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What we learn from Multi-Level Models: A Critical Review of Past, Present, and Emerging Trends

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Abstract

This paper, considering regional disparities in climate change and policy impacts, highlights the need for a multi-regional level modelling that accounts for non-identical socio-economic and environmental dynamics at the sub-national level. Through a systematic literature review, we aim to identify and summarise heterogeneous approaches and research's focus from existing literature concerning multi-level and multi-regional models used to address sustainability issues. We identify the most relevant themes, trends and topics investigated by the papers for which multi-level models have been used. While environmental and ecological issues are frequently addressed by these models, social dynamics are not particularly investigated and little to no interest is devoted to regional-national links. From the methodological perspective, most of the computational models employed utilise static systems (primarily Input-Output and CGE) and dynamic Integrated Assessment Models (IAMs). The paper provides a welcome basis for how multi-level models can contribute to addressing sustainability issues in economic research.

Indeed, national areas deal with non-identical climate shocks and are characterised by inconsistent socio-economic dynamics. Through an analysis of the current literature, of relevant papers concerning multi-level and multi-regional models, and of analyses spanning across multidisciplinary subjects, the most relevant themes, trends and topics are shown. This examination shows how social dynamics are not particularly investigated in the considered papers, and little to no interest is devoted to regional-national links. Moreover, this literature exploration highlights that most computational models employed utilise IAMs and static systems (primarily Input-Output and CGE) and that the interest concerning ecological economics related issues, has been growing in the past years.

Keywords— Sustainability; Energy Transition; Environment; Multi-level; Multi-regional; Climate Policy; IAMs, I-O; CGE; Ecological Economics

JEL: C6; Q5; Q4; R1; D6; O1

1 Introduction

Socio-economic systems are outstanding examples of "complex adaptive systems" (Giampietro et al., 2018), characterised by endless interaction and co-evolution between human societies and the ecological systems in which they are embedded. Drawing on foundational contributions in Ecological Economics (Georgescu-Roegen, 1971), this perspective emphasises that economic processes are not autonomous, but materially grounded in and constrained by biophysical processes. These systems are characterised by emergent properties, non-linear feedbacks, multi-level interactions, and historical path dependencies, all of which challenge reductionist or single-scale modelling approaches (Reinert et al., 2023). Crucially, spatial and temporal scales influence how *sustainability* is conceptualised (namely, the capacity of a system to maintain its functions over time) and how *transitions* are judged (specifically, who gains and who bears the costs during a change of state). While sustainability raises the question of durability under ecological and social constraints, transition dynamics pose inherently political questions about distribution, timing, and geographical impacts. As such, analysing socio-ecological systems requires modelling approaches that can represent the interactions, tensions, and alignments between nested levels of organisation: local, regional, national, and even global. A multilevel perspective is thus not only analytically necessary to capture the complexity of coupled systems, but also essential for informing governance mechanisms that are context-specific, adaptive, and socially just.

From an environmental viewpoint, the consequences of climate shocks are intensifying, both in frequency and magnitude, with profoundly heterogeneous spatial effects. These disruptions are not homogeneously distributed across the globe; rather, they reveal geographically specific dynamics shaped by local ecological conditions and systemic vulnerabilities. In the Arctic, for example, rising temperatures are accelerating permafrost thaw, altering hydrological cycles and releasing large quantities of methane, thus creating dangerous feedback loops (Schuur et al., 2015; Schuur et al., 2022). In the Amazon Basin, increasing temperatures and shifting precipitation patterns are contributing to forest dieback and biome destabilisation, threatening global carbon regulation (Boulton et al., 2022). Meanwhile, in the Sahel region, prolonged periods of drought and erratic rainfall patterns are driving desertification processes, reducing vegetation cover and altering regional albedo (Yang et al., 2022). In temperate regions, such as parts of Central Europe, shifts in seasonal patterns and more frequent extreme weather events (such as floods or late frosts) are disrupting long-standing ecological equilibria, with cascading effects on soil stability, water availability, and biodiversity. These spatially heterogeneous impacts underscore the need for models that can account for multi-scalar environmental processes, as well as the cross-scale feedbacks that shape the resilience or fragility of ecosystems in the context of accelerating climate change (Doblas-Reyes et al., 2021).

Beyond biophysical disruptions, the socioeconomic consequences of climate change are deeply stratified, shaped by the vulnerability, resilience, and institutional capacities of affected populations (Felice 2018). Climate shocks do not act upon a homogeneous dimension; rather, their impacts are mediated through pre-existing inequalities in wealth, access to resources, infrastructure, and governance (Islam and Winkel, 2017; Markkanen and Anger-Kraavi, 2019). As such, poorer populations (particularly in low- and middle-income countries) are disproportionately exposed to climate-related hazards while possessing fewer means of adaptation or recovery (Hallegatte et al., 2020; Rentschler et al., 2022). For instance, the increasing recurrence of droughts in the Horn of Africa has led to acute food and water insecurity, with devastating effects on pastoralist communities whose livelihoods depend on climate-sensitive ecosystems and who lack robust infrastructural or institutional buffers (Cooper et al., 2019). In contrast, in Southern Europe, prolonged heatwaves and altered precipitation patterns (such as those observed in Spain and Italy) have intensified water scarcity, reduced agricultural productivity, and increased energy demands for cooling, placing mounting pressure on public services and rural economies (Toreti et al., 2019). Even in high-income countries, climate disruptions exhibit socio-spatial asymmetries. Recent extreme flooding events in Germany and Belgium illustrate how climate risks transcend income boundaries, particularly when intersecting with infrastructural deficits or land-use legacies (Koks et al., 2021).

Within-country disparities are equally salient: in the United States, sea-level rise and saltwater intrusion pose acute threats to coastal urban centres like Miami, while inland agricultural regions such as California's Central Valley face chronic drought and aquifer depletion, endangering the livelihoods of migrant workers and small-scale farmers (Stewart et al., 2020). Similarly, in China, pronounced regional differences amplify climate vulnerability. Coastal mega-cities like Shanghai and Guangzhou are increasingly exposed to sea-level rise and typhoon risks, while the country's arid northern provinces (such as Inner Mongolia and Ningxia) struggle with desertification, water shortages, and declining agricultural output. Rural areas in western China often lack the infrastructural resilience and state support available in more affluent eastern regions, exacerbating rural-urban divides in adaptive capacity (Renaud et al., 2015; Lei et al., 2016). These examples demonstrate how climate change amplifies existing social and spatial inequalities, underscoring the need for multiscale modelling approaches that can capture the diverse interactions between environmental hazards and socio-economic vulnerabilities at local, regional, and national levels. Addressing sustainability transitions demands models that go beyond aggregate representations, recognising that policies must respond to context-specific risks and adaptive capacities rather than relying on uniform solutions that risk deepening inequality (Mercure et al., 2016).

In the current study, we aim to provide a comprehensive critical review of the existing literature on multi-system, multi-scale and multi-dimensional modelling for sustainability transitions, identifying the key themes addressed, methodologies applied, and their respective strengths and limitations. We seek to outline future directions for the development of more refined modelling approaches capable of dealing with spatial heterogeneity and social complexity. We also draw on the lens of *Post-normal Science* (Funtowicz and Ravetz, 1990; Kvacic and Funtowicz, 2024), which advocates for the inclusion of "extended peer communities" and transdisciplinary knowledge in addressing high-stakes, uncertain, and value-laden problems such as sustainability transitions (Pereira and Saltelli, 2017). While the integration of societal actors into model development and policy design is desirable, we also acknowledge the real-world constraints: data availability, limited time for participatory processes, divergent priorities among stakeholders, and the growing computational demands of complex, spatially explicit models. These challenges highlight the trade-offs and methodological decisions that must be confronted to make multiscale modelling both scientifically robust and socially relevant (Accetturo et al., 2022).

This paper is structured as follows. Section 2 introduces the main concepts of multi-level models, focusing in particular on how sustainability challenges and climate-related impacts are addressed within these frameworks. In order to ease the review, we complement the analysis with the list of abbreviation in the Appendix (Table A.1). Section 3 outlines the methodology employed for the literature review, including the data sources and criteria used for selecting and analyzing relevant studies. Section 4 presents the main results, identifying key trends, thematic focuses, methodological approaches, and knowledge gaps in the existing literature. Finally, Section 5 offers concluding reflections and suggests future directions for developing models better equipped to address the multi-dimensional and multi-scale nature of sustainability transitions.

