

Ecological Economics and Dynamic Games: A Systematic Literature Review

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Abstract

Ecological and environmental economics are inherently dynamic systems requiring dynamic optimization tools. Understanding the interplay between environmental economics, ecological economics, and dynamic games is crucial. This systematic literature review analyzes a dataset of 88 peer-reviewed articles from international journals. The study identifies clusters related to resource management, taxation, and policy. It also reveals niche and motor research themes, such as policy, biological invasions, pollution, taxation, abatement, and efficiency, paving the way for future research avenues. By comprehensively examining the literature, this review provides insights into current and future challenges faced by companies, consumers, regulators, and society. It contributes to a deeper understanding of the complex relationship between ecological and environmental dynamics and the field of dynamic games in economics.

Keywords: ecological economics, environmental economics, dynamic games, systematic literature review

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1 Introduction

Ecological and environmental issues have long-term implications and involve different parties. Regular calls by administrations and media insist on these elements. For instance, The Conversation (2023) investigates the long-term risk of a chemical train derailment. The Organisation for Economic Co-operation and Development (2022) looks at the environmental impact of the Ukraine war, the possibility of a green reconstruction, and the role of different players. The European Environment Agency (2023) measures the health impacts of pollution in the European Union. Ecological issues, when neglected or mismanaged, can have significant consequences for individuals and communities, especially in the long run, making the dynamics of these systems complex and challenging to explain (The Washington Post, 2023).

Controversial perspectives and differing approaches further contribute to the intricacy of ecological and environmental challenges (The Guardian, 2023). Additionally, the widespread scale of issues such as resource management and pollution makes them common concerns across diverse regions, sectors, and stakeholders (Nature, 2022). Understanding the interplay between these fields and the domain of dynamic games is crucial to comprehending the complexities of ecological dynamics. Therefore, this paper presents a systematic literature review that analyzes the relationship between ecological and environmental issues and dynamic games.

This paper addresses the question: How do ecological and environmental economics intersect with dynamic games intersect, and what are the key contributions in this field? To delve deeper into the interaction between ecological economics and dynamic games, this article undertakes a systematic literature review that offers a thorough examination of the theoretical foundations and identifies areas in research that require further exploration (Aria and Cuccurullo, 2017; Di Vaio et al., 2020). The review provides a comprehensive understanding of the concepts, highlighting their theoretical underpinnings and existing gaps in current research. Throughout this investigation, three fundamental premises have been identified, which encompass utilizing multiple data sources, incorporating market information, and implementing advanced algorithms (Jungell-Michelsson and Heikkurinen, 2022). We examine a dataset of 88 peer-reviewed articles from international journals accessible on the Web of Science out of 32.200 references in Google Scholar. By conducting a systematic literature review, this research aims to provide a comprehensive understanding of the existing knowledge, identify gaps or deficiencies in prior work, and highlight the contributions made by the reviewed articles. The goal is to offer insights into the complex relationship between ecological and environmental dynamics and the field of dynamic games in economics.

Previous studies have explored the topics of ecological and environmental economics with dynamic games in specific contexts. For instance, extensive work has been done in pollution (Jaakkola, 2019; Kalkuhl et al., 2020; Walter, 2018), resources (Naevdal and Skonhoft, 2018; Shevchenko et al., 2022), and options (Haavio, 2005; Helm and Mier, 2021), to name a few. In contrast, the goal of this systematic literature review is to look at the field from a broader point of view. While some studies have addressed specific aspects or applications of dynamic games in environmental economics, a comprehensive analysis that encompasses the broader spectrum still needs to be developed. This paper builds upon the existing literature but aims to fill the gaps and provide a more holistic understanding of the subject.

This paper makes several contributions relative to the antecedents in the field. First, it systematically analyzes a dataset of 88 peer-reviewed articles, providing an extensive review of current research on the interplay between ecological and environmental economics and dynamic games. By identifying clusters related to resource management, taxation, and policy, this review offers insights into the critical focus areas within this domain. Second, it reveals niche and motor research themes, such as policy, biological invasions, pollution, taxation, abatement, and efficiency, which have not been extensively explored in prior work. These themes pave the way for future research avenues and highlight the evolving trends within the field. Third, this review contributes to a deeper understanding of the challenges faced by companies, consumers, regulators, and society in the context of ecological and environmental dynamics. By

synthesizing the existing knowledge, this paper offers valuable insights for decision-makers and researchers, aiding in developing effective strategies for sustainable resource management and environmental policy.

Our article is structured as follows: The methodology of our systematic literature review is described in Section 2, which also includes a description of the phases of data gathering and search. The results based on the abstracts and keywords, the nations and affiliations, the journals and articles, the various clusters, and the thematic map are shown in Section 3. Section 4 discusses the literature around the major clusters and the thematic map. Section 5 explores the findings while highlighting their theoretical and practical ramifications, research needs, and limitations. Additional comments on dynamic games and environmental economics are made in the concluding Section 6.

2 Method

In line with the methodological approaches and frameworks proposed by Tranfield et al. (2003) and Paul and Criado (2020), this study presents a systematic literature review focusing on dynamic games in environmental economics. Strictly speaking, dynamic games refer to the strategic behavior of several players over discrete time. Nevertheless, we are interested in the decisions over time. Thus, we understand in this article dynamic games in the broad sense of dynamic behavior over time. So our study includes differential games—dynamic behavior of several players over continuous time—and optimal control—dynamic behavior of a single decision-maker over time. For completeness, our interest in environmental economics also encompasses the economics of ecological issues.

Given the ongoing discussions surrounding dynamic games in environmental economics, our data analysis primarily aims to provide an interpretative understanding of the field rather than relying solely on statistical and bibliometric analyses (Sandelowski et al., 1997; Tranfield et al., 2003). Table 1 outlines the critical components of the systematic literature review, adopting the 6W framework introduced by Callahan (2014), which has also been applied by Di Vaio et al. (2020).

Table 1: Main elements about the systematic literature review

Who conducted the review?	The authors of the paper
When were the data collected?	May 2023
Where were the data collected?	Web of Science
hoW were the data found?	Sampling
What was found?	Final data set 88 articles Search word in title, abstract, and keywords
Which selection criteria?	Peer-reviewed article with pdf, English, ("environmental economics" or "ecological economics") and ("dynamic game" or "differential game" or "optimal control")
Adapted from Callahan (2014)'s 6W framework	

2.1 Data collection

We systematically review the literature available till 2023, following the methodology of Tranfield et al. (2003) and Paul and Criado (2020). Pilot research on the three most accessible databases, Google Scholar, Elsevier, and ScienceDirect, for ("environmental economics" or "ecological economics") and ("dynamic game" or "differential game" or "optimal control"), with no further restriction, yields 32.200, 54.271, and 872 results. Consequently, numerous research has been conducted on dynamic games and environmental economics. Finding the correct papers to include in a reliable, systematic literature review remains

challenging. The search was not time-limited, but the sample was gathered in three stages due to the dynamic nature of the discussion surrounding artificial intelligence and dynamic pricing. Figure 1 depicts the path from the pilot search to the final data.

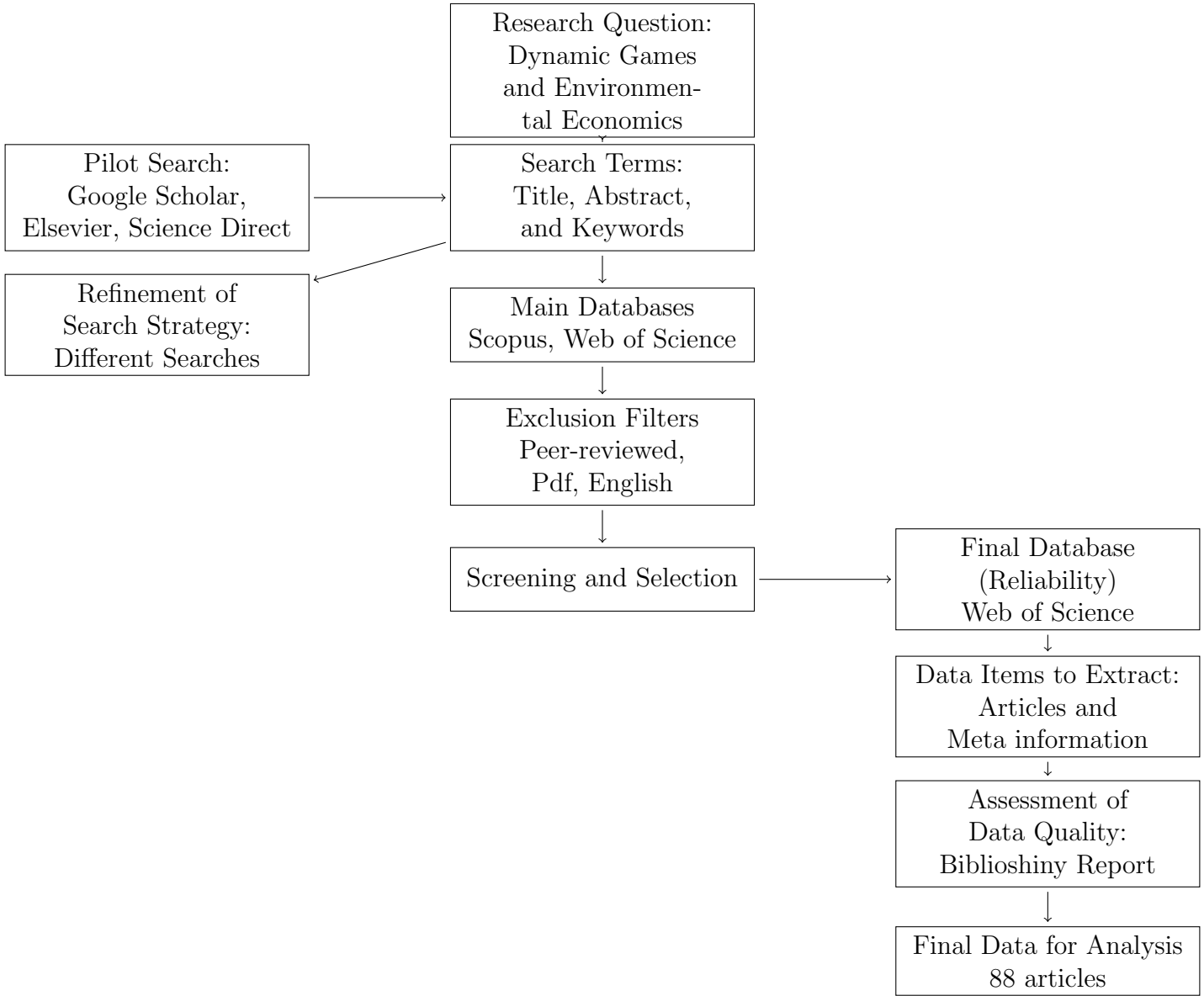


Figure 1: Search path and data selection

2.1.1 First search phase: Database selection

In the initial stage of our methodology, we commenced by selecting a database. According to Aria and Cuccurullo (2017), Web of Science is recognized for its superior data quality compared to other databases. Hence, in line with more recent research conducted by Fink (2019) and Di Vaio et al. (2020), we also employed Web of Science as the primary database for our study. Web of Science is extensively utilized in socio-economic disciplines and offers a similar content size to Scopus (Hicks and Wang, 2011). Additionally, Web of Science has the advantage of a standardized format and requires fewer data-cleaning operations compared to Scopus (Zupic and Čater, 2015).

