D5.1 Report- Telecoupling frameworks

Analysis of telecoupling frameworks on land-use and climate changes and biodiversity protection, highlighting SSH aspects

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Revision and history chart

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ABSTRACT

Deliverable 5.1 - Telecoupling frameworks (Analysis of telecoupling frameworks on land-use and climate changes and biodiversity protection, highlighting SSH aspects) is written in the framework of WP5 – Supporting climate change mitigation and adaptation efforts and biodiversity policy design (Task 5.1) of the Europe-LAND project under Grant Agreement No. 101081307. The aim of Task 5.1 is to conduct a systematic review of the existing telecoupling research, from the lens of interdisciplinary and transdisciplinary approaches and emphasizing the importance of SSH's contribution, to provide a state-of-the-art evaluation of analytical approaches that have characterized the telecoupling science to date. Telecoupling papers published in scientific peer-reviewed journals in Web of Science and Scopus databases have been reviewed using PRISMA framework and MAQXDA software. This systematic review in the form of a qualitative description of results (descriptive literature review) focuses particularly on disclosing existing methodological approaches (quantitative and qualitative). Adhering to the PRISMA (Preferred Reporting Items for systematic Reviews and Meta-Analysis) standard leads to improved quality providing substantial transparency in the selection process of papers. Selected quantitative results and graphical displays complement the description. By reviewing 138 telecoupling papers, the report demonstrates how telecoupling – i.e. an empirically driven approach that comprehensively analyzes both the socioeconomic and environmental impacts over long distances - is used in a broad variety of ways across various disciplines and research topics. It also points out the strengths of this concept, areas to be improved, and promising avenues for future study in the field of land-use and climate changes and biodiversity protection.

KEYWORDS

Telecoupling, quantitative research, qualitative research, social science, PRISMA framework, literature review, climatic research, sustainable land-use, climate change, mitigation, adaptation, biodiversity.

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List of Abbreviations and Acronyms

IAMs	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
JCR	Journal Citation Reports
SJR	SCImago Journal Rank
SSH	Social Sciences and Humanities
SUA	Slovak University of Agriculture in Nitra
WP	Work Package

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Executive Summary

Aligned with the European leading efforts in climate science and multiple initiatives on climate action and sustainability, the project Towards Sustainable Land-use Strategies in the Context of Climate Change and Biodiversity Challenges in Europe (Europe-LAND) focuses on the integration of natural and social sciences to identify, develop, test and implement integrated tools to improve the understanding of the factors behind land-use decisions as well as the stakeholders' awareness and engagement in terms of climate change and biodiversity challenges.

Europe-LAND expects to go beyond the state-of-the-art and fill in specific gaps associated with integrated indicators for monitoring land use and land cover change, the effects of awareness and behavioural typologies on pathways to more sustainable land use across Europe, and interactive tools to explore land use under different scenarios and with participatory approaches.

Deliverable 5.1 - Telecoupling frameworks (Analysis of telecoupling frameworks on land-use and climate changes and biodiversity protection, highlighting SSH aspects) is written in the framework of WP5 – Supporting climate change mitigation and adaptation efforts and biodiversity policy design (Task 5.1) of the Europe-LAND project under Grant Agreement No. 101081307. Its aim is to provide all partners with a systematic review of the state-of-the art of existing telecoupling research from the lens of interdisciplinary and transdisciplinary approaches and emphasizing importance of SSH's contribution. The report demonstrates how telecoupling – i.e. an empirically driven approach that comprehensively analyzes both the socioeconomic and environmental impacts over long distances - is used in a broad variety of ways across various disciplines and research topics. It also points out the strengths of this strategy, areas to be improved, and promising avenues for future study in the field of land-use and climate changes and biodiversity protection. While telecoupling research has gained momentum since 2013, the interdisciplinary and empirical application of the framework is claimed still novel. Europe-LAND will contribute to filling such knowledge gap by developing and applying a telecouling framework in the course of the project.

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1. Introduction

The Europe-LAND project consortium is composed of an interdisciplinary team of experts from natural and social sciences to ensure meaningful and significant societal impact of the related research activities. The consortium involves proven natural scientists with backgrounds as diverse as geoinformatics, engineering, biology, landscape ecology and oceanography as well as development and environmental studies, along with recognised social scientists from social geography, social ecology, sociology, law, economics, management science, political science and international development. These experts collaborate within and across the different WPs, cross-fertilising each other and producing interdisciplinary insights.

The drivers of climate change are explored in a wide range of scientific discourses and climate assessment literatures. This report presents an interdisciplinary overview of the ways in which the telecoupling concept has been used to disclose socioeconomic and environmental interactions over distances and pays special attention to the ways in which social science disciplines contribute to this area of research. Each social science discipline has unique perspectives and contributes significantly to a shared understanding of the human dimensions of climate change, while at the same time complementing each other and contributing to integrated, multidisciplinary frameworks.

Within the Europe-LAND project, the social sciences contribution is based on the fact that scientific knowledge will be co-developed with different categories of societal stakeholders, and it will specifically focus on contextualising activities, such as explaining the social implications of observed issues and problems and focus on processes of meaning, which may give rise to decision-making. Another role of social sciences knowledge in this project is to seek an understanding of social change and to aid the design of appropriate tools for improved social planning, prediction and control.

This systematic review on methodologies in telecoupling models research was conducted as a deliverable D5.1 of the project Europe-LAND: Research report on Telecoupling frameworks. The review was specifically designed to inform the project's objectives by synthesizing existing methodologies and identifying suitable approaches for modelling telecoupling within the context of sustainable land use, climate change, and biodiversity in Europe. The review was not registered in a systematic review database such as PROSPERO, as it was developed as part of a targeted research project rather than as independent research. While a formal protocol was not registered in a traditional sense, we adhered to a predefined methodological framework aimed at synthesizing methodologies in telecoupling models' research. All Appendixes are stored in the Digital Commons Data repository Mendeley Data, under a CC license with a distinctive DataCite DOI.[1]

The purpose of the review aligns with the project's goals to contribute to academic knowledge and practical strategies for addressing telecoupling in land-use planning and policy. Upon completion and approval by the Europe-LAND project consortium, this review will be made publicly accessible. The intention is to disseminate the findings broadly to facilitate their application in both research and practice, supporting the project's aim to enhance sustainable land-use strategies in Europe. Stakeholders, including researchers, policymakers, and practitioners interested in sustainable land use and telecoupling models, are encouraged to engage with the findings of this review. The results are

[1] Moravčíková, D. et al. (2024). Europe-LAND telecoupling framework, Mendeley Data, V1, doi: 10.17632/yn6bh3z5cp.1

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intended to catalyse further research, inform policy development, and guide practical applications in managing land use sustainably in the face of global environmental challenges.

1.1 Social sciences perspective on climate change research

At least since the 1990s, it has been clear that a robust science of climate change must engage the social sciences. Recently, social scientists have become much more involved in the large-scale scientific assessments that synthesize the state of knowledge and often have influence on policy design (e.g., Moss & Schneider, 2000; Thomas et al., 2018; Dietz, 2017; Dietz et al., 2020; Fecher et al., 2021). Generally, research in the social sciences deals with the behaviour of social actors in different roles, and it tries to understand the dynamics of social institutions and phenomena. Consequently, problems related to climate change effects and biodiversity loss are also attributed to certain societal behaviour of their actors. For example, anthropologists, archaeologists, geographers, and sociologists have demonstrated that land-use transformation is an underlying cause of anthropogenic climate change (e.g., Dietz et al., 2016; Jorgenson & Clark, 2012; Jorgenson et al., 2018; Thomas et al., 2018; Tierney, 2019). Some evidence to support this conclusion is derived from the long, continuous record of human-induced changes (Jorgenson et al., 2019). The long-term and short-term drivers of climate change are constantly interacting. Anthropogenic factors studied by social scientists include economic systems, power, social stratification and inequality; population growth and demographic change; technology; infrastructure; and changes in land use and land transformation (e.g., Rudel, 2009; Smith et al., 2014; Paladino & Fiske, 2017).

According to Dunlap and Brulle (2015), climate change is a social process embedded in specific social systems, past and present, and concretely sociology offers a wide range of important perspectives including analysis of political-economic and institutional drivers of climate change, the social factors that influence both mitigation of and adaptation to climate change, and the nature of political and cultural struggles over how climate change should be addressed. They point out six key aspects that demonstrate the importance of social sciences knowledge for global climate change research - historical and contextual complexities, consequences, conditions and visions for change, interpretation and subjective sense making, responsibilities, governance and decision making.

Land use and land transformation are considered important drivers of climate change because they are the result of complex interactions at multiple levels. In addition to exploring this complexity, the social sciences are proposing alternative adaptation and mitigation strategies that take into account historical ecology and the different temporal relationships between the natural and social worlds (Jorgenson et al., 2019). Long-term perspectives on the human drivers of climate change help to understand tipping points in the development of planning scenarios. Understanding the current impact of past human activities and the long-term evolution of the processes that drive human behaviour are critical not only for understanding the drivers of climate change, but also for designing mitigation and adaptation measures. Effective policies and initiatives at the global scale need to be linked to regional and local conditions and social contexts (e.g., Carmin et al., 2015; Nicolosi & Corbett, 2015; 2018; Jorgenson et al., 2018).