2 Theoretical concepts and current models

Understanding and governing sustainability transitions requires models capable of capturing the inherent complexity of socio-ecological systems. In this context, three intertwined concepts have gained increasing relevance: multi-dimensional, multi-scale, and multi-system models. *Multi-dimensional* models aim to go beyond purely economic variables by incorporating environmental, social, institutional, and cultural dimensions of change, reflecting the plurality of values and objectives involved in transitions by respecting planetary boundaries (Raworth, 2018; Finstad and Andersen, 2023; O'neill, 2024). *Multi-scale* models address the fact that sustainability challenges unfold across both temporal and spatial hierarchies where local, regional, national, and global dynamics interact in non-linear and path-dependent ways (Aragão and Giampietro, 2016). In our review, we primarily focus on *spatial* scales, particularly the often-overlooked subnational level, where policy interventions are implemented and experienced (Distefano et al., 2025). *Multi-system* models, finally, are those that explicitly represent interactions between distinct but interdependent systems—such as energy, food, land, water, and social systems (whose feedbacks shape transition dynamics and trade-offs) (Löhr and Chlebna, 2023). The System of Systems (SoS) approach has a long tradition, and it is a problem-solving methodology first elaborated by engineers and management scientists (Raz et al., 2024). This approach recognises that changes or interventions in one subsystem can have cascading effects on others, thus calling for a systemic perspective (Sterman, 1994; Schot and Kanger, 2018). These concepts reflect an emerging paradigm in sustainability science that rejects oversimplified, reductionist approaches in favour of integrative frameworks. They also highlight the need for policy-relevant models capable of representing spatial diversity, systemic inter-dependencies, and the plurality of development pathways in the face of accelerating environmental change (D'alessandro et al., 2020; Andersen and Geels, 2023).

To further broaden our research and include as many papers as possible, while remaining coherent with the purpose of this article, we gather both terms (multi-dimensional and multi-scale) under the umbrella term "multi-level". As described by Giampietro and Mayumi (2000) multi-dimensional and multi-scale modelling approaches are often referred to as *"multilevel integrated analysis"*. Hence, again, *multi-level* in this paper is used as an overarching category encompassing these concepts. When necessary, we will specify which of these dimensions is being explicitly addressed. These models have fallen under the Integrated Assessment Models (IAM) category, therefore, throughout this work, and in our query, we will refer to these models as IAMs.

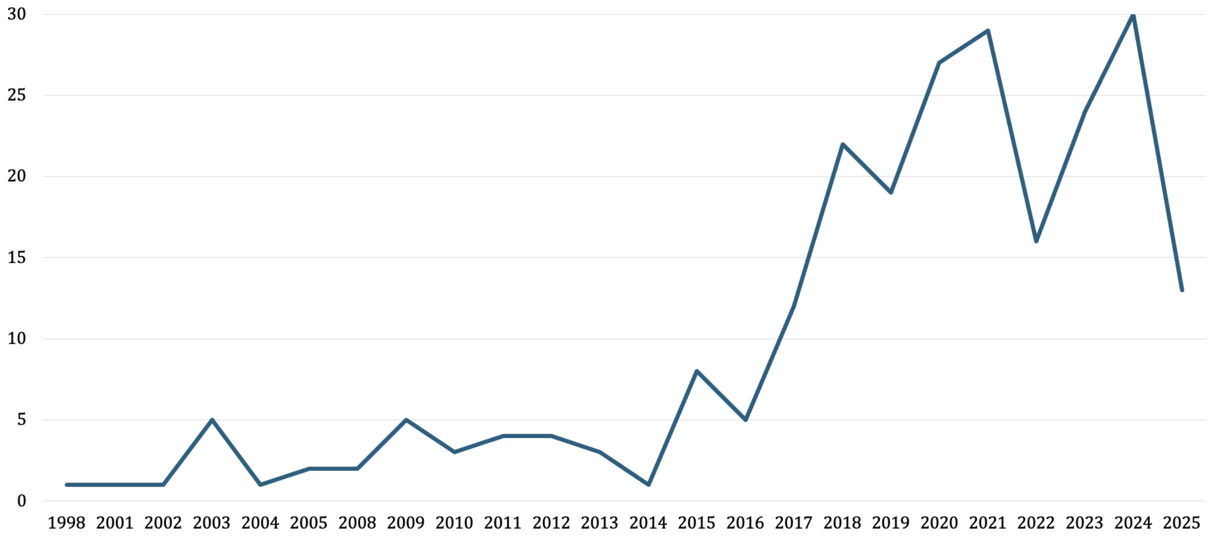

Figure 1: Number of works per publication year.

Source: Authors' elaboration based on WoS.

Figure 1 illustrates the temporal evolution of the selected publications of the types of *multi-level* models developed over time, revealing a rapidly expanding discipline, particularly over the past decade. Three distinct phases in the development of multi-level modelling applied to socio-environmental issues can be identified. The first, a "latency phase" (1998–2008), is characterised by a very low number of publications, typically no more than one or two per year, except for 2003. This suggests that the field was still in its embryonic stage, marked by pioneering but sporadic contributions and the absence of a consolidated research community. This is followed by an "initial growth phase" (2009–2016), during which the number of studies increased more consistently. This period likely reflects the progressive establishment of methodological foundations and the growing recognition of multi-level as well as IAMs models as effective tools for tackling complex sustainability challenges. The most recent “acceleration phase” (2018–2025) has seen a marked surge in academic output, with publication peaks in 2020, 2021, and a record high in 2024. This sharp rise can be attributed to several converging factors: the mounting urgency of global challenges such as climate change (Haunschild et al., 2016; Santos and Bakhshoodeh, 2021), growing access to high-resolution and sub-national data, and advancements in computational capabilities that have made these models increasingly accessible and scalable (Li et al, 2024).

In terms of modelling techniques, the early years (pre-2010) were dominated by Computable General Equilibrium (CGE) models, post-evaluation approaches such as Difference-in-Differences (DiD) and spatial regression analysis. From the early 2010s onwards, however, the field has undergone notable methodological diversification (see Figure 2). Multi-Regional Input-Output (MRIO) models, including advanced variants such as Multi-Scale MRIO (MSMRIO) and Multi-Scale Geographically Weighted Regression (MGWR), have become increasingly prominent. This shift reflects growing awareness of the global interconnectedness of supply chains and the need to trace embodied environmental impacts through international trade, such as carbon, water, and material footprints (Miller and Blair, 2022).

This diversification has also contributed to the fragmentation and renewal within the broader family of IAMs, originally developed to integrate environmental and economic dynamics across systems. In their early iterations, IAMs were dominated by mainstream approaches, most notably the DICE model developed by Nobel Laureate Nordhaus (1993), which sought to translate environmental impacts into monetary terms for cost-benefit analysis.

These models have been widely criticised for their reductive assumptions, especially in valuing ecosystems and long-term climate damage (Stern, 2007; Pindyck, 2017).

The DICE model and the "neo-classical" IAMS model, for example, assume that climate-related damages are solely represented by a simplified function that links global warming to a decline in global GDP. This implies that climate impacts are translated exclusively in terms of loss of aggregate economic output, ignoring multiple social and ecological dimensions (Kalkuhl and Wenz, 2020). Moreover, these models assume that environmental losses and damages can be compensated by an increase in capital availability or economic efficiency, implying perfect substitutability between natural resources and economic production factors. Lastly, these models also assume gradual and linear climate impacts. Climate impacts are, therefore, globally homogeneous and do not include tipping points or spatial variability. Given these assumptions, ecosystems, biodiversity, but also more quantifiable measures as gender inequalities as well as income inequality, are not specifically quantified (Rao et al., 2017; Safarzyńska and van den Bergh, 2022)

In response, an alternative and increasingly influential field has emerged under the label of Ecological Macroeconomics (EM) (Victor, 2023).

EM introduces a more comprehensive treatment of socio-ecological interactions by combining Environmentally Extended Input-Output (EEIO) frameworks—grounded in national accounting—with Stock-Flow Consistent (SFC) modelling to incorporate financial and material constraints, and System Dynamics (SD) to capture feedback loops, delays, and nonlinear dynamics across levels (Hardt and O’Neill, 2017). As shown in Figure 2, the number of EM publications has grown significantly since 2015, highlighting its rising relevance and adoption across multiple disciplines. Together, these developments point to two complementary trends: *specialization*, as modelling tools are increasingly designed to address specific research questions and contexts; and *hybridisation*, reflecting a growing effort to bridge different epistemological and disciplinary approaches to more accurately represent the complex, multi-level dynamics of socio-ecological systems.

In recent years, *specialization* has been developed by scholars with the purpose of tackling precise challenges (climate finance, resource depletion, or inequality). For instance, ABMs have been tailored to simulate household energy consumption (Castro et al., 2020) and low-carbon behaviour (Lamperti et al., 2019), while spatially explicit EEIO frameworks are employed to assess regional environmental footprints (Jiang et al., 2020). This trend responds to critiques of "one-size-fits-all" models, acknowledging that socio-ecological systems require context-specific tools to capture localised feedback (D'Alessandro et al., 2020), institutional constraints, or behavioural heterogeneity.

On the other hand, *hybridisation*, has been emblematic concerning how scholars aim to integrate different methodologies across disciplines to overcome single-approach limitations. SFC models, tracking financial stocks and flows, have been paired with EEIO models to consider biophysical constraints, allowing for a more precise analysis of the interaction between monetary policies and ecological thresholds (Jackson and Victor, 2020). Similarly, SD has been combined with network theory to capture cascading disruptions in supply chains or ecosystems (Ghadge et al., 2021).

