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Review

An AI-Enhanced Systematic Review of Climate Adaptation Costs: Approaches and Advancements, 2010–2021

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Abstract: This study addresses the critical global challenge of climate adaptation by assessing the inadequacies in current methodologies for estimating adaptation costs. Broad assessments reveal a significant investment shortfall in adaptation strategies, highlighting the necessity for precise cost analysis to guide effective policy-making. By employing the PRISMA 2020 protocol and enhancing it with the prismAId tool, this review systematically analyzes the recent evolution of cost assessment methodologies using state-of-the-art generative AI. The AI-enhanced approach facilitates rapid and replicable research extensions. The analysis reveals a significant geographical and sectoral disparity in research on climate adaptation costs, with notable underrepresentation of crucial areas and sectors that are most vulnerable to climate impacts. The study also highlights a predominant reliance on secondary data and a lack of comprehensive uncertainty quantification in economic assessments, suggesting an urgent need for methodological enhancements. It concludes that extending analyses beyond merely verifying that benefits exceed costs is crucial for supporting effective climate adaptation. By assessing the profitability of adaptation investments, it becomes possible to prioritize these investments not only against similar interventions but also across the broader spectrum of public spending.

Keywords: climate change adaptation; cost assessment; systematic literature review; generative AI; open science

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1. Introduction

The rapid changes in today's climate pose one of the greatest challenges to global human development. Broad assessments of both current expenditures and needs reveal a significant investment shortfall in strategies for both climate change mitigation and adaptation. This shortfall is evident globally [1] and in Europe [2], highlighting a long-standing critical issue with potentially severe cumulative effects [3,4]. The widening gap in investment is alarming, as the economic and human costs of inaction are projected to be exceedingly high [5].

Understanding the costs of climate adaptation is essential for effective policy-making. Without this knowledge, assessing the adequacy of current efforts and pinpointing areas in urgent need of attention becomes impractical. Cost assessments are crucial in prioritizing investments across various sectors and regions, thereby enhancing resilience to climate change. Moreover, equitable distribution of costs and benefits, both across geographical spaces and generations, demands informed and accountable decision-making. This addresses urgent needs and allocates resources effectively to mitigate the adverse impacts of climate change. Therefore, assessing the cost of climate adaptation transcends academic interest; it is a critical endeavor vital for the well-being and survival of large segments of the global population.

However, and this forms the central thesis of our work, current conceptualizations and assessment approaches for climate adaptation costs are largely inadequate and unsatisfactory. For instance, in many policy and scientific documents, including some previously cited, the term 'climate adaptation costs' is ambiguously used. Sometimes it refers to the

expenses incurred while adjusting human systems to new climate-related hazards. Other times, it denotes the costs associated with failing to adapt, namely, the adverse impacts resulting from this inaction. This inconsistency complicates the accurate assessment and effective management of climate risks, as well as scientific methodological innovations.

In this urgent and complex context, science must offer clearer definitions and more precise methodologies for data collection and assessment. The objective of this study is to provide an updated evaluation of the status and recent evolution of these concepts and methodologies. Understanding the current state and its recent dynamics is essential for identifying inaccuracies and determining necessary improvements.

To clarify our discussion and enhance its utility, this work distinctly separates 'climate adaptation costs' from 'climate adaptation impacts'. The former refers to the expenses related to investments made to reduce human exposure to natural hazards, while the latter pertains to the benefits of such adaptations, such as avoided losses or the challenges humanity faces due to incomplete or inadequate risk mitigation.

Recent systematic literature reviews on climate adaptation costs are crucial in identifying gaps and key areas for assessment, as well as in highlighting critical issues associated with these efforts. These reviews offer valuable insights into the current state of research, expose inconsistencies in data and methodologies, and emphasize the necessity for standardized approaches to better guide policy and investment decisions.