Selecting an appropriate database is pivotal in ensuring the quality of results obtained in a literature review. In our study, we meticulously considered various databases and ultimately chose Web of

Science as the central database. Additionally, we conducted searches in other databases, namely Scopus, Google Scholar, and ScienceDirect, to identify any relevant references that may have been missed (Jungell-Michelsson and Heikkurinen, 2022; Massaro et al., 2016; Rashman et al., 2009). However, despite these efforts, new publications emerged during the search process. It is worth noting that while we also considered Dimensions and PubMed as potential databases, we found them to yield unreliable results and, therefore, excluded them from our analysis.

2.1.2 Second search phase: Article selection

The relevant publications were carefully chosen in the second phase through content analysis, which required carefully reading the abstracts. We paid close attention to how each article related to the topics covered in our study.

In the second step of our procedure, we chose the relevant articles through content analysis after choosing the database in the previous step. Finding relevant papers required identifying those that satisfied a set of requirements about ecological economics and dynamic games, which we outline in this paragraph. We selected peer-reviewed articles written in English that mention the terms “dynamic game,” “differential game,” or “optimal control,” as well as “ecological economics” or “environmental economics” in the title, abstract, or keywords. First, we conducted a general search of Scopus and the Web of Science. We saw that some publications were from applied mathematics and biosciences. They were not relevant to our study. Second, after limiting our search to the appropriate fields (business, management, and economics), we found 1.193 articles on Scopus and 88 articles on the Web of Science. The PDFs were accessible through the Web of Science, but not through Scopus. The 88 articles from the Web of Science also belonged to the 1.193 articles from Scopus.

2.1.3 Third search phase: Data organization

Thanks to the content analysis, we could arrange the data in a dependable and repeatable way. Each author examined each document’s relationship to the subjects of our inquiry individually before comparing their findings. This individual and comparative method made the research more trustworthy (Di Vaio et al., 2020). No article elimination was made from the data selection.

Following the collection of a list of articles that satisfied the requirements for inclusion, a content analysis was required to guarantee the accuracy and consistency of the data. To ensure that no crucial publications were overlooked, this procedure includes an independent study by each author. There were no missing articles. Therefore the final list of 88 articles remained the same.

2.2 Data analysis

With the help of the statistical language R and the library Bibliometrix, we examined the final dataset of 88 articles (Aria and Cuccurullo, 2017). The Biblioshiny report assessed the quality of our final dataset and the meta information based on the references and the associated links.

3 Results

This section displays the findings in the following sequence for ease of understanding: bibliometric components, abstract and keywords, nations and affiliations, journals, and articles. The clusters that emerged from our comprehensive literature analysis are also used in this part to structure our discussion. Finally, it employs a thematic map to direct our conversation around the significant issues. For completeness, Appendix A provides additional components.

3.1 Bibliometric elements

The chosen publications underwent bibliometric analysis to highlight the spatial and temporal elements of the findings and statistically and graphically analyze the research. A systematic literature review that is visible and reproducible is made possible by bibliometric analysis (Aria and Cuccurullo, 2017, pp. 959–960), ensuring accurate results and reducing the chance of ignoring earlier publications.

We conducted a bibliometric analysis after choosing the pertinent publications to statistically and graphically examine the research and highlight the spatial and temporal features of the findings. The essential literature data examined in the systematic literature review are provided in Table 2. The analysis covered a timespan from 1993 to 2022, encompassing 88 articles, of which 87 were regular articles, and 1 was a review article. The average annual growth rate remained null, emphasizing a constant interest in the field. The document’s average age was to be 13 years. On average, each article received 25.6 citations, highlighting the impact and visibility of the research in the field.

The literature examined contained 2,957 references, demonstrating the extensive use of existing knowledge within the field. The presence of 334 keywords further illustrates the breadth and diversity of the topics covered. The literature involved the contribution of 180 authors, with 21 single-authored articles and 23 articles authored by a single author. On average, each article had 2.3 co-authors, indicating collaborative efforts within the research community. Furthermore, international co-authorships accounted for 25%

By conducting this bibliometric analysis, we gained valuable insights into the characteristics and trends within the literature, providing a deeper understanding of the research landscape. The findings from this analysis and the systematic review contribute to the comprehensive evaluation of the field and its spatial and temporal features.

Table 2: Main data information

Timespan	1993:2022
Articles	88
Regular articles	87
Reviews	1
Annual growth rate %	0
Document average age	13
Average citations per article	25.6
References	2957
Keywords	334
Authors	180
Authors of single-authored article	21
Single-authored article	23
Co-authors per article	2.3
International co-authorships %	25

3.2 Abstracts and keywords

Thanks to the bibliometric analysis, we developed a keyword tree map and a conceptual diagram showing the relationships between the terms in the database (Aria and Cuccurullo, 2017). The keywords are displayed in Figure 2 by color match, making it simpler to read the ideas and connections (Liu, 2004). The color coding emphasizes the intertwined questions being examined and displays the frequency of word occurrence.

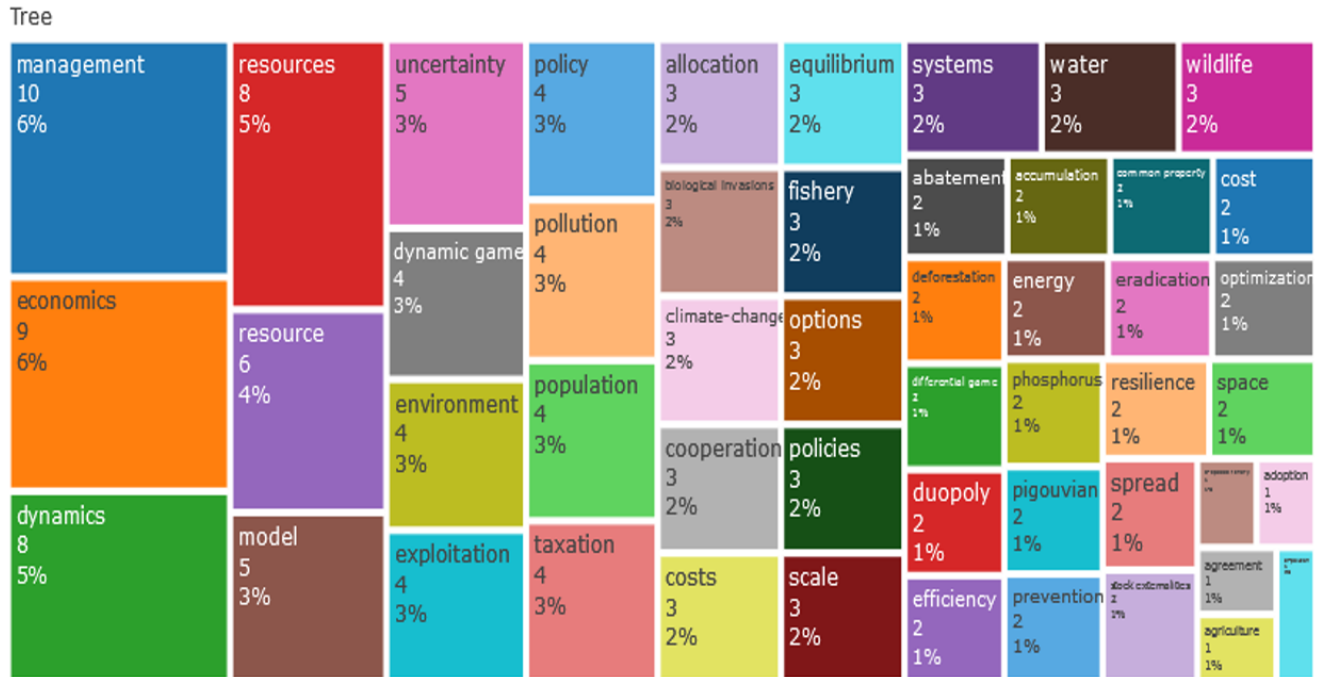


Figure 2: Word tree map in keywords: color measuring word occurrence

The word tree map visualization comprehensively represents the keyword distribution and their respective occurrences in our systematic literature review. Each branch of the tree represents a specific keyword, and the size of the branch reflects its occurrence frequency. The tree map provides valuable insights into the main themes and concepts explored in the reviewed literature. Main keywords with higher occurrence frequencies, such as ‘management,’ ‘economics,’ ‘dynamics,’ and ‘resources,’ are represented by larger branches, indicating their central importance in the field of interest. These keywords highlight the focus on effectively managing dynamic systems, studying economic principles, understanding system dynamics, and addressing resource-related challenges. Additionally, moderately sized branches represent keywords like ‘model,’ ‘uncertainty,’ ‘dynamic game,’ and ‘environment,’ indicating the significance of modeling approaches, dealing with uncertainty, exploring dynamic games, and considering environmental factors within the reviewed articles. Other branches, including ‘exploitation,’ ‘policy,’ ‘pollution,’ ‘population,’ and ‘taxation,’ emphasize specific aspects of interest, such as resource exploitation, policy formulation, environmental pollution, population dynamics, and taxation policies. The word tree map further illustrates the occurrence of various keywords related to specific domains and topics, including ‘fishery,’ ‘cooperation,’ ‘costs,’ ‘options,’ ‘water,’ and ‘wildlife,’ suggesting exploring these subjects within the literature. The visualization provides a comprehensive overview of the keyword distribution. It allows for quick identification of the most prevalent concepts, highlighting the main thematic areas covered in our systematic literature review on dynamic games in the context of environmental economics.

Because of the shared colors, the keywords ‘management’ and ‘cost’ are strongly connected. Similarly, ‘economics’ and ‘deforestation’ also share connections. Eventually, ‘dynamics’ is associated with ‘differential game,’ ‘resources’ with ‘duopoly,’ and ‘resource’ with ‘efficiency.’