Therefore, the interplay between *specialization* and *hybridisation* is particularly beneficial and synergistic. On one hand, specialised tools provide granular insights, while on the other, hybrid frameworks embed them within broader systemic interactions. For example, climate-economy models like EUROGREEN merge SFC macroeconomic structures with ecological modules while allowing sector-specific refinements (Distefano and D'Alessandro, 2023).

3 Methodology and Data

The construction of the sample of scientific articles for this analysis was based on a rigorous, transparent and multi-stage selection process, aimed at identifying the most relevant contributions in the field of multi-regional and multi-level modelling. This process is inspired by established bibliometric methodologies. Indeed, the lexical analysis methodology, supported by IRAMUTEQ, is well established in textual data processing (Camargo and Justo, 2013; Ratinaud and Déjean, 2009). This approach relies on lemmatisation and statistical clustering techniques (Reinert, 1990) and has been widely applied in systematic literature reviews (Ramos et al., 2018). Our process was designed to ensure not only the consistency and relevance of the analysed body of literature, but also the replicability of our research procedure (see Table[1] 1).

Table 1: Steps employed to select the relevant literature.

Step	Description	Key decision
1	Initial search on Web of Science (WoS)	Multi-regional/Multi-level keywords
2	Filter by model type (e.g., CGE, I-O, IAM)	Focus on relevant architectures
3	Filter by topic (e.g., climate, sustainability)	Excluded irrelevant subjects
4	Preliminary sample (∼12,000 articles)	Confirmed interdisciplinarity
5	WoS category filter (e.g., economics, environment)	Reduced articles available
6	Manual abstract screening	Ensured thematic consistency
7	Applied inclusion criteria (3 requirements)	Rigorous selection
8	Full-text review for uncertain cases	Guaranteed alignment with goals
9	Final sample (238 articles)	Basis for lexical analysis

Our primary source of data is the Web of Science (WoS) database, selected for its broad interdisciplinary coverage, its indexing of high-impact scientific journals, and its widespread international use as a standard for evaluating research output across disciplines. This choice ensures a solid and recognised foundation for our dataset. The decision to only employ WoS as a database, while not considering Scopus nor the grey literature,

[1] This table breaks down the nine steps we employed to finalize the corpus of literature used for this literature review. Starting with an initial search on WoS, applying filters by model type and topic, and ending with a final sample of 238 articles after rigorous screening and review. Key decisions at each step ensured interdisciplinary relevance and thematic consistency.

was guided by methodological rigour and supported by bibliometric research. Mongeon and Paul-Hus (2016) showed that WoS and Scopus largely overlap in core journals, with Scopus adding mainly niche publications less relevant to the study of established multi-level modelling methodologies. The stringent selection criteria characterising WoS (Martín-Martín et al., 2018) ensure the high-quality, peer-reviewed focus essential for our analysis of modelling techniques. Grey literature was excluded following Mallet et al. (2016) and PRISMA guidelines (Page et al., 2022), as our review of methodological approaches prioritises peer-reviewed studies with documented rigour over broader but less standardised sources. However, we acknowledge certain limitations of this source: the WoS database includes only contributions published in WoS-indexed journals and excludes publications in books or other languages (Merli et al., 2018; Vadén et al., 2020). Our dataset comprises a selection of articles collected by WoS and published in international scientific journals between 1998 and 2025. The first selection goal was to gather a wide range of potentially appropriate articles. The research methods were conceived to include as many works as possible to minimise the risk of excluding potentially relevant papers. A detailed topic search has been performed within the WoS database, strategically combining different keywords to maximise papers coverage. This search strategy has been developed on two intertwined conceptual levels, providing a solid starting base.

The first step aimed at identifying the relevant methodological approaches. To do so, the employed terminology used the following words: "multi-regional" and "multi-level".[2] These terms were chosen because they represent the conceptual core of our investigation, allowing us to capture the spatial dimension and integration between different scales of analysis (from local to global scale), a central aspect of our study. The second conceptual step was aimed at specifying both the most popular model architectures and their main application areas. The first of these two layers was indeed conceived to search and highlight the most common models[3] employed in the climate change-related multiregional analysis, and the input words were (Table 2).:

- "Input-Output",
- "CGE" (Computable General Equilibrium),
- "GCAM" (Global Change Analysis Model),
- "Globiom" (Global Biosphere Management Model),
- "Partial Equilibrium",
- "Agent-Based",
- "System Dynamic".

This selection represents the state of the art in economic and environmental modelling, covering a range from structural macroeconomic models to bottom-up models that simulate individual behaviour (Doole and Pannel, 2013; Barkalova et al., 2017; Drechsler at al., 2022; Nuzi, 2023; Solano-Pereira et al., 2025). The third step, instead, aimed to analyse the relevant topics, hence the chosen words were:

- "Climate Change",
- 'Land Use",
- "Water Use",
- "Biodiversity, Environment",

[2](To avoid missing data we also considered their plausible variations such as "multiregional" and "multilevel" or "multi regional" and "multi level", and similia.

[3]All models acronyms have been included in the appendix, Table A.1.1

- “Sustainability”,
- “Biodiversity”.

These topics were chosen for their undisputed relevance in the contemporary scientific and political debate related to the challenges of sustainability (Tomislav, 2018; Kraft, 2021). The same process was then applied for IAM modelling.[4] This term was then coupled with the most relevant IAM models (Weyant, 2017) and models resulting from broader research that paired "IAMs" and "Ecological Macroeconomics" as per Table 3. The combination of these keywords (Table 2) made it possible to construct a comprehensive and inclusive search query. This initial phase produced a large preliminary sample of around 12,000 scientific articles. This large number, while confirming the breadth and interdisciplinary nature of the topics covered, made subsequent refinement stages essential to isolate the truly relevant contributions. Given the heterogeneity and the size of the initial sample, an initial systematic filtering process was necessary to narrow down the field to the studies most relevant to the objectives of our research. We applied a filter based on the disciplinary categories defined by Web of Science (WoS Fields). This strategic choice allowed us to efficiently exclude entire bodies of literature that, although using homonyms of our keywords, belonged to irrelevant scientific contexts. For example, physics articles on non-linear “system dynamics”, or marketing works on “multi-level” were eliminated. Hence, the categories selected for our scope of investigation were: “Environmental Studies,” “Ecology,” “Environmental Sciences,” “Economics,” “Development Studies,” “Business Finance” and “Business” (Table **??**).

Table 2: Selection criteria employed to select the relevant literature.

Selection criteria	Description
Methodology	Multi-level; Multi-regional
Model employed	Input-Output; CGE; GCAM; GLOBIOM; Partial Equilibrium; Agent-Based; System Dynamics
Relevant topics	Climate Change; Land Use; Water Use; Biodiversity; Environment; Sustainability
WoS Fields	Environmental Studies; Ecology; Environmental Sciences; Economics; Development Studies; Business Finance; Business

Source: Authors’ elaboration based on WoS.

[4]The acronym "IAM" was used along with its plausible variations ("IAMs", "Integrated Assessment Modelling", "Integrated Assessment Model", "Integrated Assessment Models").

Table 3: Selection criteria employed to select the relevant IAM literature.

Selection criteria	Description
Methodology	IAM
Model employed	Ecological Macroeconomics; MEDEAS; WILLIAM; EUROGREEN; GEMMES; DICE; RICE; IF (International Future); WORLD-3; C-ROADS; MINICAM; PGCAM; ICAM; GCAM; Imagine 1.0; Imagine 2.0; ESCAPE; TARGET; AIM; MERGE; SFC; TIMES; E3; HUBBERT; AIM; FUND; UKIAM
Relevant topics	Climate Change; Land Use; Water Use; Biodiversity; Environment; Sustainability
WoS Fields	Environmental Studies; Ecology; Environmental Sciences; Economics; Development Studies; Business Finance; Business

Source: Authors' elaboration based on WoS.

The application of these filters significantly reduced the number of articles, focusing on those published in academic journals central to the debate on economics, environment and sustainable development, and ensuring greater thematic coherence of the sample to be analysed. The final step of the selection process was the most qualitative, intensive and crucial. In this stage, we carried out a careful review of all articles resulting from the previous stage. The abstract was used as the first and fundamental indicator of a paper's relevance. In all cases of uncertainty or when the abstract did not provide sufficient information, the article was read selectively or in full to determine its actual adherence to our criteria. To be included in the final sample, each article had to simultaneously and unequivocally meet the following three inclusion criteria: i) the papers must mention one or more defined models, ii) the study must focus on the linkage between regional and national scales, and iii) the papers must include socio-economic dimensions within their definition of multi-level. More precisely, the first criterion required the publications to be based on a well-structured, explicit and recognisable quantitative analysis model (e.g. CGE, MRIO, IAM etc.). This criterion was crucial to exclude purely theoretical articles, unsystematic literature reviews[5], or papers that mentioned models only marginally without any actual empirical application. The aim was to focus on research that produced quantifiable and replicable results. Whereas for the second, the study had to analyse the impact of a certain phenomenon (e.g. a policy change, a climate event) in at least one specific geographical region. This criterion ensures the policy relevance of the selected works, as policy decisions require an understanding of impacts at different territorial scales. Lastly, the third criterion implies that for studies adopting a so-called "multi-level" approach, the selection required the analysis not to be limited to the economic or biophysical dimension alone. Explicit integration of social dimensions (e.g. distributional impacts on income inequality, changes in employment by sector or qualification, effects on household welfare or food security) was required. This criterion ensured that the concept of "multi-level" was interpreted in a broad and holistic sense, covering the different spheres of sustainability as defined by international agreements. This meticulous "funnel" review process resulted in a drastic but necessary reduction in the number of articles. The final selection resulted in a corpus sample of 238 articles. This corpus sample, although numerically small, is highly selected and forms the solid empirical basis upon which the entire analysis conducted in this paper is based (Table 3).