Fankhauser's 2010 analysis [6] highlights the significant discrepancies in cost estimates and underscores the nascent state of this research domain. The paper discusses the complexities of defining and estimating the costs of adaptation, which range from as low as USD 25 billion to over USD 100 billion annually by 2015–2030. The author points out that these variances are indicative of the profound knowledge gaps in both the scope and depth of current research, suggesting that adaptation costs may have been underestimated in earlier studies. The study emphasizes the need to integrate adaptation costs into broader economic and development frameworks to craft more effective climate resilience strategies.

Hartzell-Nichols' 2011 work [7] explores the ethical dimensions of climate adaptation, emphasizing the moral implications surrounding the distribution of adaptation costs. It points out that often, the populations least responsible for climate change—typically the poorest—are the most adversely affected. This intersection of ethical considerations and development issues highlights a significant gap in the literature on the ethics of adaptation and underscores the need for further research to navigate these complexities.

Moore's 2012 study [8] critically assesses the methodologies employed in estimating adaptation costs and contrasts them with economic theory, uncovering notable discrepancies. It reveals that many studies overlook autonomous adaptation and typically assume a scenario of complete adaptation without considering efficiency or optimality. These studies fail to account for the most cost-effective measures necessary for achieving an acceptable level of adaptation, often ignoring the concept of diminishing returns. Moore attributes these discrepancies to the politicized nature of adaptation cost estimates, which serve as boundary objects to navigate normative claims and political agendas under the guise of scientific rationality. This critique calls for a more nuanced understanding and application of economic principles in adaptation studies.

Logar's 2013 study [9] investigates various methods for assessing drought-related costs, including damage costs and the costs of policy measures aimed at both mitigation and adaptation. The study categorizes drought costs into direct, indirect, and non-market costs, and evaluates different estimation methods across economic sectors. The review assesses these methods based on precision, data requirements, and their applicability to future climate change risks. It concludes with recommendations for best practices in the application of these methods and policies to effectively mitigate and adapt to drought.

Sussman's 2014 article [10] focuses on the United States, reviewing key studies across various sectors and highlighting methodological issues. The article emphasizes the need for more comprehensive and comparable studies to enhance policy and decision-making. It points out significant gaps in sectoral and geographic coverage, as well as inconsistencies

in methodologies and assumptions used, underscoring the urgency for improved research frameworks to better inform adaptation strategies.

Markanday's 2019 review [11] evaluates the use of cost estimates in the cost-benefit analysis (CBA) of climate change adaptation. It underscores the methodological challenges and limitations of CBA, such as difficulties in monetizing benefits, handling uncertainties, and addressing equity concerns. The review examines various case studies and suggests improvements to make CBA more applicable and robust for adaptation planning. It stresses the importance of incorporating broader socio-economic factors and ethical considerations into the analysis to better inform policy decisions.

Chapagain's 2020 study [12] provides a meta-analysis of adaptation cost estimates in developing countries, categorizing them into three types: national plan-based, bottom-up science-based, and global top-down estimates. The analysis reveals that adaptation costs escalate significantly with higher levels of global warming and vary according to a country's economic status and the methodologies used. The study indicates that current climate finance pledges are considerably lower than the estimated global adaptation costs, highlighting the urgent need for increased financial support for developing countries to effectively adapt to climate change.

It is, therefore, our foundational assertion in this work that measuring adaptation costs presents multiple scientific challenges. Our objective is to systematically map recent approaches, outline their main shortcomings and key points, and determine if any emerging trends indicate a specific direction that the scientific community is adopting. To conduct the systematic literature review, we adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA 2020) protocol [13], augmenting the traditional analysis approach by incorporating the prismAId tool [14]. This tool utilizes generative AI models within an open science framework, enhancing the accuracy, replicability, and extensibility of our review.