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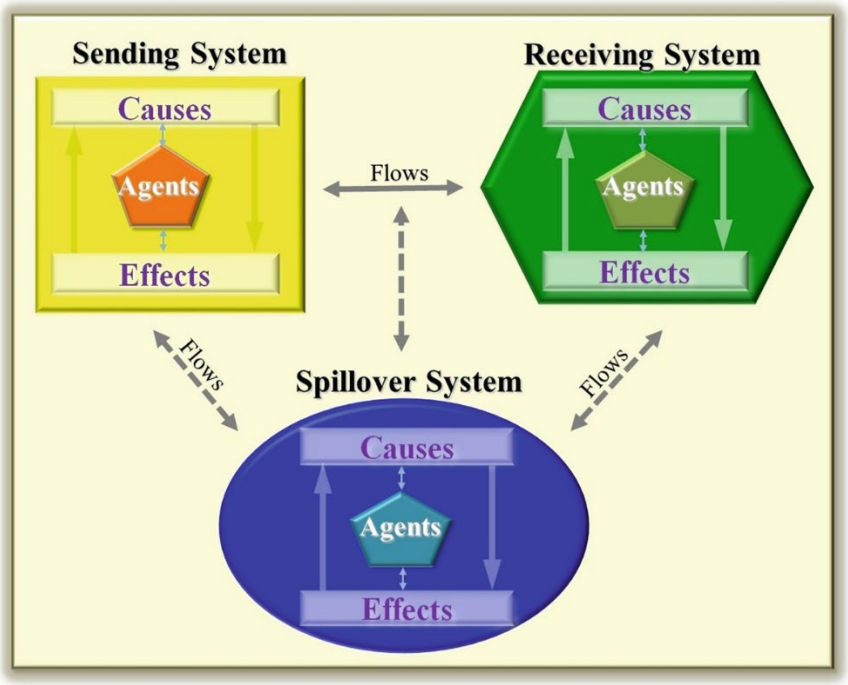
1.2 Telecoupling framework and research

In Europe-LAND, we perceived the telecoupling framework as an appropriate paradigm for examining human–environment interactions in contemporary societies. It was first proposed by Liu et al. (2013) and is deeply rooted in coupled human-natural, human-environment or social-ecological systems analysis.

Figure 1: Five major and interrelated components of the telecoupling framework[2]



Source: The telecoupling framework as presented by Liu et al. (2013)

Since its inception, Telecoupling has been applied in various fields to develop more specialised frameworks to address specific issues. Regardless of the specific topics to which the telecoupling framework is applied, feedback between different systems is an important feature of all telecouplings. The telecoupling framework draws specifically on systemic thinking when dealing with human-environment interactions such as land-use change, while also emphasising the need to understand the networked relations of actors that mediate cross-scalar flows and feedbacks between systems (e.g. Voulvoulis et al., 2022; Arts et al., 2017). This requires attention to the place-based, as well as the flow-based human-environment processes shaping land use in specific places (e.g. Köppel, 2020; Munroe et al., 2019; Newig et al., 2020; 9. Challinor & Benton, 2021). For telecoupling research to succeed in its interdisciplinary ambition, there still appears to be a need for a more systematic and conscious recognition of the limits of specific research approaches and disciplines, as well as the need to engage more consequentially in a combination of different modes and logics of interdisciplinarity and emphasises joint problematisation, understanding and problem solving (Friis & Nielsen, 2019). While

[2] Sending / receiving / spill over systems, flows, causes, agents, and effects.

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telecoupling research has gained momentum since 2013, the interdisciplinary and empirical application of the framework is claimed still novel (Busck-Lumholt et al., 2022).

Whereas the origin of the telecoupling concept is based in the land use science, telecoupling as an implementation framework has developed in several ways (Liu et al., 2013). Some scholars have operationalized this concept, whereas others just use the word to refer to distant systems and flows. Telecoupling offers various perspectives - referring to a phenomenon, a conceptual framework and methodological approaches (Hermans et al., 2023). Landscapes can be telecoupled based on different flows. Their connections and relations might be via material products and markets, energy, finance, governance, technology, information and knowledge, movement of goods or products, movement of people and their wellbeing. This means that measuring or evaluating telecoupling can be done in diverse ways with various units (Busck-Lumholt et al., 2022).

Specific areas that have to date been understudied include how telecouplings emerge and dissolve, their impact on sustainability and best practices for encouraging positive rather than negative impacts, and more explicit accounting for local and regional interactions in a broader context (Liu, 2017). Further operationalisation of the telecoupling framework for quantitative and qualitative analyses of environmental and socioeconomic issues will help to address current limitations and future challenges. Here, qualitative research allows to get to some of the more immaterial interactions such as social relations, trust, discourses, and information that are difficult to arrive at with other methodologies that rely on more quantitative data. Telecoupling research also opens up an opportunity for identifying relevant processes and stakeholders that are essential to include in solution-oriented sustainability research (Friis & Nielsen, 2019).

As it is stated in the *COUPLED White Paper* (Bager et al., 2021), the EU may utilize telecoupling to identify areas in which carbon leakage and the displacement of environmental harm occur, as well as gauge the social and economic effects of these flows and how it alters the behaviour of the many actors involved. Telecoupling can provide a valuable lens to allow EU policy makers to assess the effects of their policies on sustainability and climate outcomes in other parts of the world (e.g., The EU's Biodiversity Strategy for 2030, The Farm to Fork Strategy, The Organic Action Plan, The European Industrial Strategy, The Green Deal etc.).

2. Design of the literature review

2.1 Purpose and objectives of the review

The extensive and continuing land degradation throughout the world spurs the need to identify and foster more sustainable land-use causes. To address this need and as mentioned above (in 1.2), the telecoupling concept has been particularly proposed in the relevant scientific literature yet it needs to be further operationalised for quantitative and qualitative analyses (e.g., paying higher attention to the place-based and flow-based human-environment interactions and to the deeper understanding of local, regional and global processes and their interconnectedness via various material and immaterial flows).

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The rationale behind this systematic review is to collect and identify the current state of knowledge and its uncertainties in applying telecoupling frameworks. The results of this review are of key relevance for the Europe-LAND project as it seeks to construct and test a dedicated conceptual telecoupling framework to analyse and inform to which extent land use strategies may support climate change mitigation and adaptation efforts, as well as biodiversity policy design.

The aim of producing this systematic review of the existing literature is to identify the use of telecoupling models that incorporate environmental, ecological, geographic and social parameters. The above can be expressed using the following **research questions**:

- What different types of telecoupling models have been developed?
- How have telecoupling models been used to study different environmental and social issues?
- What are the strengths and weaknesses of different telecoupling models?

The methodology of scanning the relevant scientific literature points to a descriptive systematic literature review on the current literature on telecoupling. In 2013, the first major article on conceptualizing telecoupling as a framework was published (Liu et al., 2013), and in 2019 a review paper was published recapping the last 5 years on telecoupling literature (Kapsar et al., 2019).

Telecoupling as a concept started in the land use and environmental science (Liu et al., 2013), recent literature concentrated increasingly on governance (e.g., Arts et al., 2017; Hermans et al., 2023), on influence of policies and treaties) and actor-based networks (e.g., Eakin et al., 2014; Newig et al., 2019; Martín-López et al., 2019; Newig et al., 2020). **Over the years, discourse on telecoupling understood as an implementation framework has developed in several ways and therefore offers various models and approaches referring – just to a phenomenon, to a concept or to a framework** (e.g., Hull & Liu, 2018; Hermans et al., 2023). The latter refers to the operationalisation of the components and we distinguish between two main approaches – (a) the structured approach presented by Liu et al., 2013 (this approach focuses on analysis based on five components: Sending / receiving / spill over systems, flows, causes, agents, and effects) and b) the actor network-based approach and governance presented by above mentioned authors, that included in the initial telecoupling framing actors (institutions included) and governance processes.

Based on the facts indicated above, and the aim of the Europe–LAND project to focus on the telecoupling framework based on the actor network approach and governance (focusing particularly on use- and user- centred frameworks), the scanning of the relevant scientific literature starts 2018 onwards on telecoupling as the framework in general.

2.2 Scanning methodology

The methodology for scanning the relevant scientific literature addressing the telecoupling concept is based on the **PRISMA** Statement, an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses. To make the whole process transparent, recording relevant information in the PRISMA Checklist and PRISMA Flow Diagram documents at each step is essential.

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Searches in databases were based mainly on the following **keywords**:

- '*telecoupl*'* or '*telecoupl*'* + *climate change* (mitigation and adaptation)
- or + *biodiversity* (conservation)
- or + *land-use* (strategies)
- or + *ecosystem services*
- or + *social* or *policy*
- geographic scale at which data were analysed: any (local, regional, national, international).

In order to reduce the possibility to include unreliable material from questionable studies, it was necessary to limit the selection of publications to respected scientific databases. These databases only include articles that have undergone a rigorous review process known as double blind review. Afterwards, during the process of selecting the publications for the analysis, four experts in quantitative and qualitative research conducted a content check. No contradictory information was found that would justify excluding any of the research articles. To ensure the quality of the academic outputs, the literature review includes publications indexed in the **Web of Science** database ranked **Q1 to Q4** according to the Journal Citation Reports (JCR) and publications indexed in the **Scopus** database ranked **Q1 to Q4** according to the SCImago Journal Rank (SJR) and published mainly between 2018 and 2023. Only a few exemptions were allowed - that was a book dedicated to telecoupling (Web of Science BKCI) and twelve significant papers published in the period 2013-2017.

All Europe–LAND project partners, SUA included, were asked to identify publications relevant to their field of study based on defined eligibility criteria. Partners were requested to mark down identified articles into a prepared excel sheet and record the basic areas: Title, Authors, Journal, Publishing house, Year, Study objectives, Research methods, Telecoupling models used, or fields included, Key findings, DOI. Available full texts with identified DOI were downloaded.