The frequency of keywords over time provides insights into the evolving research focus. From 1996 to 1999, the keywords ‘management’ and ‘economics’ occasionally indicated early interest in these areas. However, other keywords like ‘resources’ and ‘environment’ have yet to gain significant attention. In the

early 2000s, there was a gradual increase in the occurrence of keywords related to ‘resources,’ ‘environment,’ and ‘dynamic game.’ This increase suggests a growing emphasis on studying resource dynamics, environmental factors, and the strategic interactions involved in dynamic games. From 2004 to 2010, there was a notable increase in the occurrence of keywords such as ‘management,’ ‘economics,’ ‘resources,’ and ‘dynamic game.’ This increase indicates a broader recognition of the importance of management strategies, economic principles, resource dynamics, and strategic decision-making in dynamic environments. From 2010 onwards, the keywords ‘management,’ ‘economics,’ ‘resources,’ and ‘dynamic game’ consistently appeared with higher frequencies, suggesting a sustained research focus in these areas. Furthermore, keywords like ‘model,’ ‘uncertainty,’ and ‘environment’ also gained prominence, indicating an increasing interest in modeling approaches, uncertainty analysis, and environmental considerations within the studied literature.

Overall, the keyword frequency analysis over time reflects the evolving research landscape, highlighting the growing attention to topics such as resource management, economic principles, dynamic game theory, and their intersection with environmental factors. This trend suggests an increasing recognition of the complexities involved in managing resources, understanding economic dynamics, and addressing strategic decision-making in dynamic environments.

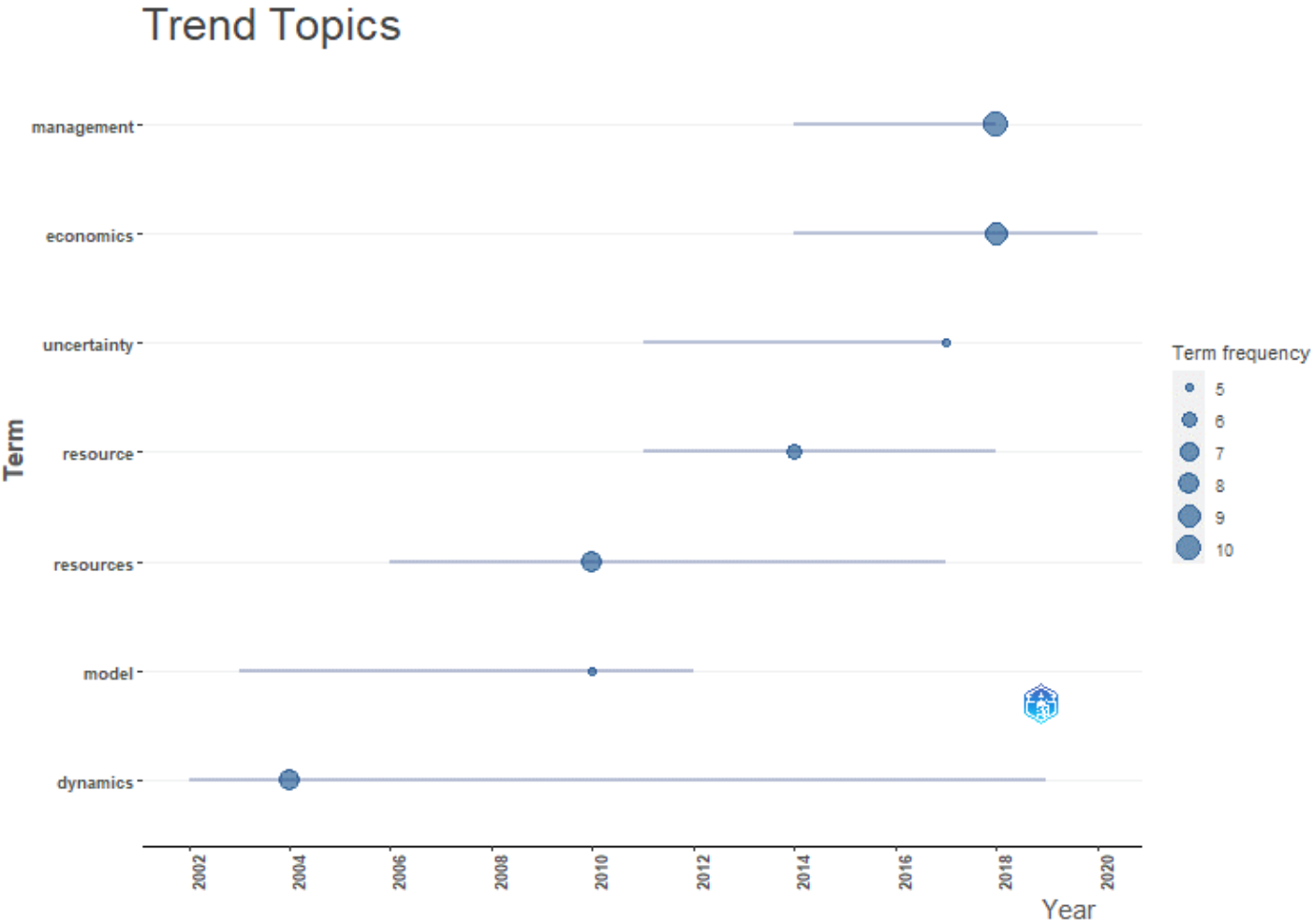


Figure 3: Trend topics of keywords

Figure 3 provides an overview of the trend topics based on the occurrence of keywords over time. The keywords included in the table are dynamics, resources, model, resource, uncertainty, management, and economics. Let us discuss the trend topics represented by these keywords:

Dynamics: The keyword “dynamics” appears eight times throughout the analyzed period. It shows a gradual increase in occurrence from 2002 to 2004 and remains relatively stable until 2019. This increase suggests that the study of dynamics, possibly referring to ecological or system dynamics, has been a consistent topic of interest over time.

Resources: The keyword “resources” also appears eight times in the dataset. Its occurrence gradually increased from 2006 to 2010, peaking in 2017. This occurrence indicates a growing focus on managing and utilizing natural resources.

Model: The keyword “model” appears five times, indicating the utilization of models for various analyses. The occurrence of this keyword shows a gradual increase from 2003 to 2010, followed by a plateau until 2012. This increase suggests that modeling techniques have been employed consistently in the research field, but with a potential decrease in relative importance after 2012.

Resource: The keyword “resource” appears six times, representing a similar concept to “resources” but possibly referring to specific types of resources or singular instances. The occurrence of this keyword shows a steady increase from 2011 to 2014, followed by stability until 2018. This occurrence indicates sustained attention to the management and exploration of specific resources.

Uncertainty: The keyword “uncertainty” appears five times, suggesting a focus on uncertainty within the research articles. Its occurrence shows a peak in 2011 and then remains stable until 2017. This pattern indicates a sustained interest in investigating and addressing uncertainties associated with natural resource management.

Management: The keyword “management” appears ten times, indicating a significant emphasis on management strategies within the analyzed literature. Its occurrence shows a substantial increase from 2014 to 2018, with a plateau at the same level until the end of the analyzed period. This occurrence suggests a consistent and prominent focus on management practices and approaches in natural resource-related studies.

Economics: The keyword “economics” appears nine times, highlighting the economic aspects of natural resource management. Its occurrence shows a significant increase from 2014 to 2018 and continues to be highly prevalent until 2020. This pattern suggests a sustained interest in understanding and incorporating economic considerations into the analysis of natural resource management.

Overall, the trend topics derived from the occurrence of keywords over time reflect the changing research landscape and evolving interests in the natural resource management field. The analysis highlights consistent focus areas such as dynamics, resources, and management, as well as emerging topics like uncertainty and economics. Understanding these trends can help identify key research themes and guide future investigations in the field.

3.3 Clusters

The article’s contents are grouped into six major clusters in Figure 4. The co-occurrences of the main keywords, as presented in the figure, provide insights into the relationships and associations between different research topics within the studied literature.

In Cluster 1, we observe that ‘management’ is a central node with a relatively high betweenness centrality and PageRank score. This result indicates its influential position within the network, suggesting it is frequently associated with other keywords. ‘Resources’ and ‘resource’ are also part of this cluster, although they do not exhibit high betweenness centrality or PageRank scores. This pattern suggests they are less central but co-occur with ‘management’ in the literature.

Cluster 2 includes keywords like ‘dynamic game,’ ‘exploitation,’ ‘allocation,’ and ‘equilibrium.’ The presence of ‘dynamic game’ as a central node with a relatively high betweenness centrality and PageRank score indicates its strong association with other keywords in this cluster. This idea suggests that the concept of dynamic game theory is frequently discussed concerning topics such as exploitation, allocation,

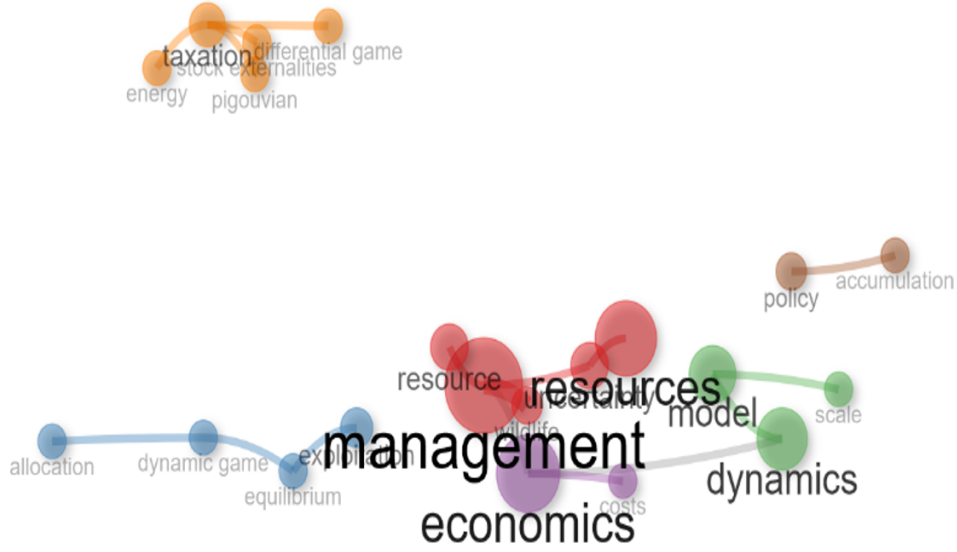


Figure 4: Cluster of content

and equilibrium.

Cluster 3 contains keywords like ‘dynamics,’ ‘model,’ and ‘scale.’ Although ‘dynamics’ appears as a central node with a moderate betweenness centrality, ‘model’ stands out with a relatively higher betweenness centrality and PageRank score. This trend suggests that modeling approaches and the study of dynamics are closely intertwined within the literature, with the concept of scale being less central but still associated with these topics.