This paper is organized as follows: We begin by detailing our methodology, thoroughly explaining the protocol and its application. Particular emphasis is placed on describing the many advantages introduced by the AI-enhanced approach during the literature analysis phase. Subsequently, we present results concerning the current approaches to assessing climate adaptation costs as featured in recently published studies. Finally, we conclude the paper by discussing the results and the methodological innovations introduced by this study.

2. Materials and Methods

The workflow we followed is summarized in Figure 1. The systematic review begins with the identification phase, starting with the definition of a search query. This query is executed on the Web of Science database, yielding an initial set of 69 records. During the screening phase, these records are first checked for duplicates to ensure each study is unique. Systematic reviews within these records are identified and removed, resulting in the exclusion of 7 reviews, leaving 62 studies. Further scrutiny is applied to ensure the relevance of the studies to the review's scope, leading to the removal of 14 out-of-scope studies, narrowing down the list to 48 relevant studies.

The analysis phase then proceeds exclusively with an AI-enhanced approach. While the traditional analysis method, involving thorough reading and manual tagging of information from studies, is depicted for context in Figure 1, it is not employed in this review. Instead, the review project is defined to specify the information that AI models will extract. The project is then executed using generative AI models, which automate the extraction and compilation of data systematically entered into a results database.

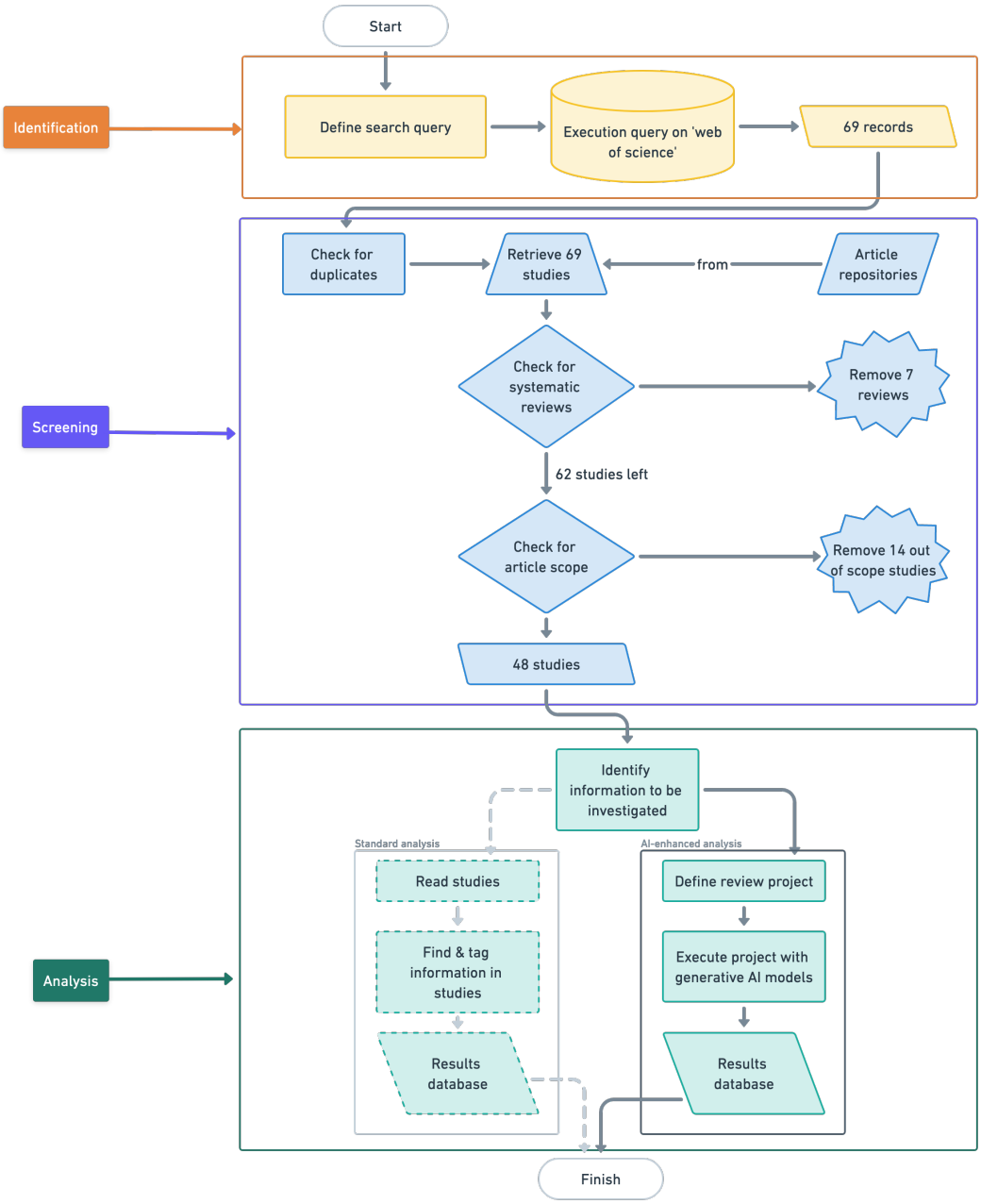

Figure 1. Literature review flow diagram. Source: Adapted from [13], with Creative Commons Attribution License permission from publisher BMJ, 2021.

2.1. Identification of Studies

To ensure a comprehensive and relevant collection of data for our research, we formulated the following search query tailored to our specific interests and subsequently we executed it on the Web of Science portal https://www.webofscience.com (accessed on 29 May 2024):

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(cost AND adaptation) in title
(cost AND (climate OR "climate change") AND adaptation) in abstract
from 2010 to 2021
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This query was strategically designed to capture a comprehensive set of studies pertinent to our review. By specifying "cost" and "adaptation" in the title, we targeted contributions where these themes are prominently featured by the authors. Furthermore, we expanded the keywords to include a climate component in the abstracts to selectively filter contri-