Table 1: Inclusion and exclusion criteria

Inclusion	**Exclusion**
Use of telecoupling as the framework, where at least one component of the telecoupling framework is explicitly labelled and telecoupling is mentioned.	Telecoupling suggested as a phenomenon (indicates the mentioning of the word telecoupling, but not applying in the context of the research), or recommendation.
Articles published mainly 2018 onwards.	
English language only.	

All searches and identified articles that met basic search requirements were added into the dataset. Identical articles were removed having **one final dataset with 138 unique articles and 1 book publication**. In the process of collating research materials for further scholarly investigation, a total of 139 articles were initially imported into the Mendeley citation management software. Upon review, the software's sophisticated duplicate detection capabilities identified a single instance of redundancy within the imported dataset. This resulted in the removal of the duplicate article to ensure the integrity

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and uniqueness of the research database. Consequently, the finalized collection, earmarked for subsequent analysis, comprised **138 unique articles**. This meticulous approach to database curation underscores the importance of utilizing advanced tools in academic research to maintain high standards of data quality and reliability.

The full texts of the database of 138 articles (see **Annex 1**) were subjected to a thorough manual analysis by a small SUA team of 4 people (3 of whom focused on quantitative research and 1 on qualitative research). The criterion for accepting an article for further advancement was whether it addressed the issue of telecoupling models, including specific examples, and at this stage it was irrelevant what type of research methods were used; review articles were also accepted. Subsequently, three groups were defined for categorizing the articles in the database, namely articles primarily with unique quantitative research, articles primarily with unique qualitative research, and review articles. Based on expert discussions and content analysis, the expert team categorized all articles into the above categories as follows:

1. Articles primarily with unique quantitative research: **48**
2. Articles primarily with unique qualitative research: **19**
3. Review articles: **71**

Based on the above categorization, after excluding review articles (Table 1), a subset of 67 articles was prepared. The detailed examination of these 67 distinct papers involved qualitative and quantitative methods, utilizing suitable tools to extract the required information. The papers were transferred to MAXQDA software using the Mendeley tool. Afterwards, a group of SUA experts in qualitative and quantitative research conducted the content analysis within the specific software environment (**MAXQDA, R Studio**). The focus was on obtaining details regarding the particular research methodologies, indicators, and sources of follow-up data utilized. The analysis focused on the frequencies of individual keywords and pairwise combinations of individual words in two-word phrases. Pairs of phrases by frequency were extracted in the software and exported to excel file. Subsequently, irrelevant word phrases were manually excluded, and the data were imported into the R Studio software.

After the literature review, a visualisation was developed in form of a word cloud and a biplot (see **Annex 2** and **Annex 3**). These figures will also be used for following scientific work on task T5.2 Developing a telecoupling framework including evaluation of various socio-spatial structures and deliverable D5.2 Draft Europe-LAND telecoupling framework, to support the scientific imagination and to realize brainstorming and mind mapping.

The synthesis of results in our study focused on the collection, summary, and comparison of methods and input data used in primary research studies related to telecoupling models. We included studies employing a range of methodologies, including primarily quantitative and primarily qualitative research approaches. Our objective was not to select or advocate for a specific method but to catalogue and compare the variety of methods and inputs used in the field. Given the nature of our goals and the diverse methodologies of the included studies, we determined that traditional statistical meta-analytic techniques were not appropriate for our synthesis. We only considered studies that represent primary research on telecoupling models, encompassing a wide array of methodologies such as quantitative, qualitative, or a combination thereof. This inclusive approach allowed us to capture a broad spectrum

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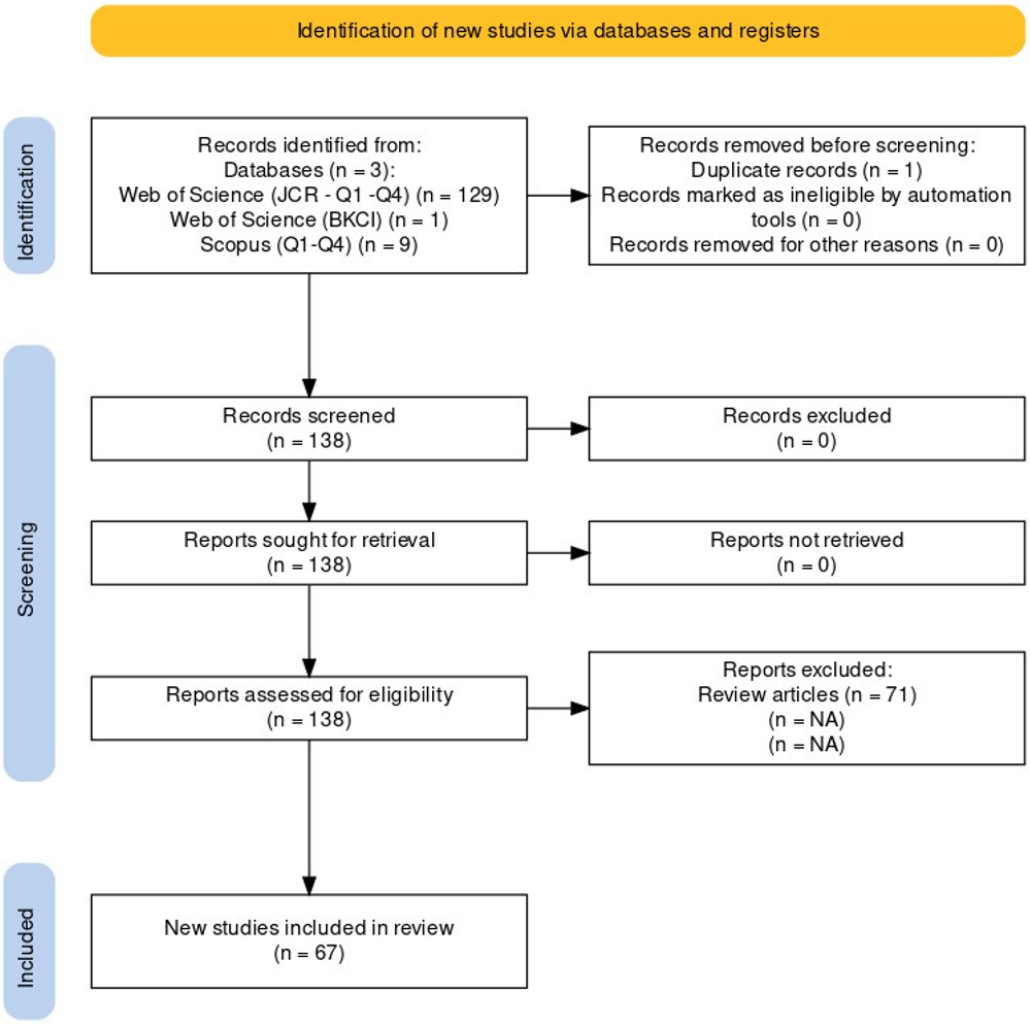
of research practices within the telecoupling community. The review process is depicted in Figure 2 below.

Figure 2: PRISMA of the literature included for review



Source: Figure generated from own data in PRISMA

Given the diverse nature of the studies reviewed, including primarily quantitative or primarily qualitative research, **missing data was an anticipated challenge**. We noted the absence of these data points and discussed the potential impact on our synthesis in the limitations section. For qualitative studies, missing thematic data or unspecified methodological details were also noted, and an attempt was made to interpret the findings within the context of the available information. To facilitate the comparison across studies employing different methodologies and data reporting formats, we standardized the presentation of the methods and inputs used in each study. This involved categorizing the methodologies as primarily quantitative and primarily qualitative methods and summarizing the input data types (e.g., satellite imagery, survey data, interview transcripts) in a consistent format. This standardization enabled us to compare and synthesize the diverse array of approaches used in telecoupling research more effectively. The use of software tools like Mendeley, MAXQDA, and R Studio was crucial in managing the data extraction and synthesis process. Mendeley facilitated the

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organization and citation of the vast literature. MAXQDA was instrumental in the qualitative analysis, allowing for efficient coding and synthesis of themes across studies. R Studio supported the organization of extracted data and the preparation of visual aids to enhance the presentation of our findings.

We began by **categorizing** the included studies based on their research methodology— primarily quantitative or primarily qualitative research methods. This initial categorization allowed us to assess how differences in methodological approaches might contribute to heterogeneity in study results. For instance, variations in the use of statistical models versus thematic analysis could lead to divergent findings or interpretations of similar phenomena. Recognizing the complexity of telecoupling models, we conducted a thematic analysis to identify common and divergent themes across the studies. This included examining the specific aspects of telecoupling being investigated (e.g., socio-economic, ecological, or combined factors) and the contexts in which they were studied. We compared the indicators used to measure telecoupling phenomena and the data sources cited across studies. This comparison helped to identify whether differences in these indicators or the reliance on distinct data sources might explain variations in findings.

Within each methodological category, we further described the **specific research methods** used in each study (e.g., surveys, remote sensing, interviews) and identified the **key indicators** associated with these methods. This allowed us to detail the types of data collected or analysed and the various ways in which telecoupling processes were measured or assessed across studies. For each study, we also catalogued the data sources used, aligning them with the respective research methods and indicators. The information from our database was tabulated in a comprehensive manner to facilitate quick reference and comparison. Tables were designed to display, at a glance, the research methodology, specific methods and indicators used, and the corresponding data sources for each included study. This tabulated format served as a valuable tool for synthesizing the diverse methodologies and data types encountered in telecoupling research. To deepen our analysis and presentation of the textual data extracted from the studies, particularly the descriptions of research methods and data sources, we utilized a biserial word combinations chart. This chart is a sophisticated tool designed to visualize the relationships between pairs of words within our dataset, highlighting the most frequently occurring methodological terms and their associations with specific data sources and indicators.