Cluster 4 primarily revolves around ‘economics’ and ‘costs.’ ‘Economics’ appears as a central node with a relatively high betweenness centrality and PageRank score, indicating its strong association with other keywords in this cluster. The presence of ‘costs’ suggests that economic considerations, including cost analysis, are frequently discussed within the literature.

Cluster 5 focuses on keywords such as ‘taxation,’ ‘differential game,’ ‘energy,’ ‘Pigouvian,’ and ‘stock externalities.’ ‘Taxation’ stands out as a central node with a relatively high betweenness centrality and PageRank score, indicating its strong association with other keywords in this cluster. The co-occurrence of ‘differential game,’ ‘energy,’ ‘Pigouvian,’ and ‘stock externalities’ suggests that these topics are often discussed with taxation and economic externalities.

Cluster 6 involves keywords like ‘policy’ and ‘accumulation.’ ‘Policy’ appears as a central node with a high closeness centrality, indicating its proximity to other network nodes. ‘Accumulation’ is also present in this cluster, although it does not exhibit high centrality measures. This result suggests that the discussion of policy-related topics and the accumulation concept often co-occur within the literature.

Overall, the analysis of keyword co-occurrences provides insights into the interconnectedness of different research topics within the studied literature. It highlights the prominent role of keywords such as ‘management,’ ‘resources,’ ‘dynamic game,’ ‘economics,’ and ‘policy’ as central themes frequently associated with other keywords. The associations and relationships between these keywords shed light on the interdisciplinary nature of the research field and the interconnectedness of various concepts and perspectives.

3.4 Thematic map

The theme map visually depicts the clustering of the 88 articles content, as shown in Figure 5. Each keyword's importance and evolution are considered when determining where it should be located on the map. The top right quadrant of the map contains keywords with high degrees of relevance and development, whereas the lower left quadrant contains keywords with low degrees of relevance and development.

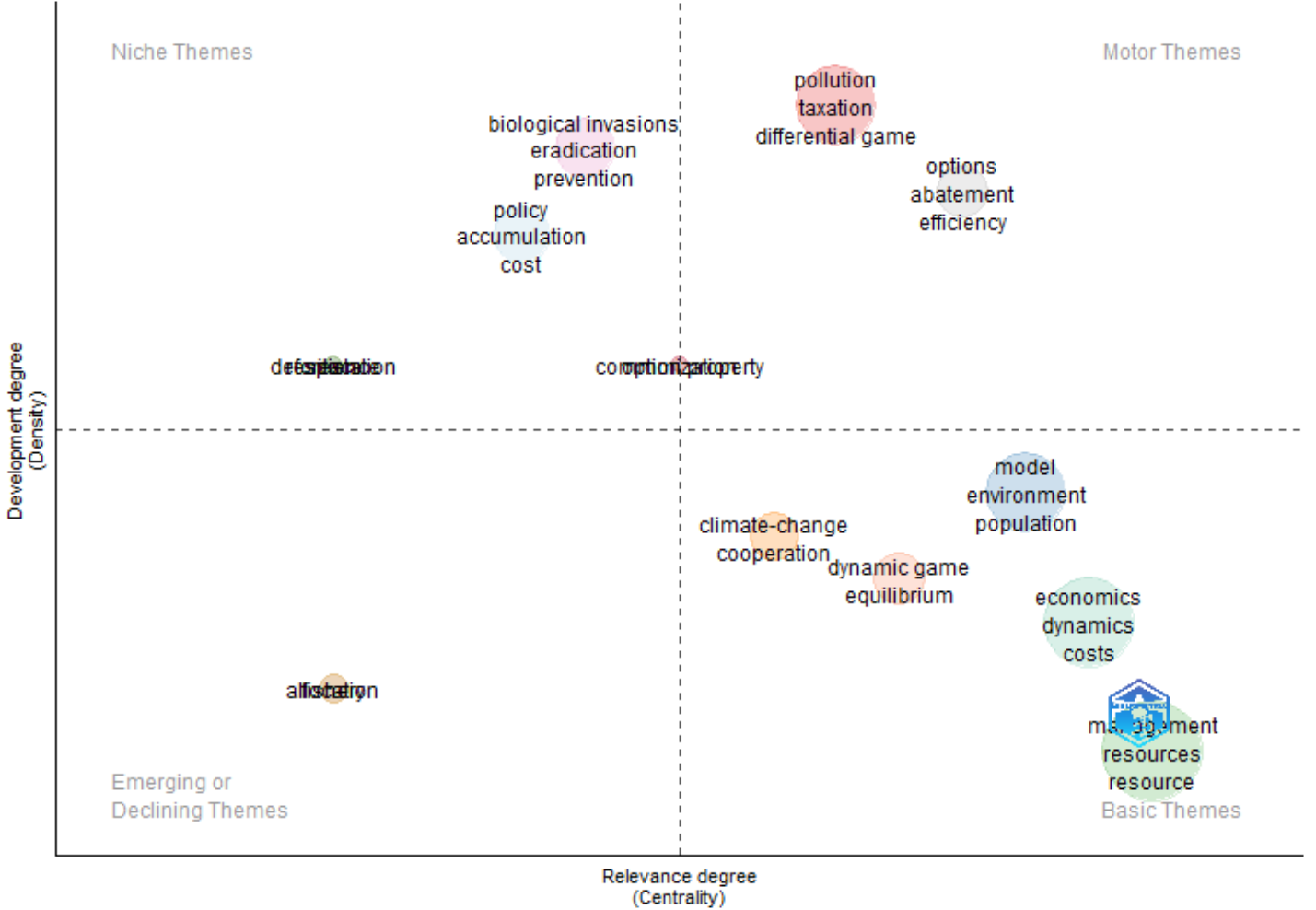


Figure 5: Thematic map

The keywords can be divided into four groups using this map: emerging or declining themes, basic themes, niche themes, and motor themes. These categories shed light on the current status of the literature and help direct future studies. The themes identified in the thematic map are as follows:

1. Emerging or declining themes

The emerging or declining themes consist of keywords such as model, environment, population, scale, and phosphorus. These keywords revolve around developing and applying models to understand complex ecological systems, including population dynamics and environmental processes. The model theme demonstrates high pagerank centrality, suggesting their importance in information flow within the thematic network.

2. Niche themes

The niche themes encompass keywords such as management, resources, resource, uncertainty, exploitation, policies, wildlife, and fishery. These keywords emphasize the management and governance

aspects of natural resources, addressing resource allocation, uncertainty, and sustainable exploitation issues. The management theme demonstrates a high frequency of occurrence, reflecting its prominence within the analyzed literature.

3. Motor themes

The motor themes comprise keywords such as pollution, taxation, differential game, duopoly, energy, Pigouvian, and stock externalities. These keywords highlight the environmental aspect and implications of pollution, exploring topics related to pollution management, pricing mechanisms, and addressing externalities. The pollution theme demonstrates high betweenness centrality, indicating their significance in connecting different parts of the thematic network.

4. Basic themes

The basic themes comprise keywords such as economics, dynamics, costs, systems, and water. These keywords explore the economic dimensions of natural resource management, focusing on economic models, dynamics, cost-benefit analysis, and economic systems. The economics theme demonstrates a high Callon centrality, indicating their significance in being highly connected and influential within the thematic network.

By visually analyzing the thematic map, it becomes apparent that the research articles covered in this study primarily focus on addressing pollution-related concerns, developing models to understand ecological systems, investigating management strategies for natural resources, and analyzing the economic aspects of resource management. The clustering of keywords into themes helps identify the prominent research themes and facilitates a comprehensive understanding of the literature landscape in this domain.

Further exploration of the tables' co-occurrences, centrality measures, and theme properties would provide valuable insights into the interrelationships and significance of specific keywords within their respective themes.

4 Discussion

In this section, we delve into a comprehensive discussion on the various dimensions of the relationships between dynamic games and environmental economics. Building upon the literature's extensive review and systematic classification, we present a conceptual framework encompassing six distinct categories of relationships. Each category emerges from rigorous analysis, identifying the associated mechanisms and processes. While we treat each relationship individually, it is essential to acknowledge the inherent interdependence between dynamic games and environmental economics, leading to inevitable overlaps between categories. Additionally, we shed light on the varying levels of attention that different relationships have received in empirical and conceptual studies. Within this overarching discussion, we focus on several vital subsections to explore the implications and significance of these relationships: pollution, economy, resources, management, modeling, and options. By examining these specific aspects, we aim to provide a deeper understanding of the multifaceted nature of dynamic games in the context of environmental economics.

4.1 Pollution

The papers here share the common theme of examining the optimal policies related to environmental regulations, specifically about transboundary pollutants and climate change.

List and Mason (2001) and Kalkuhl et al. (2020) both explore whether environmental regulations should be carried out centrally or locally in a second-best world. Both papers acknowledge that decentralized

control can be advantageous under certain circumstances, namely when there are sufficiently heterogeneous payoffs and small initial pollution stocks. However, while List and Mason (2001) focuses specifically on transboundary pollutants, Kalkuhl et al. (2020) examines a broader range of environmental regulations and also considers the issue of stranded assets within the context of political economy considerations.

Brock and Xepapadeas (2010) and Walter (2018) both investigate the impact of cooperation in R&D on the effectiveness of environmental policies. In Brock and Xepapadeas (2010), patterns of interaction among agents in a spatiotemporal ecosystem are explored under different institutional arrangements, including a social planner who internalizes spillovers between agents. The authors find that R&D cooperation leads to higher social welfare than competing in R&D or merging into a single entity. Similarly, Walter (2018) utilizes the optimal control approach to show that the social welfare is highest when the firms cooperate in R&D with regards to clean technology, in comparison to the scenarios when they compete in R&D or merge into a single entity. The papers both highlight the importance of considering the cumulative nature of R&D for effective environmental policies.

Wirl (2012) and Jaakkola (2019) examine dynamic games related to climate change in the context of fossil fuel suppliers and consumers. Wirl (2012) explores how the choice of instruments for regulating climate change impacts the interactions between fossil fuel suppliers and consumers in a stock externality game. According to the authors, a carbon tax implemented through a price instrument is preferable for both players. They anticipate a shift towards tax policies if global warming is effectively addressed. In contrast, Jaakkola (2019) examines a differential game where an oil cartel and an importer invest in R&D to decrease the cost of a green alternative to oil. The study suggests that carbon taxes are insufficiently high and that relying solely on green R&D programs will result in more costly climate policy.

Overall, the papers reveal various complex issues and interactions in designing effective environmental policies, including the institutional arrangements, the role of R&D, and the dynamic games involved in regulating climate change.