butions that focus on the costs of adapting to climate change, distinguishing them from adaptations related to other phenomena.

The decision to conduct the query exclusively on Web of Science is justified by the research scope, as this platform is recognized as a comprehensive source of scientific literature with multidisciplinary coverage [15]. Moreover, we intentionally excluded 'gray literature' from our review because our aim is to explicitly evaluate the scientific status of adaptation cost estimation, rather than considering other pertinent but non-scientific documents, such as policy reports and similar texts.

2.2. Screening Phase

The initial search query performed on the Web of Science portal yielded 69 papers. From this collection, we excluded 7 contributions identified as literature reviews. Although these reviews were not directly included in our final analysis, they provided valuable insights that helped to frame our work. Specifically, we utilized these reviews in the introductory part of our work and to identify key scientific challenges to investigate further in our analysis.

From the remaining 62 articles, we further excluded 14 (over 20%) because they primarily addressed adaptation costs in terms of the adverse impacts resulting from a failure to adapt to the changing climate. These articles were focused on assessing potential damages rather than detailing the actual costs associated with implementing climate adaptation measures. Moreover, this specific focus was often not clearly indicated in the titles or abstracts, leading to ambiguities in their classification and relevance to our defined research criteria.

2.3. Literature Analysis

As depicted in Figure 1, the analysis phase of the systematic review process involves two primary steps. Initially, it is essential to identify the specific information to be searched within the literature. Following this identification, the literature is systematically analyzed to extract and assess the pertinent data, which forms the basis of our findings.

Following the description of scientific challenges in the introductory part, we define several aspects of interest to investigate in the reviewed studies. Firstly, the process cannot rely on standardized data sources, as there are no national or international standards for recording climate adaptation costs for private entities or public organizations and governments. Consequently, cost values must be derived from a broad and diverse range of expenditure categories, including both capital and current expenditures.