In our review, we transparently discussed the **potential biases and limitations** related to missing results, including the steps we took to mitigate these issues and the overall assessment of their impact on our findings. Acknowledging and discussing these potential biases enhances the transparency and credibility of our review, providing readers with a clearer understanding of the factors that might influence our synthesis. To ensure the **reliability and credibility** of our findings, we employed a systematic approach to assess the certainty or confidence in the body of evidence for the outcomes identified in our review on telecoupling models. This assessment was crucial given the inclusion of diverse methodologies (primarily quantitative or primarily qualitative research methods) and the complex, interdisciplinary nature of the telecoupling field. Recognizing the complexity of telecoupling models and their applications, we consulted with subject matter experts to inform our assessment of the evidence. **Expert input** helped ensure that our assessment of certainty was informed by deep domain knowledge and that we appropriately accounted for field-specific considerations in our evaluation.

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3. Results and discussion

This systematic review focused on studies that provided valuable information about the current knowledge and areas of research that need further exploration in telecoupling frameworks. We particularly emphasized methodologies and approaches described in the literature that directly contribute to the development of a comprehensive scientific review. For the Europe-LAND project, this review is crucial in supporting the exploration of land use strategies that aim to address climate change, adaptation, and biodiversity policies. We carefully chose publications that are relevant and contribute to our main objective. We prioritized methodologies or approaches that were thoroughly validated and closely fit with the project's objectives when many options were available. When synthesizing this body of work, particular emphasis was placed on research that not only enhanced our conceptual comprehension of telecoupling but also provided practical and actionable insights. This rigorous method of choosing literature guarantees that the fundamental aspects of our telecoupling framework are strong and representative of the latest advancements in current research. As a result, it enhances the effectiveness of the framework in tackling the crucial environmental issues confronted by the Europe-LAND project.

The analysed studies comprised a combination of qualitative and quantitative research methodologies. This mixture emphasizes **the interdisciplinary character of telecoupling research**, accommodating a wide range of approaches ranging from intricate numerical analysis to more descriptive, conceptual frameworks. Publications utilized **234 distinct research methodologies**, highlighting the wide range of analytical procedures employed in telecoupling studies. The methods employed in investigating socio-ecological systems across distances are likely to encompass statistical models, simulations, content analysis, and case studies. These methods reflect the intricate and diverse character of such investigations. The researchers analysed a total of **207 distinct indications** to demonstrate the diverse metrics employed in assessing and comprehending the dynamics inside telecoupled systems. These indicators may include environmental implications, social-economic considerations, and governance issues, among other aspects, demonstrating the extensive range of studies under the telecoupling paradigm. The database obtained from analysed pertinent publications has **102 unique data sources**, which include governmental databases, international organizations, field surveys, and remote sensing data. The variety of data sources enhances the research results by offering a wide range of information, allowing for a detailed comprehension of telecoupled interactions in many settings and sizes. The widespread utilization of diverse methodologies, indicators, and sources of data demonstrates the intricate and vast nature of telecoupling research. An interdisciplinary approach is crucial for comprehending and controlling the ecological, economic, and social connections that extend over far geographical regions.

Given the objective of our systematic review to synthesize and compare the methodologies employed in telecoupling models research, our approach to assessing and presenting the risk of bias differs from traditional systematic reviews that evaluate the outcomes or effects of interventions. Our **review emphasizes the identification, summary, and comparison of research methods across studies**, rather than assessing the risk of bias in study findings. We acknowledge the inherent diversity in methodological approaches across the studies included in our review. Given this diversity and our focus on synthesizing methodologies rather than quantitatively assessing study outcomes, a conventional risk of bias assessment for each study was not the primary focus of our analysis. While a detailed risk of bias assessment per study was outside our review's scope, we paid attention to the transparency

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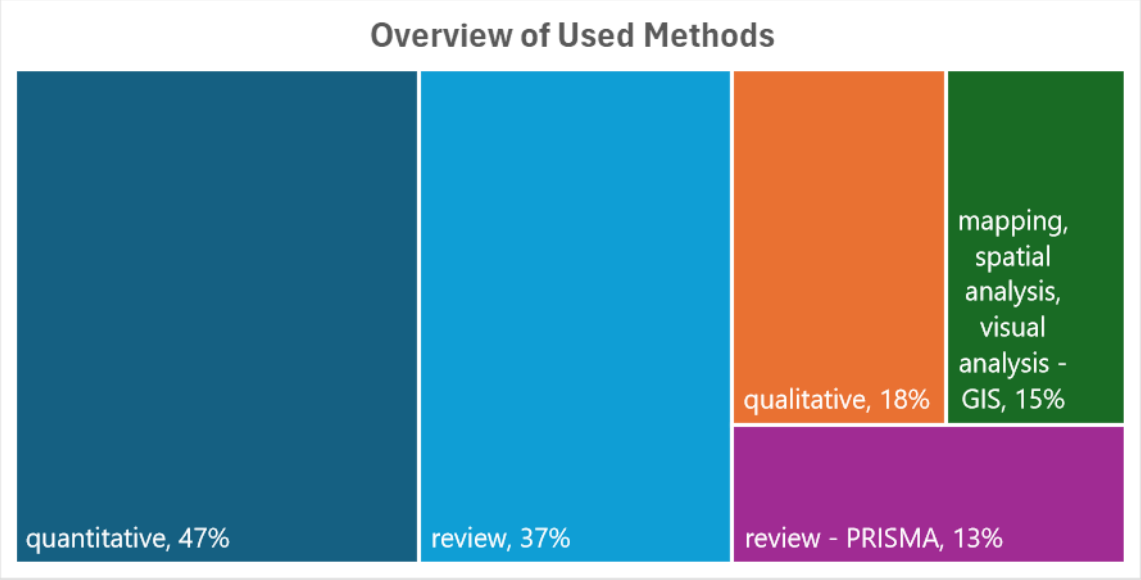
and completeness with which each study's methodology was reported. This assessment aimed to ensure that the methods used were sufficiently described to allow for their inclusion in our synthesis and comparison. We established criteria for the inclusion of methodologies in our synthesis based on the clarity of description, the relevance to telecoupling models, and the potential for replication or application in further research. In our synthesis, we included a narrative discussion on the overall quality of methodological reporting across the studies reviewed. This discussion highlighted trends in methodological transparency and identified areas where reporting could be improved to enhance the reproducibility and rigor of future research in telecoupling models. We discussed how the level of methodological detail (or lack thereof) in the studies could impact the synthesis and comparison of methodologies. This included reflecting on how variations in reporting quality might influence the comprehensiveness and applicability of our synthesized findings.

Our systematic review synthesizes the range of methodologies applied in telecoupling models' research. Instead of traditional outcome-based summary statistics and effect estimates, we focus on summarizing and comparing the methodological approaches and their applications.

Figure 3: Overview of used methods



Source: own elaboration

For each study included in our review, we present a descriptive summary of the methodological approach(es) employed, categorized as primarily quantitative or primarily qualitative research methods. This includes a brief overview of the specific techniques and tools used (e.g., statistical models, GIS mapping, interviews, surveys), the telecoupling processes examined (e.g., socio-economic, ecological, or combined factors), and the study's scope and scale (see Figure 3, Table 2 and Table 3).

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Table 2: Overview of primarily qualitative methodological approaches

No. of paper[3]	Research methods	Indicators	Data source/ Tools
23.	qualitative document analysis; semi-structured interviewing; in-depth secondary research; regression models with linear, quadratic, and logarithmic versions of this variable; spatial clustering; logistic regressions with robust standard errors; join count analyses	telecoupling governance measures; water use, waste generation, greenhouse gas emissions, chemical consumption, and land-cover change; sustainable winemaking - wine producers	pROC package
29.	ecosystem service (ES) maps; Value Chain Analysis (VCA) methods	seafood provision; human well-being assessment methods; ES mapping and modelling	
34.	case analysis; spatiotemporal analysis	co-certified forestry products and demonstrates; multitemporal and spatial approach	Rural Environment Cadastre (CAR)
42.	empirical analysis; pooled, cross-sectional regression analysis; scientific survey	multiple telecoupling; trade liberalization; beef supply chain; GHG emissions	
56.	case study; Focus groups and actor survey; Social network analysis; Agency analysis	Sustainable Development Goals (SDGs)	
58.	review; case study; mental models	Forest transitions; Multi-level Perspective Theory Framework - modelling socio-technical transitions	
69.	moving window analysis	agricultural land-use changes; soybean land changes	MODIS data
78.	Case study landscapes; focus group interview; participatory mapping workshop; field walks for enhanced spatialization; feedback workshop	dynamic land use change	GIS

[3] See Annex 1.