[5] Systematic literature reviews have been included when they matched the three criteria aforementioned.

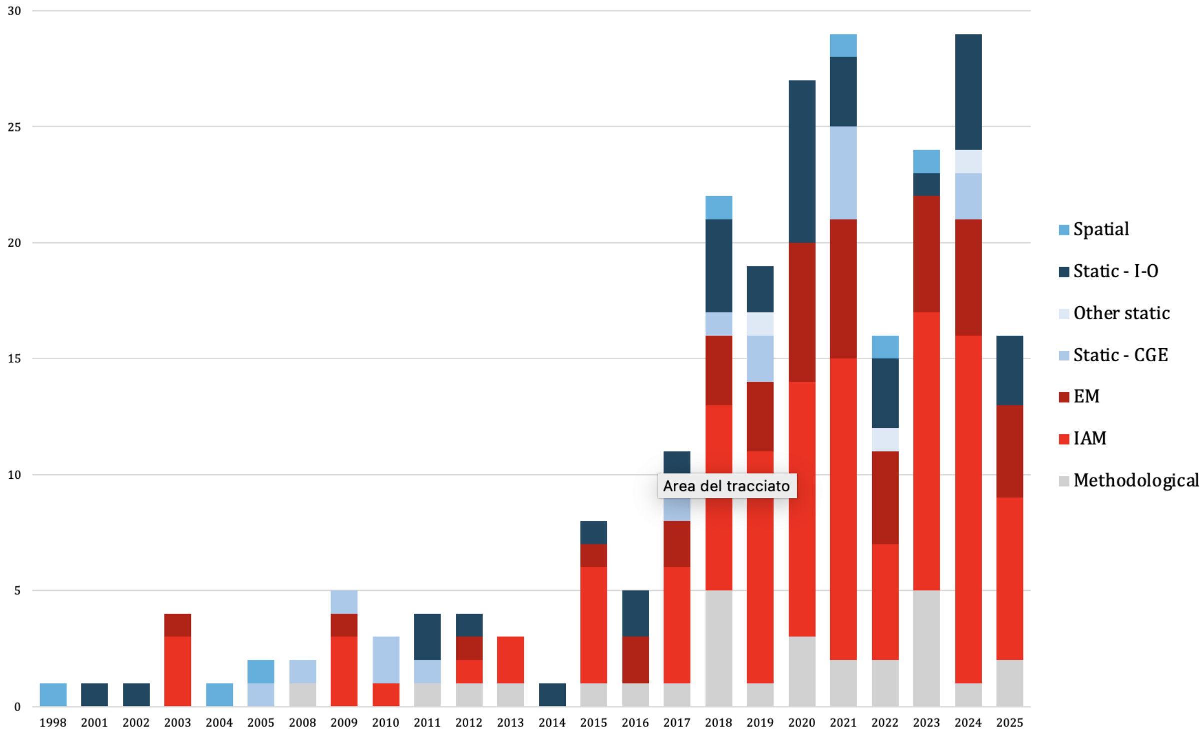

Figure 2: Models employed in the analysed sample's annual evolution and publication year. In this figure, models are divided into seven categories. 1. Spatial refers to spatial regression analysis and includes papers using *Spatial Regression* and *Multi-scale Geographically Weighted Regression*. 2. Static - I-O refers to Input-Output models and includes *Environmental Extended Input-Output* analysis and *multi-regional and multi-scale Input-Output*. 3. Other static refers to other models that are not included in the "Spatial", "Static - I-O" and "Static - CGE", categories and includes *Global-to-Local-to-Global* and *Difference-in-Difference*. 4. Static - CGE, similarly, includes *Computable General Equilibrium* and *Partial Equilibrium*. 5. Ecological Macroeconomics includes *Stock Flow Consistent, System Dynamics, WILLIAM, WORLD-3, C-ROADS, E3, EURO-GREEN, MEDEAS and lastly MERGE.* 6. IAMs refers to neoclassical models: *RICE, TIMES, UKIAM, Agent-Based Models, AIM, DICE, FUND, GCAM, GLOBIOM, GROWTH, GUIDE, HUBBERT, IAM CGE, International Future, IMAGINE 1.0 and IMAGINE 2.0*. 7. Lastly, methodology refers to those papers addressing a literature review of a few models, highlighting the advantages of the considered models. *Source: Authors' elaboration based on WoS.*

4 Results

As mentioned, the sample selection provided 238 papers out of which 55 employ static models while 183 use IAMs.

A comprehensive analysis of this result reveals several dominant thematic patterns while highlighting the existence of gaps regarding multi-level dynamics and social dimensions.

In the 55 articles employing static models MRIO and CGE are the most used modelling techniques, as 36 papers (65%) use these frameworks. These works, although methodologically sound, mainly adopt top-down perspectives and only 22% (12 papers out of 36) incorporate cross-scale interactions between local, regional, and national levels (Palazzo et al., 2017; Hertel et al., 2019; Sheykhha et al., 2022; Chen et al., 2023; Zhang et al., 2023; Rum et al., 2024 and others). The remaining 24 papers address social or institutional factors, though often as secondary considerations rather than central analytical components, and do not fully integrate social dynamics into the economic-environmental modelling (Diaz-Maurina et al., 2018; Sjöstrand et al., 2018; Buchhorn et al., 2023; Palm et al., 2019 and others).

An interesting result is found regarding scale integration. While 41 papers (75%) claim multi-level analysis, only 9 studies (16%) operationalize this through explicit modelling of feedback mechanisms across scales. Amongst these 9 works, for instance, Palazzo et al. (2017) and Hertel et al. (2019) stand out as exceptions by systematically linking local stakeholder inputs with global economic models. The majority of the studies instead employ parallel multi-scale assessments, yet they do not model inter-scale dynamics, de facto generating what could be called "multi-scale illusion", the appearance without the substance of true cross-level integration.

The results concerning treatment of social dimensions are equally interesting. Just seven papers include substantive social variables beyond aggregate employment statistics (Dubina et al., 2017; Garaffa et al., 2021; Yuan and Wang, 2021; Holscher et al., 2022; Chen et al., 2023; Zhang et al., 2023; Cunico et al., 2024). In this group two works stand out: Chen et al. (2023) demonstrates the potential of integrating migration data with economic resilience analysis, while Zhang et al. (2023) innovatively captures community perceptions of ecosystem services. However critical social factors including institutional arrangements, distributional impacts, and cultural contexts are yet underdeveloped in the analysed literature.

IAM models show a wide employment of "macro top-down" approaches (50% of analyzed IAMs publications). This trend consolidates a tradition of research focused on macroeconomic consistency and aggregate policy analysis, well represented in a vast body of the analyzed literature (Liu et al., 2018; Ciarli et al., 2019; Delzeit et al., 2020; de Bortoli et al., 2025). This approach, though correct in its own right, tends to largely ignore economic agents' heterogeneity and local systems complexity, hence they risk to fail to coordinate on rational equilibrium outcomes (Kaplan and Violante, 2018; Hommes, 2021).

On the other end of the spectrum "bottom-up approaches" are also represented. An emblematic example is showcased by ABM modelling. ABMs have been developed expressly to overcome the aforementioned limitations (Kukacka and Kristoufek, 2020). The fundamental added value of ABMs lies in their ability to represent a world populated by heterogeneous agents. Unlike CGE models, which are based on "representative agents" (e.g. a single consumer or a single company representing the industry average), ABM models simulate an ecosystem of individual and diverse actors (Hertel et al., 2019; Yilmaz et al., 2019; Bourceret et al., 2021; Wu et al., 2024). However, the strength of ABMs is also their greatest weakness. Their abundance of detail at the micro level makes it extremely difficult to "scale up", hence, to link local dynamics robustly and coherently with economic and institutional structures at the macro level (Lippe et al.,2019; Niamir et al., 2020). Indeed, many selected articles are based as standalone case studies.