4.2 Economy

We have conducted a comparative analysis of seven academic papers that discuss various aspects of environmental and resource management. The papers examined are Bene et al. (2001), Buhle et al. (2005), Fujii and Karp (2008), Gsottbauer and van den Bergh (2014), Fresard and Ropars-Collet (2014), Arguedas et al. (2020), and Marpaung et al. (2021). The goal of this analysis is to identify similarities and differences among the papers in terms of their research focus, methodologies used, key findings, and policy implications. By examining these aspects, we aim to gain a deeper understanding of the different approaches taken to address environmental and resource management challenges.

Bene et al. (2001) focuses on the management of a marine renewable resource and explores its viability and crisis situations. It analyzes the compatibility between state constraints and controlled dynamics, placing specific emphasis on indicators of overexploitation.

Buhle et al. (2005) addresses strategies for controlling invasive species, specifically oyster drills. It combines biological and economic data to determine the most cost-effective set of strategies for preventing the further increase of invasive species.

Fujii and Karp (2008) analyzes optimal environmental policy in situations where consumer preferences are endogenous. It focuses on climate change and utilizes a declining pure rate of time preference (PRTP) as a modeling tool.

Gsottbauer and van den Bergh (2014) develops a theoretical model to analyze optimal environmental policy, considering endogenous consumer preferences and the influence of consumption norms and commercial advertising on pollutive consumption.

Fresard and Ropars-Collet (2014) addresses the control of invasive species, particularly in cases where an invasive species competes with a native harvested species. It presents a bioeconomic model to analyze

the dynamics of both species and develop optimal control strategies.

Arguedas et al. (2020) focuses on optimal pollution standards and enforcement strategies, considering scenarios where environmental damages depend on accumulated pollution. It examines the interaction between a regulator and a polluting firm, with fines as a means of enforcement.

Marpaung et al. (2021) utilizes mathematical modeling to analyze disease transmission dynamics, particularly the interplay between dengue and typhoid fevers. It incorporates control variables such as mosquito eradication and education on healthy living.

Regarding methodologies employed, Bene et al. (2001) utilizes a simple dynamic model and the concept of viability kernel. Buhle et al. (2005) combines biological and economic data and utilizes mathematical modeling techniques. Fujii and Karp (2008) develops an algorithm for numerical analysis. Gsottbauer and van den Bergh (2014) utilizes theoretical modeling. Fresard and Ropars-Collet (2014) presents a bioeconomic model. Arguedas et al. (2020) employs game theory techniques, and Marpaung et al. (2021) utilizes algebraic modeling and optimization techniques.

Regarding key findings and policy implications, Bene et al. (2001) emphasizes the importance of considering viability and crisis situations in marine resource management. Buhle et al. (2005) provides insights into cost-effective strategies for controlling invasive species. Fujii and Karp (2008) sheds light on the influence of non-constant PRTP on optimal environmental policy. Gsottbauer and van den Bergh (2014) extends environmental policy theory by considering endogenous consumer preferences and consumption norms. Fresard and Ropars-Collet (2014) highlights the importance of controlling invasive species as competitors for native species. Arguedas et al. (2020) challenges the notion that linear fines are always preferable in controlling pollution. Marpaung et al. (2021) provides valuable insights into disease transmission dynamics and the effectiveness of control strategies.

In conclusion, the comparative analysis of these papers reveals diverse research foci, methodologies used, and key findings in the field of environmental and resource management. Collectively, they contribute to a broader understanding of effective management strategies, the importance of economic considerations, and the need to account for factors such as viability, invasive species, climate change, consumer preferences, and enforcement mechanisms. These insights can inform policymakers and resource managers in formulating more effective and sustainable environmental policies and interventions.

4.3 Resources

The four papers under consideration share a common theme of optimal resource management under uncertainty and dynamic conditions. Each paper approaches the topic differently and provides unique insights based on the underlying assumptions and modeling techniques used.

The article by Marten and Moore (2011) discusses the management of invasive species, providing a stochastic optimal control framework that accounts for uncertainty and interactions between multiple species. Using the case of hemlock wooly adelgid in the eastern US, the paper shows how combining both chemical and biological controls can be beneficial for long-term management strategies. The study stresses the significance of considering both natural and chemical management strategies, particularly when dealing with invasive species and uncertain population dynamics.

The article by Goeschl and Perino (2007) examines the ideal R&D path in a scenario where new technologies are not foolproof solutions for the pollution issue. The study highlights the connection between research and pollution policies and determines the best pollution course and R&D plan. Research indicates that pollution stocks exceed the limit and the ultimate collection of technologies is limited. The research also illustrates the benefits of diversification when handling numerous pollution stocks.

In Naevdal and Skonhoft (2018), the authors examine the standard fishery biomass model for optimal control. They provide fresh insights on the optimal management of fish stocks when they are low. The study concludes that it is best not to harvest when the marginal benefit of harvesting is finite for all

harvest levels, as long as it is not optimal to let the stock go extinct. Furthermore, under mild conditions, the shadow price on the fish stock tends to infinity as the stock approaches zero. This study emphasizes the significance of considering low stock sizes while designing optimal policies for fisheries management.

In Shevchenko et al. (2022), the classical DICE model is expanded to include stochastic shocks to reflect stressed and normal economic conditions caused by events like the COVID-19 pandemic. The study indicates that if the world gross output recovers fully after each event, the impact of COVID-19 on temperature and carbon concentration will be negligible, even if annual gross output drops by 10% over five years. However, if output falls by 5% over several years due to persistent shocks, the impact becomes noticeable. The paper also reveals that using a deterministic DICE model policy in the presence of stochastic shocks leads to suboptimal outcomes.

These four papers contribute to understanding optimal resource management under uncertainty and dynamic conditions. They employ different modeling techniques and assumptions to provide unique insights into the optimal strategies for managing non-native invasive species, pollution, fisheries, and climate change. While each paper focuses on a different aspect of the problem, the common thread is the importance of accounting for uncertainty and dynamic conditions in designing optimal management policies.

4.4 Management

The papers under study are Breton and Keoula (2014), Nkuiya (2015), Jones and McDermott (2018), Colombo and Labrecciosa (2018), Foudi (2012), Bar-Nahum et al. (2022), and Jia et al. (2018). These papers are chosen based on their diverse research topics and contributions to understanding the economics of natural resources and the environment.

In their study, Breton and Keoula (2014) analyze the Great Fish War model with coalition formation and consider players' varying time preferences and discount rates. The authors examine the equilibrium payoffs of this game and explore the effects of assuming asymmetry on both cooperative and non-cooperative equilibria. Their results illustrate that asymmetry significantly affects coalition profitability and resource allocation. The study highlights the need to account for asymmetry when analyzing players' cooperation in exploiting natural resources.

The analysis of a dynamic game between nations facing the risk of sudden and permanent shifts from pollution is explored in Nkuiya (2015). The paper examines the effects of both endogenous and exogenous threats of a global damage jump or catastrophe on the commons dilemma and welfare. Findings show that the possibility of damage jumps or catastrophe threats can alleviate the tragedy of the commons, resulting in a rise in the total discounted consumer surplus. This research is crucial as it suggests that negative consequences threats can encourage better environmental behavior changes.

This study by Jones and McDermott (2018) examines the lasting gains of investing in urban afforestation and the effects of externalities (both positive and negative), expenses related to the project, and environmental feedback. Using a bioeconomic-health model, the research demonstrates that per-tree net benefits of afforestation investments are notably lower than prior estimations. The paper underscores the importance of cost-benefit evaluations in urban afforestation to educate policymakers about how their projects affect environmental conditions and public well-being.

A study conducted by Colombo and Labrecciosa (2018) examined the cooperation of oligopolists selling a common-pool renewable resource. The study explored the long-term effects of cooperation, the influence of conservation cartels on resource conservation, and efficiency. Based on their findings, the authors suggest that promoting conservation cartels is beneficial for both resource preservation and efficiency. This research emphasizes the importance of encouraging collaboration among renewable resource sellers, which can ultimately enhance consumer welfare.

In the study conducted by Foudi (2012), the focus is on property rights and their impact on soil con-

servation. The research questions the common belief that tenants are less inclined to invest in sustainable management practices compared to landlords. The authors, however, demonstrate that tenants' investment in soil conservation is influenced by various factors, including biological, ecological, and economic elements that determine the benefits of investing in sustainable soil conservation practices. The study sheds light on the complex nature of tenants' investments in soil conservation and highlights the need for a dynamic approach to addressing soil conservation issues.

In the study by Bar-Nahum et al. (2022), the influence of lobbying on policies in a water economy managed centrally is analyzed. An optimal control model is employed to demonstrate that a stronger farmers' lobby results in quicker depletion of naturally replenished water resources and hastens investment in water-supply technologies like desalination. The research, which focuses on Israel's water economy, highlights the importance for policymakers to tackle the impact of interest groups on natural resource allocation.

In their study, Jia et al. (2018) examine the distribution of scarce water resources among various stakeholders, aiming to achieve economic, social, and environmental gains. The researchers employ game theory to evaluate the government's effectiveness in regulating the water market. They present a two-stage dynamic game model and utilize the sub-game perfect Nash equilibrium to determine the market behavior strategies of water users. The authors apply this methodology to a case study of Tianjin, Northern China, to demonstrate how the model can be used for optimal income targeting.

These seven papers have made significant contributions to environmental economics. They cover topics such as the coalitional Great Fish War model, pollution's impact on the commons and welfare dilemma, urban afforestation investment, cooperation among oligopolists selling a common-pool renewable resource, property rights' role in soil conservation, lobbying on centrally managed water economy policies, and limited water allocation across different users. Policymakers must consider the economic, social, and environmental implications of managing natural resources. Overall, these papers highlight the importance of a multidisciplinary approach to sustainable resource management.

4.5 Modeling

The academic papers discussed are diverse in their topic areas and analytical approaches to modeling. However, they all focus on managing or preserving environmental resources and using mathematical models to inform decision-making.

Carpenter (2002) explore the ecological dynamics of ecosystems and the importance of historical and future-oriented approaches to ecology. The paper argues that ecologists must assess future ecosystem states and their implications. The authors suggest a need for an ecology of the "long now" that considers past ecological influences that shape present ecologies and future consequences of current events.

Peterson et al. (2003) create a simplified ecosystem management model to demonstrate how environmental collapse can occur from seemingly rational management strategies. The model considers lake dynamics, decision-making, and learning, with a focus on model uncertainty. The simulated lake can shift between oligotrophic and eutrophic states, and managers must choose between two management models based on observed data to maximize the lake's expected net present value. Despite optimistic assumptions about the environment, learning, and management control, conventional decision theory and optimal control methods are unable to stabilize ecological dynamics, resulting in cycles of collapse and recovery.