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99.	case study; fieldwork - visit, interview; focus group discussions (FGDs); Digital elevation model: DLR	human well-being; Well-being components	
100.	very high-resolution (VHR) satellite imagery; Participatory mapping; Case study; field research; workshop	participatory mapping with object-based spatial classification using remotely sensed high-resolution imagery	ArcGIS calculating from–to land use change at the polygon level
101.	complementary research methods: workshops, participant observations, and in-depth interviews		
110.	Case study approach; Field research	sustainable palm oil; natural rubber cultivation	Roundtable for Sustainable Palm Oil (RSPO); Sustainable Natural Rubber initiative (SNR-i)
113.	Descriptive Social Network Analysis; Focus group interviews; Survey Population; Snowballing method; Expert interviews	land uses and land use changes	Network graphs
119.	Case study approach; Focus group interviews	agricultural land-use changes; land survey data; spatial data; socio-economic statistics	Public participation geographical information systems (PPGIS) - map-based survey method that allows participants to provide both geographic and non-geographic information; ArcGIS Toolbox (Telecoupling Toolbox)
120.	Empirical research; case study; fieldwork; household questionnaire survey; focus group discussion; semi-structured interview	banana plantation expansion; household characteristics, livelihood strategies, land use history, and involvement with the banana plantations	QSR Nvivo software
124.	Household questionnaire survey; Focus-group discussions; Semi-structured interviews; qualitative and ethnographic methods	case of banana plantation expansion; telecoupling framework	

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127.	case studies; empirical research; Conceptual model	social-ecological system; food system governance	
132.	hypothesized scenarios; face-to-face interview; Utility function; Random-effects probit model; Stated choice model	household socioeconomic and demographic conditions; cropland characteristics; payments for ecosystem services (PES); Grain to Green Program (GTGP); Scenario attributes: Crop damage intensity, Program payment, Social norm; parameter vectors associated with factors that describe personal traits of interviewees, the household's socioeconomic conditions, features of the household's cropland, and scenario attributes	household survey data
133.	semi-structured interviews and structured survey questionnaires	socioeconomic and ecological effects of natural disasters on protected areas - earthquake; dynamics of flows, agents, and causes of telecouplings	CHANS

Table 3: Overview of primarily quantitative methodological approaches

No. of paper[4]	Research methods	Indicators	Data source/ Tools
1.	Consumptive Use Program Plus model - dynamic soil water balance model (CUP+ model); Crop evapotranspiration model	virtual water content of agricultural products; water footprints of crop production; evapotranspiration - crop water use; crop production; drought index; harvested area	CADFA - California Department of Food and Agriculture; CDWR - California Department of Water Resources; FAF - Freight Analysis Framework; CFS - Commodity Flow Survey
3.	machine learning models	forest loss -gain, Socioeconomic change - GDP, population; Sankey diagram showing the land use transitions; Telecoupling of deforestation and	GlobeLand30 dataset; European Space Agency (ESA) – Climate Change Initiative (CCI); Hansen v1.7 - global forest change

[4] See Annex 1.

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		urbanization; spatial distribution of forest loss and gain high-resolution satellite images; analyze the spatial distribution of land changes	(GFC); GADM - Global Administrative Areas
4.	land-use index (LI); desertification index (DI); vector autoregressive (VAR) model - analyze the intracoupling between landuse change and desertification; generalized impulse response function (GIRF)	MODIS normalized difference vegetation; index (NDVI) and MODIS albedo; MODIS land cover type product (MCD12Q1).; desertification difference index (DDI); Intracoupling between land-use change and desertification	Land Process Distributed Active Archive Center of the US Geological Survey
6.	Water Yield Model - based on annual average precipitation and evapotranspiration using the Budyko curve; InVEST model; Freshwater demand model; Carnegie-Ames-Stanford approach (CASA) model - evaluate net primary productivity (NPP) - estimate the carbon sequestration supply; Multi-regional input–output (MRIO) analysis - identify the trans-boundary flows of carbon	Quantifying and mapping trans-boundary ecosystem service (ES) flows quantified the spatial patterns in ES supply and demand analysis of trans-boundary ES flows; land use/land cover (LULC); evapotranspiration and precipitation; cultural ES flows - population density as a proxy for local recreational demand, tourist numbers - visitations rate; trans-boundary flows of carbon; Telecoupling intensity quantifies the proportion of ES inflows from other countries contributing to the total ES demand met within a given country.	UN System of Environmental Economic Accounting-Ecosystem Accounting; Food and Agriculture Organisation's (FAO) AQUASTAT dataset; MODIS Terra Aqua Combined Land Cover product MCD12Q1; Digital elevation model (DEM) data; Eora dataset; World Tourism Organisation
7.	Data Standardizing; Pearson's correlation; Pairwise comparisons - linear regressions; Pairwise t-tests; Network models - network centrality proxies	163 SDGs indicators; telecoupling indicators: scarce water consumption, SO2, CO2, and nitrogen emissions, marine, terrestrial and freshwater biodiversity threatened	

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8.	Spatial statistics; Agglomeration economies; Agent-Based Models (ABMs); Computable General Equilibrium (CGE) models; Integrated Assessment Models (IAMs); Simulation modelling	Human-environment (H-E) systems	
10.	Principal component analysis; Data Standardizing; Multi-criterion decision-making method; Weighted sum method; Linear regression method; Scissor difference model; Kuznets curve	Remote Sensing Ecological Index (RSEI) dataset; nighttime light data; hydrological observations; socio-economic statistics: GDP, population, gross domestic product, output value of primary, secondary, and tertiary industry, and crop yield	MODIS imagery; National Oceanic and Atmospheric Administration (NOAA); Resource and Environmental Science and Data Center; Water Resources Bulletin of Heihe River Bureau
15.	Conceptual approach of the study; (non-parametric) two sample Kolmogorov–Smirnov test	ecosystem services (ES); cultural ES indicators; Existence and bequest values of species; human footprint	
16.	mapping and geospatial analysis; case study; factor analysis	soybean telecoupling	GIS application; Telecoupling GeoApp
19.	two-way analysis of supply and demand; local - intracoupling; tradeoff analysis	metacoupling framework; soil conservation service; soil erosion rate; soil loss tolerance value (T value); indicators to measure social-economic benefits	
26.	Environmental expansion input-output analysis (EEIO)	water scarcity; global virtual water trade; metacoupling framework; interactions across space within a place (intracoupling), between adjacent places (pericoupling), and between distant places (telecoupling); global-level evaluation	WORLD Input-Output Database (WIOD), Inter-country and Global Input-Output Accounting Table (FIGARO), OECD Inter-country Input-Output Table (OECD-ICIO), Global Trade Analysis Project (GTAP) of Agricultural Economics Department, Purdue University, EXIOBASE Database of Leiden University, ; Eora Global

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			Supply Chain Database (Eora) of the University of Sydney
27.	Bayesian hierarchical analysis of a demographic matrix model - Estimating proportional dependence; regression models	Seasonal wildlife migration; Ecosystem service (ES); spatial subsidy approach - quantify the net flow of benefits, as valued goods and experiences, between regions	GIS
31.	InVEST model; gravity model - spillover effects	Case study: ecologically fragile areas; telecoupling synthesis framework	
32.	land use/cover change (LUCC) model; System Dynamics model; Cobb Douglas production functions; Scenario analysis	agricultural change in a telecoupled world; Competition for Resources between Agent Functional Types (CRAFTY) modelling framework; evapotranspiratio	
37.	multiregional input-output (MRIO) methods; Global Trade Analysis Project model (GTAP-BIO); general equilibrium model	elecoupling is international agricultural trade; soybean trading system; economic and environmental consequences; socio-economic drivers in the model; Coupled Human and Natural Systems (CHANS)	World Development Indicators, World Bank; Global Bilateral Migration Data Base (GMig2 database); Penn World Table (PWT); Producer Support Estimates (PSEs), OECD; Tariff Analytical and Simulation Tool for Economists (TASTE)
45.	network flow analysis; network topology analysis - weighted degree analysis and page rank analysis; input-output model; Network control analysis	framework of humanwater multiplex networks (HWMNs); human-water interactions	World Input-Output Database
46.	input and output indicators of the model; data envelopment analysis (DEA) model; weighted average method; stochastic frontier analysis (SFA)	Efficiency analysis of metacoupling; water transfer; economic, social and ecological benefits of water used; water efficiency; indicator system for metacoupling	

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47.	Input Output Trade Analysis (IOTA) model; Data Normalization; relative loss risk	assessing environmental impacts of consumption	ArcGIS; Stockholm Environment Institute's; Transparency for Sustainable Economies (Trase) database
48.	gravitational spatial weight matrix; InVEST model; spatial econometric model; Benchmark regression model; robustness test	Multi-scale telecoupling; land use change/land cover change (LUCC); ecosystem services (ES); urban agglomerations; Land use, Population density and GDP; Meteorological data (Precipitation, Potential evapotranspiration, Daily mean temperature and Solar radiation, etc.); Soil data (soil texture, sand content, mud content, clay content, organic carbon content, soil bulk density, etc.)	Geospatial Data Cloud; World Soil Database; National Earth System Science Data Platform; HydroSHEDS; Watershed data
50.	Revised Universal Soil Loss Equation (RUSLE); multiregional input-output analysis (MRIO) models	cropland soil erosion; socioeconomic influencing factors; cross-provincial economic demand to local soil erosion; soil erosion prediction of cropland	R-factor map K-factor; Resource and Environment Data Cloud Platform
51.	remote sensing ecological index (RSEI) model; remote sensing ecological environment index (RSEEI) model; linear regression; Principal component analysis (PCA); local coupling and telecoupling coordination degree (LTCCD) model; coupled coordination model (CCD); trend analysis methods: univariate linear regression analysis, Theil-Sen Median trend analysis	urbanization and ecological environment quality; ecological environment quality (EEQ); RSEEI index factors: environmental pollution index (EPI), abundance index (AI), greenness (NDVI), heat (LST), wetness (WET), and dryness (NDBSI)	MODIS product data National Geographic Information Directory Service
53.	paired T-test; method of post-classification comparison; Spearman's rank-order correlation;	land-use and land-cover change; Metrics of landscape ecology	MapBiomas v4.0; TOPODATA; GIS