However, social dimension dynamics investigations, still appear to be largely superficial. Only a quarter of studies (26%) go beyond the inclusion of standard economic variables to venture into a deeper social analysis

(Garaffa et al., 2021; Holscher et al., 2022; Cunico et al., 2024 and others). Even when included, the social dimension is often limited, although there are important contributions that attempt to overcome this limitation (Ciarli et al., 2019; Lippe et al., 2019; D'Alessandro et al., 2020; Distefano et al., 2023;O'Neill et al., 2024). However, institutional arrangements, norms, power relations and structural inequalities, remain almost always absent from the field of analysis.

Furthermore, this brief review of the analysed literature remarks, as it will later be shown, two main limitations. First, the predominant methodological nationalism, as many works take the nation-state level as the primary and, sometimes only unit of analysis. Even when examining regional phenomena, although, some inter-regional analysis are performed (table 4), the majority of work mainly employ a unitary dimension approach that can either be at urban, provincial or regional level, yet lacks the multi-scale hierarchical dynamics between these jurisdictional levels. Secondly, the persistent disconnect between economic and social analysis leaves critical questions about policy impacts on vulnerable groups unanswered. Hence in this section, the results from the analysis of the selected body of scientific literature are presented and discussed. The methodological approach is twofold: first, the semantic and conceptual structure of the papers is explored through an advanced textual analysis, with the aim of mapping dominant themes and identifying significant gaps. Secondly, a deep analysis is conducted to trace the quantitative models employed. The integration of these two perspectives offers a comprehensive and critical view of the field of study, highlighting not only what the literature has investigated, but also, and more importantly, what it has been overlooked, being the most delicate and critical finding (Heymans et al., 2019).

4.1 Lexicographical analysis of the corpus: emerging themes and semantic gaps

In order to investigate the internal structure of the scientific discourse in our sample of studies, the software IRAMUTEQ was employed. This allows statistical analysis techniques to be applied to textual bodies (Jungell-Michelsson and Heikkurinen, 2022; Haynes and Alemna, 2022). Two complementary techniques were employed: Descending Hierarchical Classification (CHD) to identify thematic clusters and similarity analysis to visualise the network of interconnections between the most significant lemmas. CHD, (Reinert 1980, 1983), is a clustering method that performs a progressive partition of the text corpus into thematically homogeneous and maximally differentiated clusters. The algorithm analyses the co-occurrence of lemmas (basic forms of words) within homogeneous text segments, clustering segments that share a similar and statistically significant vocabulary. The result is a dendrogram that visualises the hierarchical relationship between clusters, showing how the corpus breaks down into macro-themes and then into more specific sub-themes. The analysis of our corpus produced a stable and robust classification, dividing 98.1% of the text into five distinct clusters, as illustrated in the dendrogram (table 4). The first and most fundamental division of the corpus separates cluster 4 and 5 from all others, highlighting a primary distinction between research centered on climate targets, mitigation pathways and technological–economic assessments. The remaining four classes are further divided into two sub-groups: one (clusters 1 and 2) dealing with governance, adaptation, and spatial and regional assessments, and another (cluster 3) purely methodological.

Table 4: CHD Dendrogram and relevant cluster identified

Table 4

Spatial analysis and regional assessment	***Governance and socio-environmental management***	***Methodological framework and IAMs***	***Climate targets and mitigations pathways***	***Energy systems and economic impacts***
15.1%	**13.8%**	**29.9%**	**18.0%**	**23.2%**
Cluster 1	**Custer 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**

Table 4: CHD Dendrogram and relevant cluster identified

Table 4

Regional	*Sustainable*	*IAM*	*Degree*	*Growth*
Multi	*Socio*	*LCA*	*Emission*	*Baseline*
Spatial	*Adaptation*	*Framework*	*Target*	*RE (Renewable Energy)*
CGE	*Management*	*Integrate*	*Paris*	*Fuel*
Land	*Governance*	*Approach*	*Temperature*	*Coal*
China	*Institutional*	*Indicator*	*Mitigation*	*GDP*
National	*Development*	*Uncertainty*	*Limit*	*Income*
MRSUT	*Ecosystem*	*Complexity*	*Carbon*	*Fossil*
Interregional	*Transformation*	*Quantitative*	*Pathway*	*Consumption*
Urban	*Environmental*	*MEDEAS*	*Budget*	*CCS*
Provincial	*Climate*	*Develop*	*Overshoot*	*Solar*
I-O	*Economic*	*Dynamic*	*CDR*	*Storage*
MRIO	*Challenge*	*Recommendation*	*Co2*	*Wind*
Trade	*Research*	*Advance*	*NZE*	*Power*
Municipality	*Transformative*	*Climate*	*NOx*	*Employment*
Grassland	*Finance*	*Policy*	*GHG*	*Scenario*
Flow	*Intervention*	*Flexibility*	*Reduction*	*Revenue*
Cultivate	*Cooperation*	*modelling*	*IAMs*	*Health*
				PM2

Source: Authors' elaboration based on WoS and elaborated with IRAMUTEQ.

4.1.1 Cluster 1: Spatial analysis and regional assessment

This cluster represents the 15.1% of the sample and it is characterized by a spatially and application-oriented vocabulary. It includes terms such as “regional”, “multi”, “spatial”, “land”, “national”, "interregional", "urban", "provincial", "municipality", "China","I-O" "MRIO", "MRSUT", "CGE", "trade" and "flow". It reflects studies adopting regional or sub-national approaches for environmental and economic assessments, often employing MRIO models or referring to specific case studies, particularly in China. The simultaneous presence of terms such as "I-O", "MRIO", "trade", and "flow" indicates a focus on economic interdependencies and material and energy flows between regions, while words such as "land", "cultivate" and "grassland",imply a strong connection with land use and agriculture, often in relation to bioenergy and territorial impacts. The inclusion of CGE suggests that some of this literature integrates spatial analysis with general equilibrium approaches. However, this cluster appears more oriented towards empirical application than towards methodological integration with complex IAM frameworks, and it lacks explicit consideration of scenario-building, uncertainty analysis, or the social distribution of impacts at the local level.

4.1.2 Cluster 2: Governance and socio-environmental management

This thematic cluster captures 13.8% of the total sample and focuses on institutional and policy-oriented lexicon. The dominant headwords are “sustainable”, “socio”, “adaptation”, "governance", "institutional" "management","transformation", "ecosystem", "climate", "finance", "intervention" and “cooperation”. It represents research focusing on governance and climate adaptation, describing environmental management practices and institutional processes that enable or hinder sustainability transitions. This cluster captures conceptual and normative discussions on policy design, institutional dynamics, and the policy instruments available to public authorities and territorial stakeholders, whilst maintaining qualitative policy analysis rather than quantitative modelling, as no models are mentioned. Once again, there is little integration with scenario-based or parameterized modelling, and the social distribution of climate impacts (across income groups, genders, or vulnerable populations) remains largely absent. The occurrence of the term "sustainable" is particularly significant, as it positions this body of work firmly within the broader sustainability discourse, indicating an explicit concern with long-term environmental, social, and economic viability. Similarly, the presence of "socio", typically used as a prefix in expressions like socio-economic or socio-environmental, suggests an awareness, at least at the conceptual level, of the interdependencies between human systems and environmental change. Nevertheless, in the current literature, this integration remains rare. The emphasis on sustainability and socio-economic considerations does not typically translate into formalised, scenario-based, or parametrised modelling exercises.

4.1.3 Cluster 3: Methodological frameworks and IAMs

Cluster 3 covers 29.9% of the total analyzed sample, making it the major cluster. It includes terminology associated with IAMs and methodological frameworks such as: "IAM", "LCA", "framework", "integrate", "approach", "modelling", "indicator", "uncertainty", "complexity", "quantitative". This set of terminology represents methodological literature on IAMs, with references to specific platforms, frameworks such as MEDEAS and database as LCA. I also includes discussions of uncertainty, parametrization, and complexity. This cluster constitutes the conceptual core where the design, articulation, and interpretation of integrated models are defined. In this cluster, even though uncertainty and parameter sensitivity are well represented, there is less evidence of equity metrics and socially disaggregated modelling modules which might suggest that in the analyzed works socially comprehensive analysis of climate policy has not been prioritized.

4.1.4 Cluster 4: Climate targets and mitigation pathways

Cluster 4, which comprises 18.0% of the corpus, is centered on the terms concerning policy objectives and goals. For example "degree", "emission", "target", "Paris", "temperature", "mitigation", "limit", "carbon", "pathway", "budget","overshoot", "CDR" (Carbon Dioxide Removal) "CO2","NZE" (Net zero Emissions), "GHG". It represents the literature that translates international climate goals—such as those in the Paris Agreement—into carbon budgets and emission-reduction pathways. Analyses here address both quantitative aspects, such as cumulative carbon budget calculations, and the technological and policy strategies required to meet these goals, including CDR and overshoot scenarios. Although IAMs are the main tools for generating such pathways, there is less systematic use of CGE or I-O models to evaluate the economic and distributional implications of these trajectories. However, the works mainly address macroeconomic consequences of these policies implication. Nevertheless, the discussions of the material, territorial, and social sustainability of proposed mitigation solutions are marginal, and the distributive consequences of climate policies are rarely addressed.