This situation leads to a significant challenge: attribution. Attribution is complicated by the fact that adaptation measures are often integrated into broader human activities and ongoing natural risk mitigation efforts, which may also address other types of hazards, such as earthquakes and fires. This integration raises critical questions about how to effectively apportion costs among different hazards.

The challenges associated with measuring climate adaptation investments are exacerbated by their complex nature. For instance, some climate adaptation investments incur significant indirect costs. Updating building codes, for example, may directly involve only the time of experts and the cost of consultations and deliberations. Additionally, climate adaptation efforts often require large initial investments, with benefits that accrue over extended periods. Due to overlapping accounting norms and practices, the available data may only reference depreciation flows or the financing of past investments, while information on the capital stock attributable to climate adaptation services can be sparse or exceedingly difficult to estimate.

When considering data sources, it is crucial to understand how new data can be directly collected to accurately capture local adaptation costs and experiences. Establishing clear conceptual definitions can significantly reduce biases and enhance all other aspects of data quality. Although secondary sources, such as those from public authorities and literature, are valuable, these sources may be too general and updated infrequently. To overcome

challenges related to data replicability, it is vital that data references and methodologies are clearly presented at the outset, rather than relegated to footnotes or Supplementary Materials. This practice promotes transparency and aids in the verification and replication of findings. Unfortunately, this method is not consistently applied in the scientific literature and is often neglected in reports and datasets from public authorities.

Estimations from models often carry limitations due to the methodologies adopted, which can be opaque. For example, estimations from Integrated Assessment Models (IAMs) may suffer from oversimplified representations of economic dynamics, characteristic of these models. Conversely, estimations from Computable General Equilibrium (CGE) models might not adequately capture long-term trends, tending to overestimate the current state of technologies. Additionally, CGE models often operate on broader and coarser scales, which may be unsuitable for accurately assessing climate adaptation costs.

The complexity of climate adaptation, coupled with profound differences within our economies and societies, often results in sparse and divergent efforts. This divergence leads to the adoption of sector-specific, ad hoc approaches and methods. While strategies for adapting agriculture and the food system may differ markedly from those required for climate-proofing infrastructure and the built environment, it is essential that underlying concepts and definitions remain consistent. Moreover, methodologies should strive for a similar level of rigor to ensure comparability and effective prioritization of potential investments at the societal level.

Finally, the intended use of cost assessments by researchers and policymakers may influence the choice of methodologies, which is not always neutral [8]. For instance, methods suitable for calculating costs in CBA might not be appropriate for identifying the most efficient adaptation strategies via Cost-Effectiveness Analysis (CEA) or Internal Rate of Return (IRR) evaluations.

In summary, our goal is to understand the current state of research on climate adaptation costs by assessing methodological preferences, geographical focuses, sector-specific issues, and the application of cost data in decision-making processes. We formally define the scope of our review analysis through the list of information variables presented in Table 1, which summarizes all the points we discussed so far.

2.3.1. Study Area

This section categorizes the geographical focus of the reviewed studies to understand the diversity of settings in climate adaptation research. It differentiates between specific environments—coastal, urban, and global—highlighting the unique challenges and solutions relevant to each. The aim is to provide insights into how geographic context influences adaptation costs and strategies, enhancing the applicability of our findings across various regions.

2.3.2. Approach to Cost Estimation

The "Approach to Cost Estimation" section explores the methodologies employed by the studies reviewed to estimate costs related to climate adaptation. This includes data sourced from surveys, authorities, or literature. It examines whether the studies have utilized advanced modeling techniques, such as IAMs or CGE models. The section also covers how costs are defined, whether as increases in production costs, shares of asset values, or based on marginal cost assessments. The aim is to evaluate the robustness and variety of methodologies used, and to understand their implications for cost estimation accuracy.