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	Shapiro-Wilk test; Spearman's correlation; Kruskal-Wallis (KW) non-parametric test		
54.	case study; index	vegetation condition index (VCI); quantity-quality-productivity-ecological balance; requisition–compensation balance of farmland (RCBF) index	
55.	Cellular Automata (CA)-Markov modelling techniques; Markov chain model; Analytic Hierarchy Process (AHP)	land use and land cover changes; analyse spatiotemporal dynamics	GIS; Terrset software package
59.	Fragmentation analyses; Mann-Whitney U-test; interquartile range (IQR)	palm oil production; forest cover index (FC) and change in forest cover index (CFC); composite fragmentation index (CFI); water scarcity (WS); grey water footprint (GWF)	Global Forest Watch
60.	composite index; data transformation - max-min standardization; Scenario analysis; model calibration; model simulation	Water scarcity and poverty; hydrological model, crop growth model, and multiple socioeconomic data; water resources, water use, water allocation, and rural income between; Evaporation (ET) and Leaf Area Index (LAI); Water scarcity index (WSI)	G R A P H I C A L A B S T R A C T
61.	Budyko hypothesis - Climate elasticity; double mass curve (DMC) method; Pearson's correlation analysis; non-parametric M-K statistical test; Theil–Sen's estimator; robust nonparametric methods - Pettitt test	Ecological restoration program (ERP); inter-rill and rill soil erosion; evapotranspiration	G R A P H I C A L A B S T R A C T; Revised Universal Soil Loss Equation (RUSLE); Moderate-resolution Imaging Spectroradiometer (MODIS); ArcGIS
62.	Virtual Water Transfer Matrix; Environmentally extended input-output	virtual water trade (VWT) vulnerability; Virtual Water Transfer Multiplier; renewable water resources	G R A P H I C A L A B S T R A C T; Eora input-output database; Food and Agriculture Organization of

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	(EEIO) model; Input-Output analysis; Scenario analysis	per capita (RWPC); Vulnerability index of global virtual water trade	the United Nations (FAO); World Input-output Database (WIOD); EXIOBASE, and Global Trade and Analysis Project (GTAP)
63.	Land use/land cover change (LUCC); biodiversity intactness index (BII); IFPRI crop distribution model; Projecting Responses of Ecological Diversity in Changing Terrestrial Systems (PREDICTS) model; habitat suitability model (HSM); countryside species-area relationship (cSAR) model	biodiversity losses; cropland displacement - urban expansion; urban expansion, cropland reclamation, value of production, biodiversity losses; Biodiversity indicators: Biodiversity intactness index (BII), Extent of suitable habitat (ESH) index, Fraction of regionally remaining species (FRRS)	G R A P H I C A L A B S T R A C T; PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) database; Worldwide Fund for Nature (WWF); International Food Policy Research Institute
64.	coupling coordination degree model (CCDM); local and telecoupling coordination degree model (LTCCDM); Principal component analysis (PCA); Regression and Correlation analysis	urbanization level and eco-environmental quality; urbanization and the ecoenvironment (UE); improved compounded night light index (ICNLI); remote sensing ecological index (RSEI)	MODIS data; GIS
65.	scenario based LULC prediction; dynamics simulation; hybrid Cellular Automata model; Markov model; multi-criteria evaluation (MCE); analytic hierarchy process (AHP); fuzzy membership function; scenario analysis; simulation analysis	LULC simulation; Ecologically Sensitive Scenario (ESS) modeling; Business As Usual Scenario (BAUS)	Landsat images from the United State Geological Survey (USGS); IDRISI software program integrates the Markov chain and cellular automata; FRAGSTATS tool
66.	Multi-regional input-output (MRIO) model; scenario analysis; Global Climate Models (GCM) and Regional Climate Models (RCM)	Urbanization and climate change; stormwater runoff; Representative Concentration Pathways (RCP); Expanded Downscaling (XDS) scenario; model of stormwater runoff distribution	

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72.	multiregional input-output model; probability density function (pdf) and complementary cumulative distribution function (ccdf); log-likelihood ratio test; linear correlation; modularity measure, centrality metrics	multilayer network - water consumption; in-strength (inflow) and out-strength (outflow) distributions	environmental multiregional input-output (E-MRIO) data
73.	multiregional input–output (MRIO) model; global crop water model (GCWM); scenario analysis; simulation analysis	snowmelt - water irritation; irrigation water consumption	Terra- Climate database; FAOSTAT database; MIRCA2000 (monthly irrigated and rainfed crop areas)
74.	InVest model; Nutrient Delivery Ratio (NDR) model; Soil Delivery Ratio (SDR) model; empirical models - ES supply an demand; Annual Water Yield model	Ecosystem services (ES); interactions between human activities and climate change	Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)
76.	Input-Output Trade Analysis (IOTA) model; multiregional input–output models (MRIOs); sensitivity analyses; Global demand MRIO model	state-of-the-art material flow, economic trade, and biodiversity impact models; Trase Spatially Explicit Information on Production to Consumption Systems (SEI-PCS) model	
82.	Agent-based model; System Dynamics model; simulation model; Cobb Douglas production functions	land use/cover change (LUCC) and agricultural production; Competition for Resources between Agent Functional Types (CRAFTY) modelling framework	data from MapBiomas project; commodity planted-area data (IBGE)
87.	linear regression model; normality test - transformation	Chinese demand for other African commodities; biodiversity; deforestation; logging roads, palm-oil production, rural population growth and wood exports	
88.	LPJ-GUESS crop model; regression analysis; simulation analysis; Calibration factor; spatial clustering; scenario analysis;		Lund–Potsdam–Jena General Ecosystem Simulator (LPJ-GUESS); PLUMv2; FAO data; Biofuel Ecophysiological Traits and

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	non-linear optimisation; K-mean clustering; MAgPIE land use model - least-cost optimisation approach; time series for calibration; time series for benchmarking; stochastic approach		Yields Database; LPJGUESS; Land Use Harmonisation version 2 (LUH2)
92.	Agent-Based Model; logistic model; household survey; Model validation; simulation analysis; scenario analysis	Forest and household dynamics; coupled human and natural systems (CHANS); demographic submodel; telecoupling submodel	Java programming language on the Swarm platform; iterative self-organizing data analysis technique algorithm (ISODATA)
94.	Evapotranspiration; Normalized Difference Vegetation Index (NDVI)	social-ecological land use transformation; land use changes (LUCs); CORONA; multi-spectral satellite images; high resolution drone-based surveys	GIS-based mapping of agriculture and natural vegetation based on historical aerial photographs
97.	Agent-Based Model; simulation analysis; calibrate and validate the model; spatio-temporal analysis	soybean trade; historical land-use changes	TeleABM, telecoupled agent-based model
106.	Input–output model	Model carbon emissions of the tourism telecoupling system (TSS); tourism flows between countries/regions; economic transaction; spatial transfer of the environmental responsibility	International Energy Agency (IEA); World Tourism Organization, Organization for Economic Co-operation and Development, European Union; Global multiregional input–output tables are from the EORA database
112.	Random effects regression model; Linear panel regression analysis; Hausman test, Breusch–Pagan test; Spatial clustering - Moran's I; Principal component analysis (PCA); Radial flow analysis	flows of international and domestic tourists; Sustainable Development Goals (SDGs); socioeconomic and/or environmental factors; road and railway length to indicate accessibility; dependent variables: annual visitation numbers and per tourist expenditure; Independent variables:	ArcGIS

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		number of tourism attractions, percentage of GDP from construction, road and rail length, per-capita GDP; Ecosystem Services (ES) Supply Quantification: crop production and livestock production, water retention and carbon sequestration, tourism attraction	
116.	Metacoupling framework; Spatio-temporal dynamics of trade flows; Autoregressive integrated moving average models (ARIMA)	Soybean, corn and wheat production data; imports, total exports, and bilateral crop trade data	FAOstat; UNComTrade
125.	network model; simulation	telecoupling framework; Spatial subsidy: Quantifying Linkages between Human and Natural Systems with Migratory Species	
126.	factor analysis for quantitative and categorical variables	qualitatively or quantitatively accomplish specific geoprocessing tasks; Telecoupling Toolbox	GIS; ESRI's ArcGIS software
128.	multiregional input-output (MRIO) tables; quantification of spillover flows	metals industry - telecoupling framework; greenhouse gas (GHG) emissions; economic and environmental flows; flows of products and embedded greenhouse gas (GHG) emissions; measure of value-added exports (VAX); coupled human and natural systems (CHANS)	World Input-Output Database (WIOD): EORA; EXIOBASE; OECD-ICIO database
134.	Network analysis - for quantifying metacoupled systems; neighbourhood analyses; association and correlation analysis; exponential random graph models; simple and multiple regression models; model	soybean sending and receiving systems and flow pathways; metacoupling framework; trade spillover effects; cross-scale dynamics	igraph; ggplot2; network packages; R packages networkDynamic; ergm package; MuMin package

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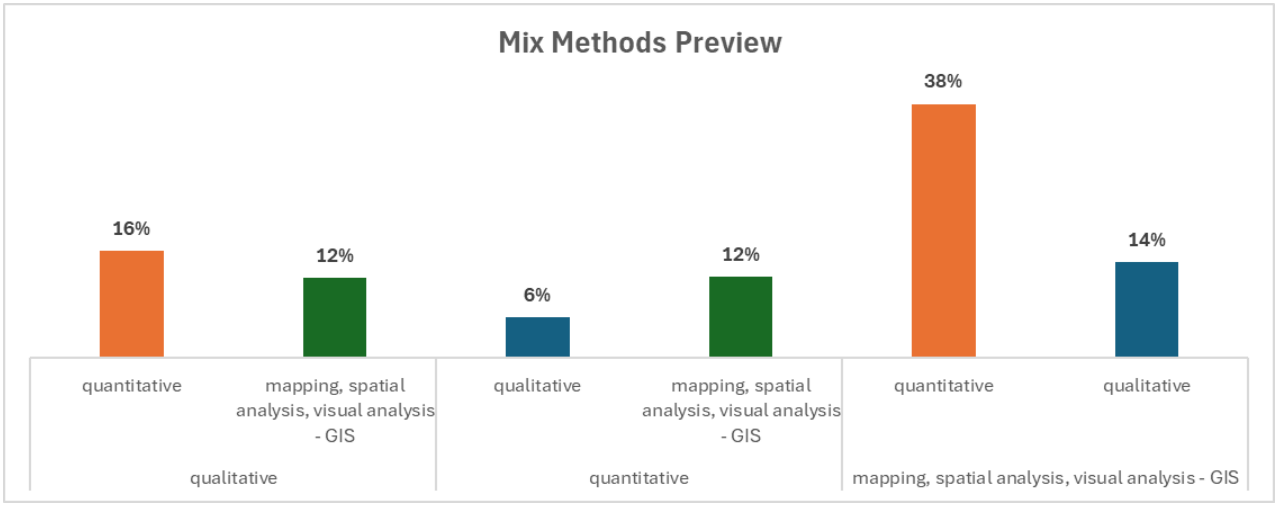
	selection - Akaike Information Criterion (AICc)		