4.1.5 Cluster 5: Energy systems and economic impacts

This fifth and last cluster encompasses 23.5% of the analyzed sample and focuses on energy systems, technologies, and economic effects. The CHD analysis highlights the following words: "growth", "baseline", "renewable energy", "fuel", "coal", "GDP", "income", "fossil","consumption", "ccs" (Carbon Capturing and Storage), "solar", "storage", "wind", "power", "employment", "scenario", "revenue", "health" and "pm2". This research also addresses co-benefits such as air pollution reduction and macroeconomic effects, measured in GDP or employment terms. The recurrent appearance of the term employment is noteworthy, as it indicates that IAMs models (while predominantly focused on economic aggregates) do incorporate labour market effects into their projections. This suggests an entry point for a broader treatment of social dimensions within these modelling frameworks. However, the consideration of employment remains largely tied to its role as an economic variable, serving as a proxy for macroeconomic performance rather than as an indicator of labour conditions, job quality, or regional and sectoral disparities in employment outcomes.

4.1.6 Comments on clusters results

The analysis of these five clusters reveals a clear and well-defined thematic structure. Indeed, the dendogram highlights two major semantic categories. The first encompassing clusters 1, 2 and 3 is more oriented towards methodological institutional and territorial analysis. The proximity between the methodological cluster and the governance/adaptation cluster indicates that much of the methodological literature explicitly discusses policy implications and management tools, while the spatial/territorial cluster is positioned slightly more peripherally, serving as a concrete application of broader frameworks. The second (clusters 4 and 5) focuses on climate targets and mitigation scenarios and strongly intertwines with technologies and their economic impacts. This division suggests a clear division between research that develops and discusses models and their policy relevance, and research that applies these models to define climate objectives and assess technological options.

Despite the wide range of topics covered by the corpus and the particular attention devoted to climate targets and mitigation strategies and their alignment with international agreements, as well as technological and economic assessments (particularly of the energy sector), the social dimension of sustainability appears relevantly lacking. Apart from few terms, as "socio" in cluster 2, key terms for the analysis of inequality and social welfare are systematically missing. Words such as inequality, GINI index, distribution, social welfare or equity (Clench-Aas et al., 2018; Barbalat and Frank, 2020; Bilan et al., 2020) do not emerge in the vocabulary of the corpus. These omissions are not trivial. It suggests that the literature analysed, although methodologically sophisticated in integrating regional and economic dimensions, tends to treat “society” as a homogeneous entity or, at best, is limited to aggregate indicators such as GDP or total employment (as per cluster 5). There is a lack of structured reflection on the distributional impacts of environmental and economic policies, e.g. on how the costs and benefits of these policies are distributed among different social groups, income categories or generations. This “distributional blindness” is a significant limitation, as policies perceived as unfair can generate social opposition and fail, regardless of their environmental effectiveness or economic efficiency (Maestre-Andres et al., 2019; Huber et al., 2020;Im, 2024).

4.2 IAMs and static modelling literature

As IAMS and static modelling techniques vary widely in terms of scope, complexity and temporal dynamics (Weyant, 2017,) so are the topics investigated by their literature. To highlight such dynamic, the same CHD analysis, previously described, has been performed separating the overall sample in two sub-samples. The first contains the 55 papers related to static models (table 5), whereas the second includes the remaining articles (183) regarding IAMs (table 6).

On one hand static models (MRIO, I-O, CGE etc.) work within a limited temporal and systemic boundaries and are designed to capture interactions within specific economic sectors, as evidenced by dominant terms like "trade," "regional," and "component" in their CHD clusters. Moreover, their analytical power stems from deterministic formulations with fixed parameters, making them particularly valuable for assessing short-term policy impacts such as carbon pricing mechanisms or sectoral employment changes (Ward et al., 2019). However, this ability also represents their greatest limitation as they do not incorporate dynamic feedback loops or temporal evolution of systems, hence, fundamentally missing the complex interdependencies characteristic of coupled human-environment systems (Ferraro et al., 2018).

On the other, IAMs deriving from dynamic systems theory, are specifically designed to capture time variant impacts by including feedback loops in their computational mechanisms (Cronin et al., 2018). Unlike their static counterparts, IAMs explicitly incorporate feedback mechanisms between economic activity, energy systems, and biogeochemical cycles, as documented by Weyant (2017). The CHD analysis reveals their distinctive lexicon, dominated by terms like "dynamic," "projection," and "policy," reflecting their core purpose of simulating long-term, cross-system interactions. However IAMs' ability to capture feedbacks and long-term dynamics comes at a cost, as increased complexity and computational demands are significantly higher than their counterparts. Terms as "MEDEAS" and "decisions" underscores IAMS' policy-oriented design, intended to inform strategic climate mitigation pathways.

Moreover, the methodological approach differences are more clearly evident in their treatment of socio-economic dimensions. Interestingly, IAM clusters include broader institutional and adaptation-related terminology ("institutional," "adaptation"), consistent with their whole-system perspective. However, even static models reveal unexpected social considerations through terms like "poverty" and "health," particularly in emission reduction policy analyses. Nevertheless, it must be noticed that the term poverty in the analyzed sample is often employed in reference to "energy poverty" rather than to address poverty in its social aspects.

Other relevant differences are found in the geographic analysis of the two sub-samples. IAMs naturally operate at global or continental scales as per "Europe," "Asia," and "federal" lexicon. This macroscopic view enables analysis of transboundary impacts and international policy coordination for the medium and long run (Riahi et al., 2017). Static models, conversely, provide finer spatial resolution, with terms like "urban" and "regional" highlighting their utility for local-scale decision-making with particular focus on short-term insights. Hence, the highlighted complementarity opens to potential strategic model coupling, where IAMs establish boundary conditions for static models to perform detailed sectoral analyses (Gilbert et al., 2018).

This dynamic is further confirmed by the most commonly employed databases. IAM literature employs cross-national databases such as the World Input-Output Database (Nieto et al., 2020; Capellan-Perez et al., 2020; D'Alessandro et al., 2020; D'Alessandro et al, 2025 and others) or the IIASA (International Institute for Applied Systems Analysis) database (Rao et al., 2017; Yang et al., 2018; Tokimatsu et al., 2019 and others) often combined with the IPCC scenarios (Schleussner et al., 2016; Fuhrman et al., 2019; Lamb, 2024; Minx et al., 2024 and others) other commonly employed database are LCIA (Life Cycle Impact Assesment) (Tokimatsu et al., 2020; Georgiades et al., 2023, Mueller et al., 2024; de Bortoli et al., 2025), EXIOBASE (Pulido-Sánchez et al., 2022; Wiedenhofer et al., 2024). Static literature, instead often opts for regional I-O table (Horridge and Wittwer, 2008; Rokicki et al., 2021; Rum et al., 2024; Wei and Xu, 2024) or tends to isolate broader I-O tables as EXIOBASE and EORA (Bachmann et al., 2015; Guo et al., 2021; Rum et al., 2022 and others).

Table 5: CHD Dendrogram and relevant cluster identified for static models

Table 5

Sustainability and Decision making	***Emission reduction policies***	***MRIO***	***CGE***	***Land use and spatial dynamics***
20.9%	**25.1%**	**15.4%**	**16.2%**	**22.4%**
Sustainability	*Emission*	*I-O*	*CGE*	*Land*
Stakeholder	*Carbon*	*Trade*	*Regional*	*Spatial*
Decision	*Reduction*	*System*	*Model*	*Cultivate*
European	*Price*	*MRIO*	*Multi*	*Efficiency*

Table 5: CHD Dendrogram and relevant cluster identified for static models

Table 5

Alternative	*Poverty*	*Component*	*Dynamic*	*Grain*
Integrate	*Domestic*	*Illustrate*	*Australia*	*Differentiation*
Support	*Consumption*	*Flow*	*Sinoterm*	*Force*
Vision	*Beijing*	*Loop*	*Economy*	*Eco*
Europe	*Revenue*	*Program*	*Impact*	*Arable*
Assessment	*Concentration*	*Algorithm*	*Capital*	*Factor*
Scenario	*Pm2*	*Approach*	*Labor*	*China*
Framework	*Technological*	*Simulation*	*Poland*	*ESSI*
Climate	*Progress*	*Difference*	*Federal*	*Interprovincial*
Intervention	*Storage*	*Market*	*Simulate*	*Development*
	Generation			*Urban*

Source: Authors' elaboration based on WoS and elaborated with IRAMUTEQ.