2.3.3. Focus of Climate Adaptation Efforts

This section identifies the specific sectors where climate adaptation efforts are focused, according to the reviewed literature. It examines whether the studies address sectors like agriculture, the built environment, infrastructure, health, and others. This categorization helps in understanding the distribution of research across different sectors and the prioritization of adaptation efforts. It also sheds light on where adaptation strategies are

considered most crucial, potentially impacting policy-making and strategic planning in these areas.

Table 1. Information analyzed in the reviewed studies.

No.	Variables (Binary Boolean Values Unless 'Open' Answers)
A.	*Study Area*
1	Case study area: coastal
2	Case study area: urban
3	Case study area: global
4	Location of the study area (open)
B.	*Approach to Cost Estimation*
1	Data from survey
2	Data from authorities
3	Data from literature
4	Reported in Supplementary Information
5	Derived from integrated assessment models—IAMs
6	Derived from computable general equilibrium—CGE
7	Defined as increase in production cost to maintain today's level
8	Defined as share of today's asset/activity value
9	Based on marginal costs assessments
10	Uncertainty quantification
C.	*Focus of Climate Adaptation Efforts*
1	Agriculture/Food
2	Built environment
3	Infrastructure
4	Health
5	Equality
6	Nature-based solutions
7	Economic development in the medium- long-run
8	Tourism
D.	*Methodological Uses of Cost Estimations*
1	Cost-benefit analysis (CBA)
2	Cost-effectiveness analysis (CEA)
3	Benefit-to-cost ratio (BCR)
4	Net present value (NPV)
5	Internal rate of return (IRR)
6	Profitability index (PI)
7	Multi-criteria analysis (MCA)

2.3.4. Methodological Uses of Cost Estimations

The final section, "Methodological Uses of Cost Estimations", details how the cost data from the studies are applied in various analytical frameworks, such as CBA, cost-effectiveness analysis (CEA) or internal rate of return (IRR). The purpose of this section is to understand the broader applications of cost data in policy-making and strategic planning, examining whether these methodologies are employed to justify investments in adaptation, prioritize actions, or assess the economic viability of different adaptation strategies.

2.3.5. AI-Enhanced Approach

The analysis phase was conducted using the prismAId tool (v0.3.1), which utilizes generative AI models to leverage Open Science features, aiming to accelerate and enhance the accuracy of systematic literature reviews.

Specifically, the traditional approach (as depicted through dashed lines at the bottom left of Figure 1) would have entailed manually reading all the articles and populating a scorecard with relevant data. In contrast, the prismAId method involves creating specific prompts for AI models to automatically extract the necessary information. This tool

requires researchers to provide detailed descriptions of the information they wish to analyze, including definitions, possible answers, and examples. By doing so, the analysis becomes more accurate due to the reduction of ambiguity in terminology and a clearer delineation of the scope of validity. The traditional approach would leave interpretation of terms to the researchers, without explicitly tracking meanings and limitations, potentially introducing inconsistencies in data interpretation.

Furthermore, this review's methodology and AI prompts are transparently documented, allowing any interested reader to replicate or extend the analysis. This article, hence, also includes the list of selected literature in the Appendix A (Table A1) and the primsAId project configuration files, which specifies the prompts and all parameters used, in the Supplementary Materials of this article.

Going deeper into the specifics of the AI-enhanced analysis, we initially prepared the studies for processing by removing non-essential parts of the documents. This decision was guided by a two-fold rationale. First, it is recognized that noise can marginally, yet significantly, affect the accuracy of information retrieval when using generative AI models [16]. Second, our aim was to avoid extracting information from sections where authors discuss or review the work of others, which might introduce redundant, contradictory, or secondary data into our analysis. Consequently, we removed the list of references and the introductory section from all the studies under consideration, except for [17], from which only the references and abstract were omitted. Additionally, for [18–20], we also removed the second section of each paper, which explicitly presented a literature review.