Blackwood et al. (2010) present a spatially-explicit, optimal control strategy for invasive species management using linear-quadratic control. This paper emphasizes reducing connectivity as a cost-effective part of invasive species control. It also provides insights regarding the effectiveness of management policies with heterogeneous patches and sedentary adults.

Fernandez (2002) consider the consequences of trade liberalization on transboundary water pollution are analyzed through a differential game. The research investigates the influence of trade policy alterations and public health costs, as well as the potential of trade liberalization to reduce pollution. The study emphasizes the importance of collaboration and trade liberalization in reducing emissions from both nations and deterring the strategic actions of one country’s pollution control endeavors.

In their 2003 publication, Odom et al. (2003) create a plan for handling environmental weeds within national parks. They establish a dynamic programming model that considers weed population changes, control method effectiveness and cost, and the park’s outputs’ value (e.g., biodiversity, recreation, and grazing). The paper outlines optimal control guidelines for any given weed population state. It highlights the significance of an integrated, strategic, ecological, and economic approach to weed management and offers recommendations for managing weeds in natural environments.

An approach presented by Zhang et al. (2007) proposes a method for determining the necessary amount of green space in areas with lower biodiversity. The method uses the ecological element threshold to calculate the required green space. The study considers factors such as population capacity, carbon-oxygen balance, and water resource equilibrium as limiting factors for green space planning. The total required green space is quantified to maintain the ecological balance. The research includes a case study of Shaliuhe town in Hebei Province, China. The findings suggest that reducing connectivity can be a cost-effective strategy for controlling invasive species, as reliable connectivity increases the cost of invasive control.

In their work, Turner and Tschirhart (1999) examine the limitations of using gross domestic product (GDP) as an indicator of societal well-being. They emphasize the significance of including non-marketed values of natural resources in economic analysis. The authors propose a model that considers both market and non-market income from natural capital, aiming to address the “welfare gap”. Their argument stresses the practicability of explicitly accounting for ecological connections in economic growth models. The study illustrates how the growth rate of GDP can significantly diverge from the growth rate of societal well-being, creating a sizable welfare gap that depends on personal preferences and the inherent growth rate of natural resources.

The focus of the study by Kawaguchi (2003) is on pollution accumulation and how to maximize long-term welfare in environmental economics. The approach involves solving the Hamilton-Jacobi-Bellman equation and developing a feedback policy. The study highlights the significance of incorporating ecological relationships into economic growth models and offers valuable information on the optimal policy and equilibrium stock for pollution.

While the papers explore different topics, they highlight the importance of accounting for the ecological relationships and dynamics of natural resources in management and decision-making processes for long-term sustainability. Moreover, all the papers rely on mathematical models, including dynamic optimization, differential games, and dynamic programming, to provide insights for policy recommendations. The papers emphasize the need for an integrated, strategic, ecological, and economic approach to environmental management.

4.6 Options

The three academic papers, Saphores and Shogren (2005), Helm and Mier (2021), and Haavio (2005), have different focuses and approaches but also share some similarities in terms of their economic themes and analytical frameworks.

A study conducted by Saphores and Shogren (2005) utilized a framework based on real options to analyze the management of exotic pests in the face of uncertainty. The investigation focused on two main aspects: determining the optimal timing of implementing control measures and identifying the optimal expenses for acquiring bioeconomic data. Notably, the research found that effective management strategies

for exotic pests must consider factors such as uncertainty, irreversibility, and bioeconomic parameters.

The policy instruments for guiding the transition to a zero-carbon future in an economy with pollutive fossils, intermittent renewables, and electricity storage are examined by Helm and Mier (2021). The research investigates the use of a Pigouvian tax, subsidies, and perfect versus imperfect carbon pricing. The authors' findings indicate that the ideal subsidy rate for renewables decreases with lower dependence on fossils and that significant payments are necessary even after fossils have been eliminated from the market.

In their research, Haavio (2005) analyze how household mobility affects policymakers' ability to address transboundary pollution externalities. They use a differential game model to demonstrate how migration costs and explicit dynamics impact the situation. Their findings suggest that imperfect household mobility can lead to a tragedy of the commons, making it challenging for individual countries to address the externality and avoid over-emitting, even when the pollution is strictly local. While the three papers have different topics and research questions, they share similarities regarding their analytical frameworks and economic themes. All three studies involve dynamic optimization models that factor in uncertainty and irreversibility. They also explore optimal policy instruments, such as subsidies and taxes, that promote sustainable and efficient outcomes.

At the same time, the studies focus on different aspects of economics, such as pest management, renewable energy, and transboundary pollution. Saphores and Shogren (2005) and Helm and Mier (2021) are focused on environmental economics, with Saphores and Shogren (2005) focusing on the management of exotic pests and Helm and Mier (2021) examining the energy transition towards a zero-carbon future. In contrast, Haavio (2005) focuses on the economics of households and migration and household mobility's role in addressing transboundary pollution.

In conclusion, while the three papers have different approaches and topics, they share similarities regarding their analytical frameworks and economic themes. They demonstrate the complexity and interrelatedness of economic and environmental issues and highlight the need for efficient and sustainable policy instruments that account for uncertainty and irreversibility.

5 Analysis and future research directions

Our research shows how dynamic games and environmental economics are intricate and multifaceted and how they might provide a thorough alternative to advancing or upending existing corporate and policy practices. However, their complexity makes deploying them on a bigger scale difficult. This part will go through potential theoretical and practical contributions, consider the study's constraints, and suggest new lines of inquiry based on the gaps found.

5.1 Theoretical and practical implications

The systematic literature review on dynamic games and environmental economics has provided several theoretical and practical implications for researchers, policymakers, and practitioners. From Section 2, the review analyzed 88 articles published between 1993 and 2022, revealing collaborative efforts, research trends, and the distribution of keywords.

In Section 3, the research landscape and trends analysis showed sustained interest in the field, with collaborative efforts and international co-authorships. From a theoretical perspective, the keyword analysis identified vital themes such as management, economics, dynamics, and resources, reflecting the focus on managing dynamic systems, studying economic principles, understanding system dynamics, and addressing resource-related challenges. The analysis of journals highlighted prominent platforms for publishing research, such as the "Journal of Environmental Economics and Management" and "Ecological Economics," among others.

The analysis of corresponding author countries revealed that the United States had the highest number of articles, followed by Canada, Spain, and Australia, indicating a global involvement in the field. This remark highlights the importance of international collaborations in advancing knowledge and addressing complex environmental and economic challenges.

The thematic map analysis provided theoretical and practical implications for natural resource management and environmental economics. It identified emerging and declining themes, niche themes, motor themes, and basic themes within the field. The analysis highlighted the growing interest in employing models to study ecological systems, management strategies, pollution control, and economic considerations. It also emphasized the importance of addressing management and governance aspects, sustainable exploitation practices, and uncertainties in resource management decision-making. The identification of motor themes related to pollution, taxation, differential games, energy, and stock externalities underscored the focus on pollution management, pricing mechanisms, and the economic implications of resource management.

From a practical perspective, the thematic map analysis offered guidance for future research by identifying prominent themes and knowledge gaps. Researchers can explore specific subtopics within each theme to contribute to a more comprehensive understanding of the field. The centrality measures provided insights into the significance and influence of keywords, aiding stakeholders in prioritizing focus areas, collaborations, and policy interventions.

In Section 4, we could conduct several discussions on different themes. In pollution, the articles offered theoretical insights into optimal environmental regulations, decentralized control in ecological governance, cooperation in R&D, and the choice of instruments for regulating climate change. The findings have practical implications for policymakers and stakeholders in designing effective environmental regulations and climate change mitigation strategies.

Regarding the economy, the analyzed papers focused on mathematical modeling techniques applied to natural resource management, environmental policy, and public health. They provided insights into the importance of economic factors in designing management strategies, balancing ecological sustainability with economic viability, and understanding cost-effective control strategies and the interplay between different populations.

In resource management, the analyzed papers emphasized the benefits of combining chemical and biological controls in addressing invasive species, the interdependence of research and pollution policies, optimal fisheries management policies, and the impact of external events on climate change policies. These findings contribute to developing optimal resource management strategies under uncertain and dynamic conditions.

In management, the analyzed papers provided insights into the economics of natural resources and the environment, highlighting the impact of asymmetry on cooperation and resource profitability in coalitional resource sharing. Analyzing a dynamic game among countries facing pollution risks demonstrated the role of threats and potential actions.

In options, the articles utilize dynamic optimization models that factor in uncertainty and irreversibility. Additionally, they explore optimal policy instruments, such as subsidies and taxes, to promote sustainable and efficient outcomes. While one paper addresses the management of exotic pests, another focuses on the transition to a zero-carbon future, and the third examines transboundary pollution and household mobility, they collectively demonstrate the complexity and interrelatedness of economic and environmental issues.

The systematic literature review on dynamic games and environmental economics has generated significant theoretical and practical implications. These implications offer guidance for future research, inform decision-making processes, and advance knowledge in the field. The findings have practical applications in sustainable resource management, environmental policy, and the development of effective environmental regulations and climate change mitigation strategies.

5.2 Research gaps

Several research gaps have emerged in our analysis of the literature on environmental economics and dynamic games. These gaps highlight areas where further investigation is needed to advance our understanding of resource management, pollution control, and sustainability. The following section presents critical research gaps based on analyzing prominent themes in the literature.

5.2.1 Management and resource allocation

A crucial research gap lies in the realm of resource management and allocation. While the literature addresses these topics, there is a need for more research on effective strategies for allocating natural resources. This need includes developing models and frameworks integrating ecological, economic, and social factors to optimize resource allocation. The dynamic nature of resource systems, coupled with uncertainties such as climate change and population dynamics, calls for sophisticated modeling approaches to capture resource management’s complexity.

5.2.2 Addressing uncertainty

Uncertainty is a significant challenge in environmental decision-making. While the literature acknowledges the presence of uncertainty, further research is needed to explore and address its implications. Developing robust decision-making frameworks incorporating uncertainty analysis, adaptive management strategies, and scenario planning can contribute to more sustainable resource management practices. Understanding and effectively managing uncertainties arising from environmental variability, market conditions, and policy changes are crucial for informed decision-making.

5.2.3 Policy design and evaluation

Policies play a crucial role in shaping resource management practices. However, there is a need for comprehensive assessments of policy effectiveness and the design of innovative policy instruments. Further research is required to evaluate the impacts of different policy approaches on resource sustainability and societal welfare, such as market-based mechanisms, regulatory frameworks, and participatory governance. This required research includes examining policy interventions’ trade-offs, synergies, and unintended consequences to inform evidence-based decision-making.