Table 6: CHD Dendrogram and relevant cluster identified for IAMs models

Table 6

Climate targets and policy	***Energy transition and emissions***	***Sustainable development challenges***	***Climate-economic modelling***
14.8%	**29.6%**	**21.8%**	**33.8%**
Degree	*Reduction*	*Challenge*	*IAM*
Temperature	*Energy*	*Research*	*Model*
Paris	*Gas*	*Process*	*Dynamic*
Target	*Renewable*	*Sustainable*	*Climate*
Limit	*CO2*	*Socio*	*Policy*
Emission	*Population*	*Propose*	*Projection*
Pledge	*GHG*	*Development*	*Change*
Carbon	*Sea*	*Ecosystem*	*MEDEAS*
Mitigation	*Domestic*	*Ecological*	*Limitation*
Feasibility	*Health*	*Dimension*	*Decision*
Budget	*Extreme*	*Economic*	*Europe*
Overshoot	*Decrease*	*Adaptation*	*Application*
Ceiling	*Efficiency*	*Institutional*	*Asia*
Removal	*Income*	*Transition*	*Structural*

Source: Authors' elaboration based on WoS and elaborated with IRAMUTEQ.

4.3 Lemmas' network analysis

The similarity analysis, represented graphically as a network map (figure 3), confirms and deepens the insights gained from the CHD.

In this visualisation, the lemmas are the nodes and the links between them represent their co-occurrence in the same text segments; the thickness of the links is proportional to the strength of this association. The map reveals the conceptual architecture of the field of study, highlighting the central constructs and the most interconnected subject areas.

At the center of the network lies a structural core composed of high-frequency and highly connected lemmas, which act as pillars of the literature. These include: “climate”, “model”, “emission”, “policy”, “IAM”, “energy” and “scenario”. This core describes the essence of the analysed research: it consists of studies that use mainly employ IAMs to assess the environmental impact of climate policies and show the results. This core is generic but reveals a strong applied and evaluation-oriented focus. The strong co-occurence links between "economic", "impact", and "policy", connecting through terms such as "model" and "climate" indicate that the field’s core intellectual activity remains the evaluation of policy interventions through an economic–environmental lens.

Peripheral but still visible clusters, such as those related to land use ("land", "spatial") and methodological approaches ("CGE, "I-O"), suggest the presence of specialized subdomains, yet their positioning underscores their secondary role within the dominant economy–climate paradigm. However, it must also be mentioned that the peripherical position of "CGE" and "I-O" could be influenced by the sample selection, as the majority of articles considered deal with IAMs rather than static models (55 vs 183).

Nevertheless, the structure highlighted by the network is coherent with the result provided by the CHD analysis. Indeed the central hub of the networks (“climate”, “model”, “emission”, “policy”, “iam”, “energy” and “scenario”) strongly resembles cluster 3 (table 4) "Methodological framework and IAMs" that also accounts for the largest share of the corpus, 29.9%.

The left-hand side of the network, where "model" links to "economic", "impact", "region", and "land", matches cluster 1 (Spatial analysis and regional assessment) and cluster 5 (Energy systems and economic impacts). Terms like "regional", "CGE", "land", and urban from cluster 1 are embedded in the network near the “regional modelling” subspace, while "GDP", "fuel", "renewable energy", and "coal" from cluster 5 form part of the energy–economy axis connecting energy to impact.

The right-hand side of the network, were terms as "emission", "reduction", "target", "carbon" are present aligns with cluster 4 (Climate targets and mitigation pathways). The CHD’s lexical set ("Paris", "temperature", "mitigation", "pathway", "NZE") can be found in this emission–policy–scenario pole, reflecting the corpus’s concerns towards mitigation strategies and their quantified targets.

Lastly, the governance oriented lexicon characterising cluster 2 (Governance and socio-environemtal management) appears in the network’s periphery, most often linked to policy and impact. Its relatively marginal placement in the similarity map is consistent with its lower proportional weight in the CHD output (13.8%) and corroborates the earlier observation that social and governance aspects, while present, are secondary to the dominant economy–climate framing.

The most significant absence, which fully corroborates the CHD analysis, is the lack of a "social pole" in the network. There is no cluster of terms related to inequality, justice, or social well-being that holds a centrality comparable to that of the economic or environmental poles. Social lemmas are either absent or relegated to an extremely peripheral position in the network, with weak and sporadic connections. Such dynamic appears to be compatible with what has been defined as "epistemic narrowing" (Beck and Mahony, 2018) that is the modelling tendency to privilege economically quantifiable metrics over multidimensional societal outcomes. This graphical visualization makes the semantic gap even more apparent, as the scientific corpus analysed seems to not have yet developed a structured and shared language to integrate the social dimension within itself.

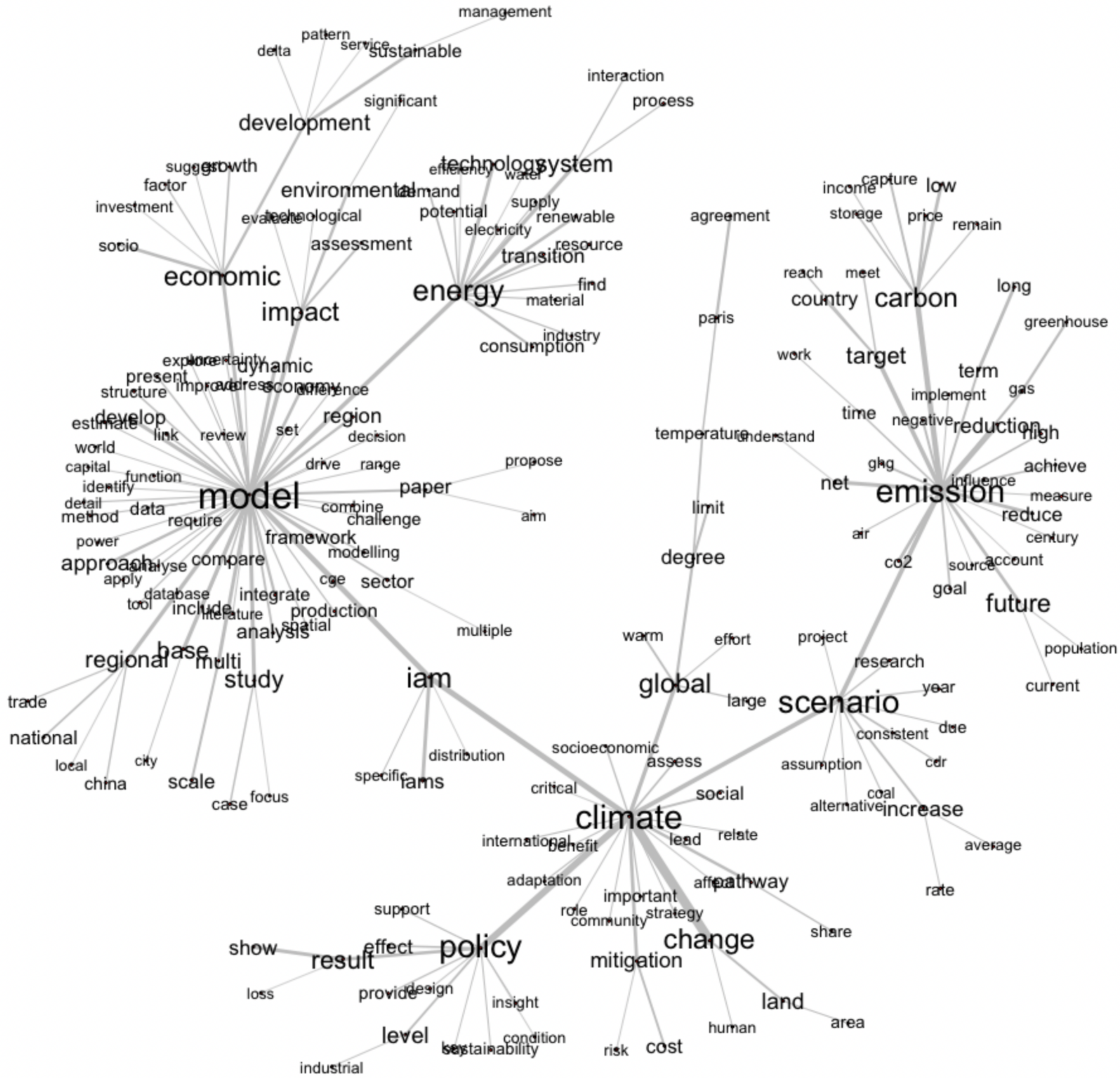

Figure 3: Most relevant terminology network

Source: Authors' elaboration based on WoS and elaborated with IRAMUTEQ.

5 Discussion

Climate-economy modelling has long relied on IAMs and static equilibrium frameworks to inform policy and evaluate climate mitigation strategies. Despite both modellistic approach being robust tools that simulate how environmental policy and shocks propagate to the entire economy, while capturing links between sectors and spatial regions, they often ignore social heterogeneity (income, vulnerability, age, gender, education...) (Niamir et al., 2020; Süsser et al., 2020). This leads to a "distributive blindness" that makes these models unable to show how policies impact unequally amongst different social groups. Indeed, the lemma analysis highlights that the selected corpus reveals a strong bond between terminology related to "economy" and "environment"; however, the policy impact produced is mainly analysed through monetary variables, not including other dimensions like the social one, often seen as an outcasts in the modelist world (Merli et al., 2018). A standard CGE model, for example, typically uses a "representative agent" for each region, assuming that all households behave in the same way. Such a model can predict that a carbon tax will increase GDP and reduce emissions, but it can say nothing about how the burden of that tax will be distributed between the rich and the poor, given that the latter spend a larger share of their income on essential energy goods (Gough, 2017). Similarly, an MRIO model can trace the carbon footprint of goods consumed in Europe, but it does not reveal whether the low-emission jobs created in Europe compensate for the higher-emission ones lost in other parts of the world, nor the quality or stability of those jobs.

