured inclusion policies. In many cases, accommodations or adjustments depended on individual initiative or interpersonal relationships rather than on institutional guidelines.

This pattern resonates with existing research on workplace inclusion, which emphasizes that inclusive cultures often emerge initially through informal practices before becoming embedded in formal organizational policies (Shore et al., 2018). While positive attitudes represent an important foundation for inclusion, long-term organizational change typically requires institutional mechanisms that ensure consistency and sustainability.

Another important finding of the study concerns the moderate perception of institutional or financial incentives supporting the employment of persons with disabilities. Respondents did not strongly agree that such incentives are widely available or effectively implemented. This suggests that structural mechanisms supporting disability inclusion may be less visible or less developed within NGO contexts.

This finding can be interpreted through the lens of corporate social responsibility. CSR frameworks emphasize that organizations have responsibilities not only toward external stakeholders but also toward their internal workforce (Carroll, 1991). Within this perspective, inclusive employment practices—such as accessibility measures, diversity management policies, and training initiatives—represent key elements of internal CSR.

The results of the present study suggest that NGOs may demonstrate a commitment to social responsibility primarily through their external activities, such as advocacy or social programs, while internal practices related to disability inclusion remain less institutionalized. Similar observations have been made in studies examining NGO accountability, which note that organizations promoting social justice externally may face challenges in translating these values into internal organizational structures (Ebrahim, 2020).

This discrepancy between external mission and internal practice highlights the importance of examining internal organizational responsibility as a critical dimension of social legitimacy. For NGOs, whose identity is often closely linked to social justice and equality, the alignment between external advocacy and internal policies becomes particularly significant.

The statistical analyses conducted in the quantitative component of the study did not reveal significant differences in experiences of discrimination across disability types or organizational roles. The absence of statistically significant differences in the Kruskal–Wallis and Mann–Whitney tests suggests a relatively homogeneous pattern of responses across participants.

This finding may indicate that experiences of inclusion or exclusion within NGOs are shaped less by formal organizational hierarchies and more by broader cultural or structural factors. In other words, individuals occupying different roles—whether volunteers, employees, or managerial staff—appear to share similar perceptions of organizational inclusion.

However, the absence of statistical differences should be interpreted with caution, particularly given the relatively small sample size. Nevertheless, the consistency of responses across groups may also reflect the presence of a shared organizational culture within NGO environments, where hierarchical distinctions are often less pronounced than in more traditional organizational settings.

The qualitative findings also highlighted the importance of accessibility and practical workplace accommodations. Participants reported examples of flexible working arrangements, adapted responsibilities, and technological or environmental adjustments that facilitated their participation in organizational activities.

These observations align with research indicating that relatively small workplace adjustments can significantly enhance the inclusion of persons with disabilities (Schur, Kruse, & Blasi, 2013). Accessibility measures such as assistive technologies, flexible schedules, or adapted communication tools often represent low-cost interventions that can substantially improve workplace participation and productivity.

However, participants also emphasized that such adjustments were not always applied consistently across organizational contexts. In some cases, accommodations depended on the willingness or awareness of specific individuals rather than on established institutional procedures. This reinforces the idea that while inclusive intentions may exist within NGOs, the systematic implementation of accessibility practices remains uneven.

A particularly important theme emerging from the qualitative analysis concerns the experience of "invisible" disabilities, including mental health conditions and neurodiversity. Participants noted that these forms of disability are often less recognized within organizational contexts, leading to uncertainty regarding disclosure and support.

This finding corresponds with previous research suggesting that employees with invisible disabilities often face unique challenges related to disclosure decisions and potential stigma (Santuzzi et al., 2014). Unlike visible disabilities, which may prompt immediate accommodations, invisible conditions require individuals to actively disclose their situation in order to receive support.

Within NGO environments, the presence of inclusive values may encourage openness; however, the absence of formal policies addressing mental health or psychosocial disabilities may still create uncertainty among employees. This highlights the importance of organizational awareness and training in fostering supportive environments that recognize the diversity of disability experiences.

Another key finding relates to the role of education and organizational learning in promoting inclusive workplaces. Many participants emphasized that inclusive organizational environments do not necessarily require extensive prior expertise in disability issues but rather systematic opportunities for learning and awareness.

Training programs, awareness initiatives, and leadership engagement can play a critical role in transforming inclusive attitudes into concrete organizational practices. Research on

diversity management similarly highlights the importance of education and leadership commitment in shaping inclusive organizational cultures (Dobusch, 2017).

In NGO contexts, leadership and human resource management structures may therefore play a central role in institutionalizing inclusive practices. By integrating disability inclusion into training programs, recruitment strategies, and organizational policies, NGOs can strengthen the internal dimension of their social responsibility.

Taken together, the findings of this study suggest that disability inclusion within NGOs currently exists in a transitional phase. On the one hand, organizational cultures often reflect positive attitudes toward individuals with disabilities and a willingness to provide support when needed. On the other hand, formal structures, policies, and systematic practices supporting inclusion remain underdeveloped.

This transition from informal goodwill to institutionalized inclusion reflects a broader challenge within many organizations seeking to implement diversity and inclusion initiatives. While values and intentions represent an essential starting point, sustainable inclusion typically requires formal mechanisms that embed these principles within organizational governance and everyday practice.

For NGOs in particular, strengthening internal inclusion policies may also enhance organizational credibility and legitimacy. As organizations that frequently advocate for social justice and equality, NGOs may benefit from ensuring that their internal practices fully reflect the values they promote externally.