Our review of the literature does not suggest that interaction with teleconnection prescribes a specific type of analysis. However, the application of teleconnection influences the analytical perspective depending on the size of the spatial contexts it encompasses and thus contributes to the generation of new knowledge and application models. It is also very important to be clear about how telecoupling is understood, as there is no consistent terminology in relation to it. Tables 2 and 3 show that the telecoupling concept can support a large scale of research issues and questions addressing relatively high level of complexity. Both overviews also declare underrepresentation of qualitative and mixed methods approaches**.** Qualitative approaches are very important for a deeper understanding of some flows in telecoupling systems that are difficult to quantify, if at all. Figure 4 provides insights and comparison of the share of quantitative and qualitative methods in papers with described mixed methodology.

Figure 4: Overview of representation of quantitative and qualitative approaches in mixed methods approaches



Source: own elaboration

To sum up, this literature review synthesizes the range of methodologies applied across studies on telecoupling models, encompassing primarily quantitative and primarily qualitative research approaches. To provide a comprehensive overview, we summarize the characteristics of the contributing studies and assess potential biases that could influence the integrity of our methodological synthesis. We categorized the studies based on their methodological orientation—primarily quantitative or primarily qualitative research methods. This categorization facilitated an organized synthesis and comparison of diverse research practices. The studies varied in their specific research objectives, ranging from examining socio-economic impacts of telecoupling to assessing environmental changes. Understanding these objectives was crucial for contextualizing the methodologies used. Contributing studies employed a wide array of data sources (e.g., satellite imagery, interview data) and analytical techniques (e.g., statistical modelling, thematic analysis),

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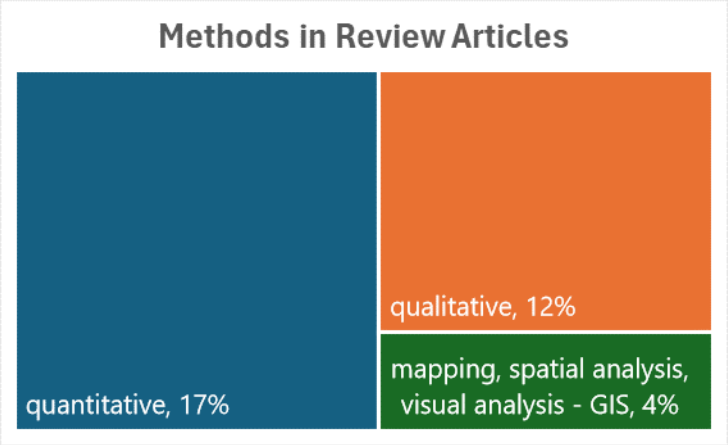
reflecting the interdisciplinary nature of telecoupling research. The studies covered various geographical regions and temporal scales, from local to global analyses and from short-term to long-term perspectives.

As it is mentioned in chapter 2.2 and Figure 2 in this document, 71 papers were excluded as they had character of meta-analysis or review article. Figure 5 shows the representation of quantitative and qualitative approaches described in this category of articles.

Figure 5: Quantitative and qualitative methods indicated in review papers



Source: own elaboration

The extensive use of varied methods, indicators, and data sources reflects the complexity and breadth of telecoupling research. This interdisciplinary approach is essential for understanding and managing the ecological, economic, and social interactions that span across distant geographical areas. The wide range of research methods indicates a robust methodological toolkit available to researchers, capable of addressing the multifaceted challenges posed by global interconnectedness. Similarly, the broad spectrum of indicators and data sources underscores the depth and detail with which these global interactions are analysed, offering insights into the mechanisms of telecoupling and their implications for sustainability, policy-making, and global governance. This review underscores the rich and diverse landscape of telecoupling research, highlighting the importance of a multi-disciplinary approach in addressing the complexities of global interconnectedness.

A dataset might represent a specific subset of the available literature on telecoupling, possibly favouring certain regions, topics, or disciplines. This could limit the generalizability of the findings and overlook significant works or emerging trends in the field. The wide variety of research methods and indicators used across studies can make it challenging to compare results or synthesize findings. This diversity, while a strength, can also complicate efforts to draw overarching conclusions or develop a cohesive theoretical framework. Although the database includes both quantitative and qualitative studies, the balance between these approaches and the depth of analysis provided for each could impact the review's comprehensiveness and the insights it offers into different aspects of telecoupling.

Given the focus of our systematic review on synthesizing methodologies within telecoupling models research, the investigation into causes of heterogeneity primarily revolves around methodological diversity rather than heterogeneity in study outcomes. We found that the research objectives varied

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widely among the studies, ranging from understanding the socio-economic impacts of telecoupling to analysing environmental and ecological changes. This diversity in objectives contributed to methodological heterogeneity, as different goals necessitated different approaches and tools. The geographical focus and scale of the studies also contributed to heterogeneity. Studies ranged from local case studies to global analyses, each requiring different methodological considerations, such as the scale of data collection and the level of detail in modelling. Our review revealed that the telecoupling processes under investigation varied significantly among studies. This variability necessitated diverse analytical frameworks and methods, contributing to the methodological heterogeneity observed. The disciplinary backgrounds of the studies further contributed to methodological diversity. Research originating from fields such as ecology, economics, sociology, and geography brought distinct methodological traditions and preferences.

Our review specifically targeted methodologies within telecoupling models' research. This focus may have excluded studies that indirectly contribute to understanding telecoupling phenomena through broader environmental, social, or economic analyses. The division of studies into primarily quantitative or primarily qualitative research categories was necessary for organization and analysis. However, this categorization might oversimplify the rich spectrum of methodologies employed, potentially overlooking nuanced approaches that straddle these categories. Assessing the completeness and clarity of methodological reporting was a key part of our review. However, this assessment relied on the subjective judgment of the experts' panel, which could introduce bias or variability in evaluating the sufficiency of reporting.

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4. Conclusions and remarks for further and future research

Telecoupling models research is a rapidly evolving field, with new methodologies and insights emerging continually. Our review captures the state of the field up to the point of the search date. In our systematic review on telecoupling models, the synthesis of results was designed to accommodate the diversity of research methodologies (primarily quantitative or primarily qualitative research methods) and the wide range of indicators and data sources identified across the included studies. Given the heterogeneity of the studies and the overarching goal to compare and summarize methodologies and inputs rather than aggregate numerical data for meta-analysis, we opted for a narrative synthesis approach. In exploring potential causes of heterogeneity among study results within our systematic review on telecoupling models, our approach was tailored to address the diverse methodologies and complex nature of the studies included. Given the qualitative and quantitative dimensions of our review, our methods for exploring heterogeneity were multifaceted, focusing on methodological, geographical, and thematic dimensions.

Given the unique context of our review on telecoupling models, where traditional statistical meta-analysis methods were not deemed appropriate due to the goals of the study and the diversity of methodologies (primarily quantitative or primarily qualitative research methods) among the included studies, conducting sensitivity analyses to assess the robustness of the synthesized results would necessitate a creative and methodologically suitable approach**.** In our systematic review focusing on telecoupling models across various disciplines and methodological approaches, we acknowledged the importance of assessing the robustness of our synthesized results.

Given the absence of conventional statistical meta-analysis, our sensitivity analyses were designed to evaluate how variations in study selection criteria and methodological categorizations could influence the overall conclusions of our review. In our systematic review focusing on telecoupling models across various disciplines and methodological approaches, we acknowledged the importance of assessing the robustness of our synthesized results.

The analyses conducted affirms the robustness of our synthesized results regarding the methodologies used in telecoupling models' research. Despite variations in inclusion criteria, methodological categorizations, and levels of methodological detail, the core findings of our synthesis remained consistent. This robustness underscores the reliability of our methodological synthesis and highlights the comprehensive nature of the methodological approaches employed in telecoupling models' research. Our findings provide a solid foundation for future research in this field, offering insights into methodological trends and gaps that could guide subsequent studies. Our systematic review sought to comprehensively synthesize the methodologies employed in the study of telecoupling models, recognizing that the completeness of methodological reporting across studies is crucial for a robust synthesis. In assessing the risk of bias due to missing methodological details (arising from reporting biases), we considered the potential for selective methodological reporting and its implications for our synthesis. We evaluated the extent to which quantitative studies provided detailed descriptions of data sources, analytical techniques, and modelling approaches. The risk of bias was considered moderate, as some studies did not fully report on the statistical methods used or the assumptions underlying their models. Our assessments of the risk of bias due to missing methodological details underline the importance of thorough and transparent reporting in telecoupling models' research. By identifying the

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strengths and limitations in current methodological reporting practices, our synthesis contributes to ongoing discussions about enhancing reproducibility and transparency in the field.