Therefore, there are deep implications related to this gap. At a theoretical level, a reductive vision of sustainability is perpetuated, confined to the economy-environment nexus. It ignores the growing body of literature that places social justice and equity at the center of the ecological transition (Agyeman et al., 2003; Schlosberg, 2007). Moreover, the aforementioned "distributive blindness" is not simply an omission but rather a structural characteristic of the current research. Indeed, it implies that society and its dynamics are to be seen as a passive aggregated entity unable to undergo differentiated impacts and to provide with a nuanced reaction (Cappelli et al., 2020).

Furthermore, even in the few instances were multi-regional (or "inter-regional") approaches are employed, often, the social consequences of the shocks analysed are not taken into account nor discussed. Also, the regional-national dynamic is lacking, limiting the analysis solely to a selected number of provinces or at most to interactions between provincial and regional levels (Rum et al., 2024, Guo et al., 2021, Horridge and Wittwer, 2008).

A common limit in many models, particularly those of multisectoral nature, is the inability to represent dynamics at multiple spatial and hierarchical scales. Models often focus on a single scale (national, regional or local) or a single spatial level of aggregation, neglecting the complex interconnections and feedbacks between them. This limitation, which is particularly evident in static models, shows how they are not able to incorporate the fluidity and variability of cross-scale interactions. Similarly, IAMs face challenges in analysing local and regional dynamics due to their macro-level focus (Gambhir et al., 2019).

For example, an IAM national or global model may not capture the regional specificities of climate impacts or socio-economic responses, while a static, local, model may not consider the influences of higher-level policies or markets (Horridge and Wittwer, 2008). The lack of a multi-regional and multi-level perspective, limits the ability to identify how environmental shocks or policies propagate across different jurisdictions and social strata, and how inequalities may be amplified or mitigated depending on interactions between scales (Hertel et al., 2019; Holscher et al., 2022;).

It is at this critical juncture (between the urgency of the climate crisis, the reality of regional disparity and the inadequacy of current analytical approaches) that this paper finds its motivation. To build an effective argument that pushes towards a new modelling and climate policy approach a deep analysis for the existing literature has been performed. Systematically mapping the most recurring themes, identifying the most employed methodology and tracking research trends evolution, allows us to have a better and precise understanding of the state of the art of the existing literature.

Perhaps more important, such analysis highlights critical gaps and blind spots in the literature. The unanswered questions that represent the frontiers of research and the most pressing needs for policy-oriented analysis.

5.1 Limitations

While this study provides a comprehensive analysis of multi-regional and multi-level modelling approaches in the context of sustainability and climate policy, few limitations should be acknowledged.

First, the research focused on English written articles and publications, inevitably this could have excluded potentially valuable contributions written in different languages.

Secondly, the lexical analysis performed employing IRAMUTEQ, while robust, is inherently limited by the vocabulary and terminology used in the selected sample of literature, which might not be fully representative of the nuances of the studies. Furthermore, the clustering technique, though effective for identifying dominant themes, might have oversimplified complex interactions between variables or interdisciplinary linkages that do not precisely fall within the represented clusters.

Third, while the selected search words and WoS fields (Tables 2 and 3) were chosen to ensure thematic consistency and a broad selection of works, we might inadvertently have excluded studies that employ innovative or hybrid methodologies, not explicitly referencing the selected research words and criteria.

Despite these limitations, this study offers a valuable synthesis of the current state of *multi-level* modelling, highlighting critical gaps and providing a foundation for future research to build upon. Addressing these limitations in subsequent studies could further enrich the understanding of how these models can better integrate social dimensions and multi-level dynamics to support equitable and effective climate policies.

5.2 Concluding remarks

The analysis of the results offers a two-faced picture. On one hand, a field of study emerges methodologically sophisticated, and rapidly evolving, having developed powerful tools to analyse the complex interdependencies between economic and environmental systems on a multi-regional and multi-level scale. The growing diversification of models, from IAMs passing through CGE and MRIO to hybrid approaches, epitomises the scientific community's ability to respond to the new challenges of globalisation and sustainability. On the other hand, however, our textual analyses have revealed a deep and systemic gap: the failure to integrate the social dimension, particularly concerning distributional aspects and equity and multilevel analysis. The analysed literature, while speaking of "impact" and "sustainability," seems to adopt an implicitly technocratic perspective, where the objective is to optimise interactions between economic variables and environmental ones, treating society as an aggregated and passive entity. This approach, however, is insufficient to guide a transition that is not only green but also equitable. A more comprehensive multi-regional and multi-level approach cannot be limited to disaggregating the analysis geographically or sectoral. It must also carefully evaluate the societal impacts, recognising the existence of multiple levels of heterogeneity within it, by incomes, skills, genders, age and regions. As argued by Amartya Sen (1999), development cannot be reduced to the growth of per-capita income but must be understood as an expansion of people's real capabilities and freedoms. Consequently, a policy, as per Rawl's principle, can only be considered “successful” if it improves the living conditions of the most vulnerable and does not exacerbate existing inequalities. Current models, as emerged from our analysis, are largely blind to these dynamics.

To overcome this limitation, a deeper dialogue between economic modelling and the social sciences is necessary, integrating concepts such as distributive, procedural, and recognition justice within evaluation frameworks.

In this dynamic PNS could offer a valuable perspective for critically examining the shortcomings of conventional quantitative models in addressing complex, uncertain, and contested socio-ecological challenges. Despite its limitations (potential difficulties in reconciling diverse stakeholder values, the risk of politicizing scientific processes, and challenges in scaling participatory methods), PNS shows the fallacies of traditional modelling approaches. On one hand static models struggle to consider non-linear dynamics, often reducing socio-ecological dynamics to oversimplified representation unable to describe adaptive behaviours and institutional and cultural contexts. On the other, IAMs show challenges concerning data intensity, computational difficulties, model development and calibrations and interdisciplinary coordination. Although PNS does not provide alternatives to these models, it calls for more flexible, adaptive and inclusive approaches. By acknowledging uncertainty, embracing plural perspectives, and prioritizing learning over prediction, PNS-aligned methodologies could complement traditional models.

Lastly, at an application and policy level, the risk is designing policies that are technically effective but socially unsustainable. Implementing environmental measures without an adequate assessment of their distributional impacts can lead to an increase in poverty and social polarization. Despite this clear and present threat and PNS emphasis on integration of uncertainty and plural perspectives, policymakers often face pressure to implement interventions without waiting for "perfect" data or consensus. In this sense both static models and even multi-level IAMs struggle. Their reliance on fixed parameters, linear projections, and deterministic assumptions can delay action. Hence, the future challenge lies avoiding two extremes: paralysis by analysis (over-relying on models) and reckless expediency (where actions are taken without scientific consultation). This issue could potentially be addressed by integrating AI in the policy design process. AI could, indeed, assist in dynamically linking local, regional, and global dynamics as well as socio-environmental and socio-economical ones, addressing key weaknesses of IAMs or CGE models.

6 Credit author statement

T.D. Conceptualisation, Funding, Supervision, Methodology, Writing - Original Draft. **L.R.** Conceptualisation, Methodology, Data Curation, Formal analysis, Visualisation, Writing - Original Draft. **M.B.** Conceptualisation, Supervision, Methodology, Writing - Original Draft. **C.V.P.** Conceptualization, Methodology.

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A Appendix

A.1 Tables

Table A1.1: List of abbreviations.

Acronym	*Definition*
ABM	Agent Base Model
CCS	Carbon Capturing Systems
CGE	Computable General Equilibrium
CHD	Descending Hierarchical Classification
CDR	Carbon Dioxide Removal
DICE	Dynamic Integrated Climate Economy model
DID	Difference-in-Difference
EEIO	Environmentally Extended Input-Output
EM	Ecological Macroeconomics
EMM	Ecological Macroeconomic Model
GHG	Greenhouse gas
GCAM	Global Change Analysis Model
GLOBIOM	Global Biosphere Management Model
IAM	Integrated Assessment Model
IIASA	International Institute for Applied Systems Analysis
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact and Assessment
MEDEAS	Modelling the Energy Development under Environmental And Socioeconomic constraint
MGWR	Multi-Scale Geographically Weighted Regression
MRIO	Multi Regional Input Output
MSMRIO	Multi-scale and Multi-regional Input Output
NZE	Net Zero Emissions
SFC	Stock Flow Consistent
SD	System Dynamics
SOS	System of Systems
WIOD	World Input-Output Database