Ultimately, the findings highlight the importance of moving beyond symbolic commitments toward structured, policy-based approaches to disability inclusion, enabling NGOs to serve not only as advocates of inclusion but also as models of inclusive organizational practice.

6. Conclusion

This study examined the extent to which Non-Governmental Organizations (NGOs) demonstrate corporate and social responsibility toward employees and volunteers with disabilities, focusing on both organizational practices and the lived experiences of individuals working within these environments. By combining quantitative and qualitative data, the research aimed to provide a more comprehensive understanding of disability inclusion within organizations operating in the social economy.

The findings suggest that NGO environments are generally characterized by positive interpersonal attitudes toward individuals with disabilities. Participants reported relatively low levels of workplace discrimination and described organizational climates in which respect and

acceptance were present. These results indicate that many NGOs cultivate inclusive values at the cultural level, reflecting their broader mission to promote equality and social participation.

However, the study also revealed that inclusion within NGOs often relies on informal support rather than on structured organizational policies. Participants frequently described supportive colleagues and managers but also emphasized the absence of clearly defined procedures, accessibility frameworks, or formal inclusion strategies. As a result, adjustments and accommodations often depend on individual initiative rather than on institutionalized organizational practices.

Another important finding concerns the limited visibility of formal mechanisms that support disability inclusion within NGO workplaces. Although these organizations frequently advocate for social inclusion through their external activities, internal policies addressing accessibility, diversity management, and disability inclusion appear to be less systematically implemented. This discrepancy suggests that NGOs may still be in the process of translating their normative commitments to equality into structured internal governance practices.

The qualitative findings further highlighted the importance of accessibility measures, organizational awareness, and staff training. Participants emphasized that relatively small adjustments—such as flexible working arrangements, adapted responsibilities, or supportive communication practices—can significantly improve participation and inclusion. At the same time, the findings pointed to the need for greater awareness regarding invisible disabilities, particularly mental health conditions and neurodiversity, which are often less recognized within organizational contexts.

Taken together, the results suggest that disability inclusion within NGOs is currently situated in a transitional phase. While many organizations demonstrate positive attitudes and willingness to support individuals with disabilities, the systematic integration of inclusive policies and practices remains limited. Moving from informal goodwill toward more structured and consistent inclusion strategies may therefore represent an important step in strengthening internal organizational responsibility.

From a practical perspective, the findings highlight the importance of developing formal inclusion policies, improving accessibility practices, and promoting education and training related to disability awareness within NGOs. Strengthening internal mechanisms of support and ensuring the participation of individuals with disabilities in organizational decision-making processes may further contribute to more inclusive and equitable working environments.

The study also acknowledges several limitations. The relatively small sample size and the focus on a specific group of NGO participants may limit the generalizability of the findings. Future research could expand the sample to include a broader range of organizations and

disability types, as well as explore how organizational policies and inclusion practices evolve over time.

Despite these limitations, the research contributes to a deeper understanding of disability inclusion within NGOs and highlights the importance of aligning organizational values with internal practices. Strengthening inclusive governance structures may enable NGOs not only to advocate for equality externally but also to embody these principles within their own organizational environments.

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Embedding ESG in European Small-Medium Enterprises: The Role of Environmental Management Systems and International Standards

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Abstract
Environmental risks threaten the continuity, compliance, and long-term competitiveness of small and medium-sized enterprises (SMEs) in a market that is increasingly sustainability-oriented and data-driven. This review develops a comprehensive framework for Environmental Management Systems (EMS) with emphasis on ISO 14001 and EMAS and examines their connections to Corporate Social Responsibility (CSR) and Environmental, Social, and Governance (ESG) frameworks. The study overviews 47 papers indexed in Scopus, Web of Science, and Google Scholar, it also assesses the emerging role of the European Sustainability Reporting Standards (ESRS) in boosting environmental action for SMEs. The contribution of this study lies in integrating EMS tools with different ESG and ESRS mechanisms. Specifically, there are two objectives: (i) to investigate the interlinkages of international standards with ESG framework and (ii) to evaluate their combined capacity to strengthen SME resilience against environmental or other risks. The empirical findings indicate that a synergistic approach not only underpins regulatory transparency but also engages to the Sustainable Development Goals (SDGs). Overall, the review provides actionable insights and policy implications for SMEs on integrating EMS within ESG, aiming to reinforce resilience to environmental risks and align with future market conditions for sustainability.

Keywords: *CSR; ESG; CSRD; SDGs; SMEs; European Green Deal.*

JEL Codes: Q56, M14, L26

Corporate Social Responsibility as a New Perspective for Tackling the Refugee Problem

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Abstract

The large and uncontrolled flows of refugees to Europe have created crisis conditions in host countries in recent years. In various European countries, there have been strong reactions that are reflected in the policies of these countries, with the emergence of political groups with extreme and conservative political rhetoric. Reactions also come from local communities that are hesitant about refugees, mainly on labor issues. However, refugees also face problems at the legal, social, and political levels. To date, the relevant discussion on refugees has been limited to the level of state policy, while there is no discussion of the possibility of the private sector contributing to solutions to these problems. The rationale for such a discussion is, first, to examine whether the private sector, within the framework of Corporate Social Responsibility, incorporates issues relating to marginalized individuals such as refugees. In this context, this paper uses the methodology of a literature review to record and highlight ways in which companies could help overcome refugee problems through CSR. The paper also aims to show how the private sector can offer assistance to the public sector, which has shouldered the burden of the refugee crisis, with a heavy economic burden being passed on to citizens either in the form of higher taxes or fewer state benefits.

Keywords: CSR, refugee crisis, labor market, and refugees.

JEL Codes: M14, F22, O15, D64:

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