This review meticulously synthesized the methodological approaches used in telecoupling models research, aiming to evaluate the certainty or confidence in these methodologies as robust tools for future studies. Given the focus on methodologies rather than direct study outcomes, our assessment of certainty considers the clarity, consistency, and comprehensiveness of methodological reporting, as well as the applicability of these methods across different telecoupling scenarios. The certainty in the body of evidence for methodological approaches to telecoupling models research varies across methodological categories. **Quantitative methodologies exhibit high certainty due to detailed reporting and broad applicability, while qualitative approaches face challenges related to the variability in application and reporting, affecting our confidence in these methodologies uniformly.** Addressing these challenges through improved reporting standards and methodological guidance can enhance the certainty in the body of evidence and support the advancement of telecoupling research.

The systematic review on methodologies in telecoupling models research, as part of the broader project "Towards Sustainable Land-Use in the Context of Climate Change and Biodiversity in Europe," provides essential insights that have significant implications for practice, policy, and future research. By focusing on synthesizing the range of methodologies employed in the study of telecoupling, this review aids in identifying the most effective approaches for understanding and managing interconnected land-use challenges. The goal is to propose an adequate telecoupling model that can address the complex dynamics of climate change and biodiversity conservation across Europe. **The synthesis highlights the importance of integrating quantitative and qualitative research approaches to capture the full spectrum of telecoupling interactions. Practitioners involved in land-use planning and management should consider adopting a multi-method approach to better understand and respond to the interconnected impacts of their decisions on climate change and biodiversity.** There is a need for ongoing methodological innovation to address the gaps and limitations identified in the review. **Future research should focus on developing and testing new methodologies that can more effectively capture the complexities of telecoupling, particularly in the context of sustainable land use. Building on the synthesized methodologies, future research should prioritize the empirical application of telecoupling models to real-world scenarios in Europe.** This includes assessing the impact of different land-use practices on climate change and biodiversity and evaluating the effectiveness of policy interventions. **The diversity of methodologies used in telecoupling research points to the value of interdisciplinary collaboration.** As the origin of the concept of telecoupling is in land use science, a quantitative approach and the use of relevant secondary data is prevalent. The various qualitative, quantitative and spatial methodological approaches identified appear to be appropriate for understanding and applying telecoupling in combination with qualitative approaches, allowing large-scale models to be linked to the nuances of local contexts. To effectively use the concept of telecoupling, it is therefore important to link different perspectives and knowledge that are often overlooked in these systems, as well as mutual interdisciplinary learning across methodologies (e.g., combining modelling, social surveys, and ethnographic-anthropological methods). **Further telecoupling research, including this project, should aim to bring together experts from environmental science, social sciences, economics, and other relevant disciplines to foster a holistic understanding of telecoupling phenomena.**

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Further telecoupling research within the project Europe-LAND should also reflect on recommendations formulated in the report ***"The next frontier for climate change science"***[5] that was published by the European Commission in February 2024. It offers great insights from IPCC authors of the 6th Assessment Report on knowledge gaps and priorities for research. It highlights open research needs to more effectively and adequately address climate change, also in terms of sustainable land management. The research gaps have been grouped together around common areas to form 11 thematic clusters, and for each research gap the relevance for five cross-cutting policy issues is flag(s)ged: (1) international cooperation; (2) digitalisation and artificial intelligence; (3) ecosystems and biodiversity; (4) social sciences and humanities; (5) gender.

For Europe-LAND, the key findings depicted below will inform the ongoing work related to the development and pilot implementation of a distictive telecouping framework.

Key messages of relevance feeding into the Europe-LAND approach (including T5.2 Developing a telecoupling framework including evaluation of various socio-spatial structures) are mainly related to following clusters:

- CLUSTER 8: LAND USE, AGRICULTURE AND CARBON DIOXIDE REMOVAL

Research should identify sustainable land-use management practices and define what institutions, strategies and policies are needed at global, national, and regional levels. This requires a more in-depth understanding of the underlying dynamics in mitigation pathways, including improvements in sectoral models and IAMs.

- CLUSTER 9: EQUITY AND JUST TRANSITIONS

Prioritising equity, social justice, inclusivity and just transition fosters transformative change and drives support for high-ambition climate policies by building consensus and social trust. The representation of justice and equity in these scenarios should extend beyond the conventional IAMs' focus on interregional equity and burden sharing assumptions for emissions reductions. It should include a bottom-up representation of well-being (social and physical) and how mitigation and adaptation efforts affect the living standards in diverse circumstances. It is also crucial to better integrate institutional effectiveness and governance in the models to improve the representation of differentiated capacity and policy feasibility. This requires a more robust integration of social sciences and empirical research into the IAMs.

- CLUSTER 10: ACCELERATING CLIMATE ACTION: LEVERS AND ENABLERS

Improving knowledge on how communication can stimulate various actions, how to measure outcomes, and understanding the interplay of behavioural change and wider societal choices within broader political, governance, economy, and policy context, is also crucial. Research should also identify the most impactful tools, messages, and co-design processes for communicating about climate change, with links to journalism and the media. Social science research is essential to determine the most effective messages and tools. There is a need to better understand social perceptions and psychological aspects of climate change, as well as the role of education in closing information gaps and bringing motivation and societal readiness.

[5] https://op.europa.eu/en/publication-detail/-/publication/72f1cb35-cee7-11ee-b9d9-01aa75ed71a1/language-en

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Annex 1: List of reviewed papers

1. Abas, A. (2023). A systematic literature review on the forest health biomonitoring technique: A decade of practice, progress, and challenge. In Frontiers in Environmental Science (Vol. 11). Frontiers Media S.A. https://doi.org/10.3389/fenvs.2023.970730
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Annex 2: Visualisation of frequencies of individual keywords

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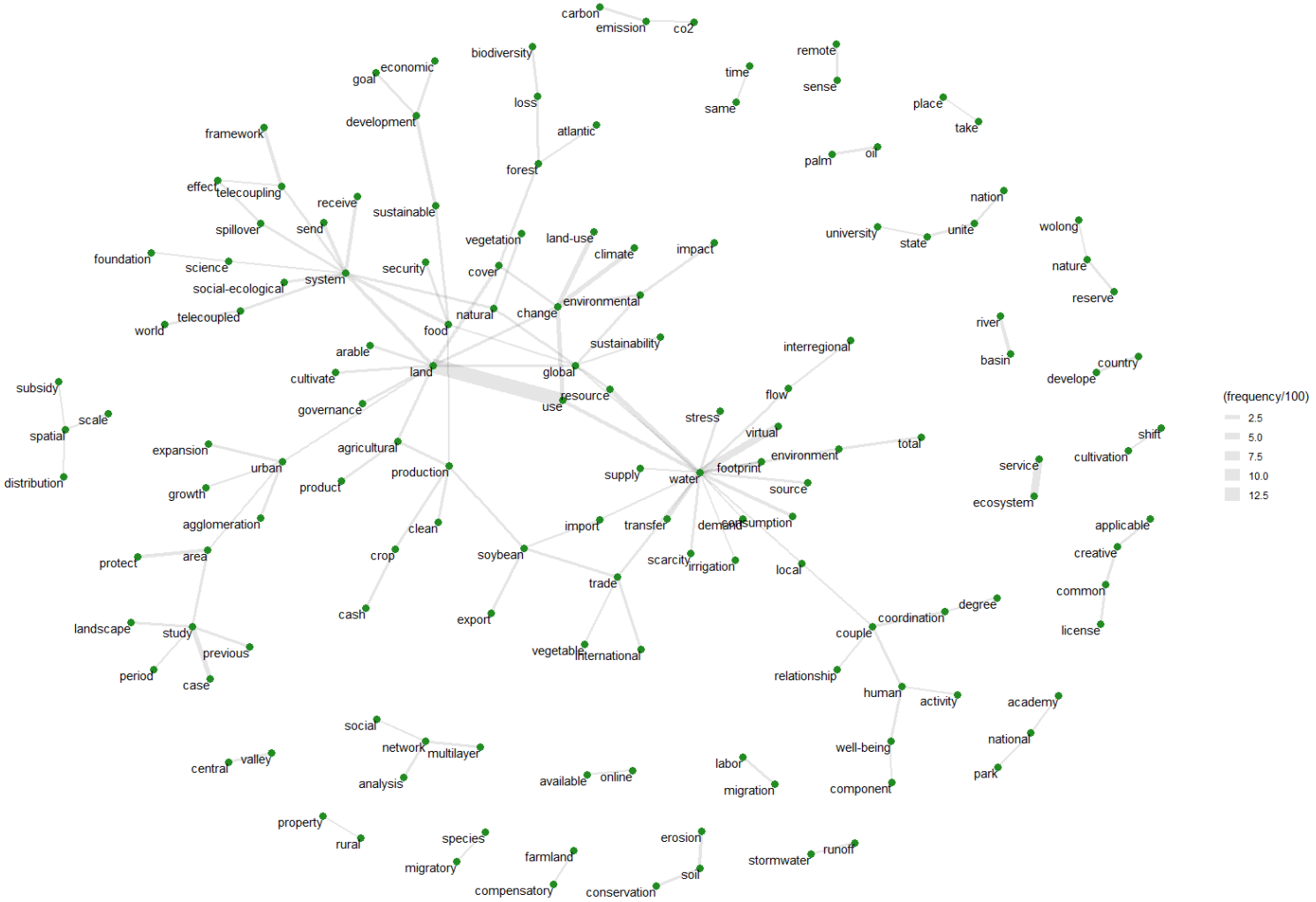
Annex 3: Visualisation of frequencies of pairwise combinations



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