5.2.4 Expanding the scope

While the literature focuses on wildlife and fishery management, a research gap exists in broadening the scope to include other ecosystems and natural resources. Examining the dynamics of diverse systems, such as forests, water bodies, and biodiversity hotspots, and their interactions with socioeconomic factors can provide valuable insights into sustainable management practices. Exploring the interconnections between different ecosystems and considering the implications for resource allocation and policy design is an essential avenue for future research.

5.2.5 Pollution management and policy interventions

Research gaps exist in pollution management and the design of effective policy interventions. While pollution control policies have been implemented globally, further research is needed to evaluate their effectiveness, efficiency, and equity. This research includes examining the impacts of various policy instruments, such as pollution taxes, cap-and-trade systems, and command-and-control regulations, on pollution reduction and economic outcomes. Assessing the trade-offs and co-benefits of different policy approaches

and understanding the factors influencing their success can inform the development of more targeted and sustainable pollution management strategies.

5.2.6 Integration of dynamic game theory

There needs to be more research on integrating dynamic game theory into environmental economics. Dynamic games provide a robust framework for analyzing strategic interactions among multiple agents over time. Exploring the application of dynamic game theory to address environmental challenges, such as transboundary pollution, common pool resource management, and renewable resource exploitation, can enhance our understanding of optimal policy design and decision-making processes. Investigating the dynamic strategies and behaviors of different actors in environmental contexts can provide valuable insights into effective policy interventions.

5.2.7 Emerging issues and interactions

Lastly, there is a need to explore emerging issues and their interactions with environmental economics. This need includes investigating the implications of technological advancements, circular economy approaches, and the dynamic relationships between environmental policies and economic development. Understanding the changing technological landscape, its impacts on environmental concerns, and the potential synergies and conflicts between environmental objectives and economic growth presents promising avenues for future research.

5.3 Research limitations

A systematic literature review is helpful in combining theories and offering group insights, according to Tranfield et al. (2003) and Aria and Cuccurullo (2017). However, they also have known (Di Vaio et al., 2020) restrictions. One restriction on the type of literature that can be included in the search technique may exclude pertinent articles because of the language used or because they are briefly mentioned in the title, abstract, or keywords. We used many databases (Scopus, Web of Science, and Google Scholar) to reduce the possibility of exclusion. We used snowball sampling to gather as much information as possible on their study questions.

In order to narrow down the search results to a manageable and pertinent data collection, particular search word combinations were also necessary (Perera et al., 2019). Based on the study's goal, we used the primary search phrases "environmental economics" and "dynamic game," as well as a few related terms ("ecological economics," "differential game," and "optimal control"). We acknowledge the possibility of other terminology connected to the study, such as "resource economics" or "mean field game," which may relate to the survey's subject. On the one hand, including these or related terms to the literature search could have given our review other viewpoints or approaches. On the other side, it might have jeopardized the validity of the research. In this compromise, we only used peer-reviewed publications from academic journals, which ensured a thorough and transparent search but constrained the review to the impact most salient portion of the argument. We did not include other kinds of publications, such as books and book chapters. The common research language, English, was another restriction on our search. It's possible that our exclusion policy ignored articles that provided a more thorough explanation of our work.

Future studies can benefit from a literature review's shortcomings. Future research could focus on particular domains of artificial and dynamic price implementation and use a less stringent approach to data collection. Other publications, including books, could be added to the data collection energy using a more targeted approach. As was previously said, experimenting with various search phrases can also yield insightful information about the connections between dynamic pricing, artificial intelligence, and other well-established ideas. Adding articles written in languages other than English would have

provided more substantial insights, notably in Chinese. Chinese articles are far and away the most common, even if American publications are the most frequently mentioned. Furthermore, combining theory-based and empirical research on applying environmental economics and dynamic optimization would be advantageous.

6 Conclusion

This article presents a systematic literature review on ecological and environmental economics modeled with dynamic games. The data collection process involved a comprehensive search on the Web of Science database, resulting in a final dataset of 88 articles. The literature review findings provide valuable insights into the field of dynamic games in environmental economics. The bibliometric analysis reveals the spatial and temporal features of the chosen publications, demonstrating a consistent interest in the field. Analyzing the research themes offers a comprehensive understanding of the interconnectedness and significance of different research topics within the literature.

These insights guide future research, policy interventions, and dynamic ecological and environmental economics collaborations. However, there are several research gaps and limitations that should be acknowledged. This review highlights the need for further investigation into effective resource allocation strategies, addressing uncertainty in decision-making, evaluating policy effectiveness, broadening the scope to include other ecosystems and natural resources, and integrating dynamic game theory into environmental economics. It is essential to acknowledge the limitations of this study, such as the search process excluding relevant articles due to language limitations or specific keywords and the review focused on peer-reviewed academic journal articles. However, future research could consider a broader range of publications and languages to provide a more comprehensive understanding of the application of environmental economics and dynamic optimization. The findings contribute to developing effective strategies for addressing environmental challenges, promoting sustainable practices, and informing decision-making processes in resource management and environmental policy.

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A Appendix

To offer a greater understanding of the systematic literature review, Appendix A provides additional elements. Table 3 lists the 88 articles of the systematic literature review. It summarizes the main contribution of each article.

Table 3: Articles for the systematic literature review

Reference	Summary
Alla et al. (2018)	They propose a dynamic response model to analyze the optimal harvest policy of a fishery system with a reserve area, based on a reasonable catch rate function and a fee per unit of landed fish biomass, and analyze equilibrium and stability using Pontryagin’s maximum principle.
Andres-Domenech et al. (2015)	The study analyzes the relationship between deforestation and CO2 accumulation and provides insights into the potential benefits of forest owners cooperating with non-forest owners to reduce negative externalities.
Arguedas et al. (2020)	They analyze optimal pollution standards and enforcement strategies in a Stackelberg differential game and find that setting standards dependent on the pollution stock is preferred if fines are sufficiently nonlinear.
Asheim et al. (2006)	The paper presents a dynamic game-theoretic model showing that regional cooperation is more effective than a global treaty for providing international environmental public goods by sustaining a larger number of cooperating parties.
Augeraud-Veron et al. (2019)	They review advances in distributed optimal control for environmental economics, exploring problems with state dynamics and existing tools in theory.
Bach (1999)	Direct subsidies to low-impact logging activities through area-dependent subsidies are more effective in promoting low-impact logging than subsidizing prices of tropical timber, as explored in the article.
Baker et al. (2017)	They determined the optimal resource allocation strategies for invasive species eradication programs using two control methods, where the control with overhead costs is applied at the beginning and with a handling time in the latter part, and both controls are used in an overlap.
Bar-Nahum et al. (2022)	Researchers developed an optimal control model to study the impact of lobbying on water policies in Israel’s economy, indicating that a stronger political power of the farmers’ lobby leads to quicker depletion of water resources and investments in water-supply backstop technologies.
Beaumont and Walker (1996)	It finds that private property fails to ensure optimal soil resource conservation in peasant agriculture.
Benckroun et al. (2020)	The authors find that imposing trade barriers could assist in maintaining renewable resources in a common-pool, oligopolistic environment.
Bene et al. (2001)	The paper defines economic and biological state constraints and utilizes the viability kernel to reveal management options for a perennial marine renewable resource.
Bhat and Huffaker (2007)	The study presents a dynamic contract that enables negotiation and flexible transfer payments between the owners of two separate mammal populations, establishing a standard for measuring the VTP’s size that is equally Pareto-efficient as a lump-sum or fixed annual transfer payment.
Blackwood et al. (2010)	The authors propose linear-quadratic control for invasive species removal, demonstrating that reducing connectivity could be a cost-effective solution.
Brechet et al. (2012)	The authors develop and analyze a vintage capital model for a firm in a tradable emissions permit market, finding that the market equilibrium may not be cost-efficient.
Brechet et al. (2014)	They analyze policies in response to climate change, finding that “business as usual” may cause a 2A degree Celsius increase versus a collectively optimal policy over the next 150 years.
Breton and Keoula (2014)	They analyze the impact of different discount rates on the coalitional Great Fish War model and demonstrate that asymmetry has a notable impact on the coalitions’ resource-sharing and profitability.
Brock and Xepapadeas (2010)	The authors examine ecosystem management and compare economic agents and social planners while exploring regulatory schemes to internalize externalities in a semi-arid system, using Fourier series type decompositions to tackle an optimal control problem.
Buhle et al. (2005)	They demonstrate the integration of biological data and economic analyses for identifying cost-effective strategies to prevent the spread of invasive species.
Caparros and Jacquemont (2003)	The article examines how economic incentives for carbon sequestration can harm biodiversity, particularly in afforestation and reforestation programs.

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Table 3 – continued from previous page

Reference	Summary
Carpenter (2002)	The authors emphasize understanding past and future ecosystems to make informed decisions for their management.
Carrasco et al. (2010)	The researchers develop a bioeconomic model to manage the risk of non-indigenous species, finding that government agencies should prioritize control over exclusion for species with certain characteristics.
Chalak et al. (2017)	They present an integer optimization model to identify optimal strategies for controlling invasive species in a spatially explicit and stochastic setting.
Chander (2017)	They model climate change, prove unique equilibrium, and explore cooperative agreements.
Colombo and Labreciosa (2018)	The authors demonstrate the benefits of oligopolist cooperation through a differential game, showcasing increased output, consumer surplus, and resource stock in the stationary equilibrium.
Costanza and Neuman (1997)	The author analyzes knowledge generation and administration in managing a rural enterprise in the Argentine Chaco region, utilizing a nonlinear model to highlight the role of silvopastoral systems in sustainable development and proposing a methodological solution for decision-making.
Danielsson (2002)	They developed a biodynamic model to assess fishery management methods and found that their relative efficiency depended on stochastic variations, the elasticity of demand, and the management objective.
Das (2018)	The paper's author analyzes a prey-predator system, determines the optimal taxation policy using Pontryagin's maximal principle, and illustrates the results through numerical simulations.
Das (2019)	An analysis of steady states and optimal harvesting methods is presented in a prey-predator fishery model using Pontryagin's maximum principle in a two-patch environment with one free fishing zone and one protected zone.
DeCanio et al. (2022)	The authors use a minimax-regret decision criterion in climate modeling to minimize maximum regret and reduce maximum future temperature increase to below 2 degrees Celsius with a low climate policy discount rate of 0.02.
de Frutos and Martin-Herran (2015)	The authors propose nonlinear incentive strategies for a class of differential games used in environmental economics, increasing the credible region of the optimal state path.
de Frutos and Martin-Herran (2019)	Researchers analyze a transboundary pollution differential game that investigates the behavior of agents in a large region with autonomous subregions controlling their emissions and study its implications on the design of equilibrium environmental policies.
De Luca et al. (2018)	The authors conducted a lab experiment demonstrating that scarce resources can lead users to resort to violence for resource appropriation, jeopardizing natural resource conservation.
Erdlenbruch et al. (2008)	The study shows that cooperation of agents involved in commonly-owned renewable resource use is largest for intermediate levels of heterogeneity.
Fernandez (1997)	The study utilizes an optimal control model with maximum entropy and time series observations to analyze a public wastewater treatment plant, revealing a prioritization of water quality enhancement and conventional treatment over cost minimization and pollution prevention.
Fernandez (2002)	The study presents a differential game to analyze how trade liberalization and cooperation can reduce emissions from transboundary water pollution.
Fischer and Mirman (1996)	The authors analyze a fishery model with two agents, identify a Nash equilibrium, and evaluate its efficiency.
Foudi (2012)	It analyzes the role of property rights in soil conservation and demonstrates the benefits of a modeling approach in understanding the associations between economic, biological, and ecological variables to promote sustainable agriculture.
Fresard and Ropars-Collet (2014)	The authors propose a bioeconomic model to control invasive species in the Bay of Saint-Brieuc scallop fishery.
Fujii and Karp (2008)	Researchers create software with an algorithm that finds Markov perfect equilibrium for optimal control problem and apply it to a simplified version of the climate change model to provide policy recommendations that are less sensitive to non-constant pure rate of time preference than believed before.

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Table 3 – continued from previous page

Reference	Summary
Goeschl and Perino (2007)	The study analyzes the optimal R&D trajectory in a setting where new technologies emit specific stock pollutants, showing gains from diversification due to convex damages in individual pollution stocks.
Gsottbauer and van den Bergh (2014)	Researchers develop a theoretical model for analyzing optimal environmental policies, which includes deriving rules for pollution taxes, subsidies, and taxes on advertising and information provision by the government in the case of endogenous consumer preferences that may lead to increased pollution with increased consumption norms.
Haavio (2005)	The paper evaluates the potential of imperfect household mobility as a disciplinary mechanism for policymakers dealing with interregional externalities caused by transboundary pollution.
Helm and Mier (2021)	It suggests that subsidies may be needed to address challenges faced by power systems due to the variability of renewable energy sources and reluctance by governments to impose carbon taxes.
Jaakkola (2019)	The article presents a differential game that examines the impact of an oil importer's investment in green technology on an oil cartel, resulting in a falling price ceiling and more expensive climate policy if relying on green R&D programs alone.
Janmaat (2005)	The paper presents a dynamic optimization problem for economic agents controlling renewable resources while discussing the tragedy of the commons resulting from resource dispersion and the inverse relationship between desired stock size and leakage.
Jia et al. (2018)	Game theory is applied to optimize the allocation of water resources in the Beijing Tianjin Hebei region of China due to extreme ecological events, as discussed in the article.
Jones and McDermott (2018)	The study finds that investments in urban afforestation produce lower per-planted tree net benefits than previously estimated, with nonlinear effects depending on canopy size, which highlights potential implications for urban environmental quality initiatives.
Kalkuhl et al. (2020)	The paper demonstrates that analyzing the government's objective function and the lobbying power of firms can lead to a time-consistent policy outcome in climate policy to understand stranded assets.
Kant (2000)	The study suggests that developing economies should use a dynamic optimal control model to integrate natural and socio-economic factors for continuous refinement of forest management regimes, considering the changing characteristics of user groups over time.
Kawaguchi (2003)	Authors solve the Hamilton-Jacobi-Bellman equation for optimal pollution accumulation policy using the viscosity solution method and analyze the equilibrium of the optimal pollution stock.
Kotchen and Salant (2011)	The article provides necessary and sufficient conditions for a profitable cost increase, discussing the impacts of regulatory constraints or expropriated taxes on the profits of a common-pool resource.
Krawczyk and Tidball (2006)	They present a method and incentive scheme to encourage environmentally-conscious actions in the context of seasonal competition for water levels among economic agents in nonstationary dynamic games.
Lee et al. (2018)	They analyze how profit-sharing affects the decision-making process of plantation owners and the locals in a dynamic game model considering illegal logging threats.
Lindkvist and Norberg (2014)	The study shows that learning-by-doing can achieve optimal management efficiency up to 90% compared to the optimal control solution and proposes guidelines for enhancing its effectiveness.
List and Mason (2001)	The paper explores the efficiency of decentralized versus centralized approaches for environmental regulations on transboundary pollutants in a dynamic model with asymmetric players, finding greater combined payoffs for decentralized control in certain conditions.
Lofgren and Li (2021)	The author explains the historical and modern applications of envelope theorems in economics, showing how they have been applied in a static and dynamic context and in deriving cost-benefit rules for environmental projects and extending the rules to a stochastic economic growth setting.
Marpaung et al. (2021)	The study presents a mathematical model to describe the interaction between dengue and typhoid fevers in a three-population environment and finds that the most effective strategy for controlling the spread of the diseases is one that employs all control alternatives.

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Table 3 – continued from previous page

Reference	Summary
Marten and Moore (2011)	They present a framework that integrates multiple species in invasive species management and demonstrate the benefits of combining chemical and biological controls in long-term strategies for managing the hemlock woolly adelgid.
Martin-Herran and Zaccour (2005)	The paper authors propose alternative strategies to evaluate the credibility of linear-state differential games' incentive equilibrium.
Martin et al. (1993)	Researchers employ a dynamic game framework to evaluate the effectiveness of a tax/subsidy plan in mitigating global climate change among transboundary polluters with varying attitudes.
Moberg et al. (2019)	The study explores the optimal adaptation strategies of a harvester facing changing species composition in an ecological community by considering interspecies interactions and pricing effects.
Naevdal and Skonhoft (2018)	They analyze and derive novel results on optimal management in the standard optimal control fishery biomass model, showing that there will always be an interval with low stock sizes where it is optimal not to harvest. Also, the shadow price on the fish stock always goes to infinity as the stock approaches zero.
Nagase and Silva (2000)	They analyze the acid rain problem in the European Union and highlight the socially optimal subgame perfect equilibrium of a game with decentralized leadership and information.
Nkuiya (2015)	The paper examines how countries can manage the threat of irreversible and catastrophic pollution with a dynamic game and the impact of threats on welfare.
Odom et al. (2003)	The authors develop a deterministic dynamic programming model to evaluate the efficacy and cost-effectiveness of managing environmental weeds in Australian national parks and the value of park outputs.
Palatnik et al. (2023)	They developed a framework that utilizes adaptive learning in all supply chain stages to assess investment value in a multi-stage supply chain.
Palmini (1999)	The minimax-regret decision rule based on game theory justifies the safe minimum standard constraint on economic development by incorporating risk-aversion and opportunity cost.
Pan (1994)	The article suggests a hybrid approach with economic efficiency and ecological sustainability to manage natural resources better, utilizing a resource enhancement function and optimal control model for effective implementation and discussing policy impacts.
Pereau et al. (2019)	The researchers compare models to optimize and manage groundwater policies while analyzing the factors influencing the results, including the discount factor and monetary value of the externality.
Peterson et al. (2003)	They highlight the inadequacies of traditional ecosystem management and provide recommendations for scientists to avert ecological collapse.
Pevnitskaya and Ryvkin (2022)	In their study, the authors experimentally investigate the effect of common access to clean technology and communication on the level of pollution in a dynamic game in which private production leads to a public bad, finding that both factors lead to lower pollution levels.
Rayhan et al. (2018)	A previous study presents numerical solutions obtained by using dynamic treatment rates and the Pontryagin maximum principle in modifying a tuberculosis and HIV/AIDS co-infection model for determining optimal control strategies for treatments that result in a decrease in both populations.
Rubin (1996)	The paper shows how optimal-control theory is used to prove that firms' decentralized behavior results in the most cost-effective solution for emissions trading, providing explicit solutions for emission and permit price time paths in various scenarios.
Saltari and Travaglini (2017)	The authors of the paper present an analysis of how to control social optimum with waste, abatement, and productive capital stocks, resulting in an environmental Keynes-Ramsey rule and a steady state with reduced consumption and output for abatement investment.
Saphores and Shogren (2005)	It examines optimal investment timing and expenditure for managing exotic pests using a real options framework, emphasizing the importance of accounting for uncertainty and irreversibility in developing simple pest management rules.
Schmieman et al. (2002)	They develop an optimal control model to analyze acidification and tropospheric ozone, determine efficient emission paths for pollutants, and emphasize comprehensive policies.

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Table 3 – continued from previous page

Reference	Summary
Schmiedeman and van Ierland (1999)	It analyzes the impact of dynamic soil acidification on abatement policies and identifies cost-effective strategies for reducing sulphur dioxide and nitrogen oxides, highlighting non-optimality of current European policies based on static critical loads approach.
Seifert et al. (2008)	The article proposes a model for analyzing CO ₂ spot price dynamics and suggests that CO ₂ prices may have a variable volatility structure.
Shevchenko et al. (2022)	The researchers found that adding a stochastic shock variable to the DICE model revealed that if these shocks persisted, the temperature would decrease by 0.1 degrees Celsius. In these situations, using a suboptimal policy can help achieve higher mitigation targets at lower costs.
Sirilersuang and Pongkijvorasin (2018)	Implementing both tourism promotion policies and environmental restoration policies are necessary to increase visitors and maintain water quality in Khao Laem Ya-Mu Koh Samet National Park, with a higher cost needed for restoration.
Tahvonen (1996)	The study analyzes the effects of emission taxation on nonrenewable resource extraction through a Stackelberg differential game model, showing that sellers gradually lose their monopoly power in equilibrium. In contrast, the buyers' emission tax decreases as a result.
Turner and Tschirhart (1999)	The study employs a model to demonstrate how the gap between societal welfare and GDP widens due to factors like population growth and the intrinsic growth rate of natural resources.
van Kooten (2000)	An optimal control model can determine the optimal level of afforestation in western Canada to reduce CO ₂ emissions. However, it must also consider path dynamics, and planting fast-growing trees may not be enough.
Walter (2018)	The study shows that firms collaborating in R&D in a duopoly market can reduce emissions and increase social welfare, even if a single profit-maximizing firm would not necessarily prioritize environmental concerns.
Wirl (2012)	The study examines how fossil fuel suppliers and consumers can benefit from using price instruments and taxes to combat global warming.
Wolfson and Koopmans (1996)	They argue that regulatory taxes on energy consumption in developing countries may restore sustainable technology while reducing the risk of harmful climate change and energy shortages.
Zaccour (2003)	They show that equivalent definitions of strategic strength of coalitions result in identical characteristic function values in a cooperative differential game applied to environmental economics.
Zhang et al. (2007)	The authors propose a green space calculation method and demonstrate its application to urban planning in low biodiversity areas using a case study in Shaliuhe town, Hebei Province, China.

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