We utilized OpenAI models https://openai.com following the cost minimization approach enabled by the the prismAId tool, which in v0.3.1 of the software selects the cheaper GPT 3.5 Turbo model when possible. However, an exception was made in the case of [21], for which the analysis required the use of the model GPT-4 Omni to achieve valid results. Furthermore, to enhance the precision and focus of our information retrieval, we divided the task into seven sub-projects. Each sub-project was dedicated to a different subset of the information variables presented in Table 1. Details on each sub-project configuration files are documented in the Supplementary Information (SI) accompanying this paper. This structured approach allowed us to tailor the AI models' prompts and processing capabilities to the specific demands of each data category, ensuring a more efficient and targeted retrieval of relevant information.

Overall, we conducted a dozen tests to fine-tune the prompts and validate the project configuration files. Given the token processing limits per minute imposed by the OpenAI API for the user tier to which the author belongs, the total runtime for our analysis was approximately 5 h. The total cost of executing the analysis in June 2024, which included both the testing of the configuration files and the actual analysis, amounted to USD 4.39.

The dataset resulting from the AI-enhanced analysis were meticulously validated by randomly verifying extracted pieces of information against the original literature sources. The data contain several binary fields for which, in our configuration, there was an option to leave the field empty if the AI model was not fully convinced of a positive or negative assessment.

3. Results

First, we studied the distribution of missing values to understand the overall level of uncertainty in our analysis. Out of 1344 possible binary values, the AI system left 71 of them (approximately 5%) empty. For the purposes of this analysis, we considered these missing values as non-positive, meaning that the model did not find sufficient information in the studies to confirm the presence of the information we were seeking.

Importantly, missing answers are almost evenly distributed across the dataset, with two notable exceptions. A higher concentration of missing responses occurs in the section discussing the methodological use of assessed costs as detailed in [22], and in the assessment of whether the climate adaptation efforts considered impact economic equality. This pattern suggests that data in these areas may be more challenging to interpret with the current

project configuration. It also highlights the potential need for future refinements in AI prompt specifications on these topics.

3.1. Study Area

Plotting the number of studies reviewed by publication year, as shown in Figure 2, reveals that there has not been a steady increase in the number of publications, as might have been hoped. Instead, the data indicate a quite limited range of annual publications with a sharp increase in the last two years. While this recent surge is encouraging, it remains limited in scope.

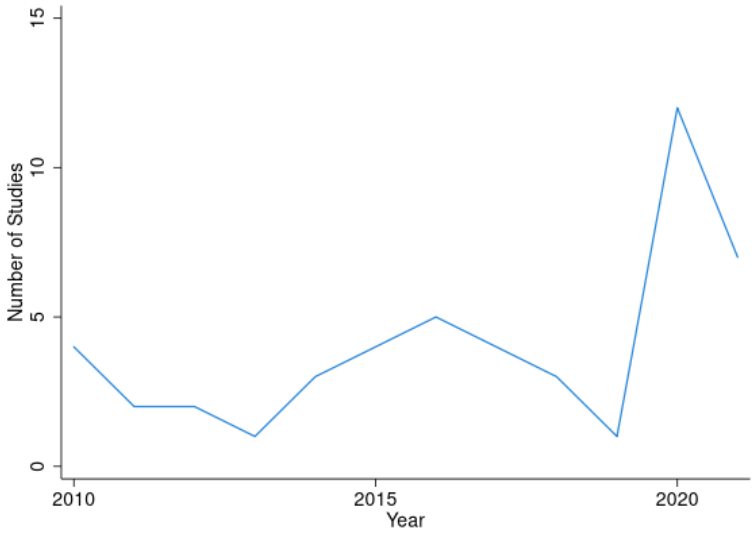

Figure 2. Number of studies reviewed by publication year.

The distribution of case study areas by continent is depicted in Figure 3. In this figure, we present the total number of studies that focus on specific locations in blue (studies with a global perspective or those without specific geographic references are naturally omitted). In contrast, we highlight in green and yellow the studies that specifically discuss coastal and urban areas, respectively.

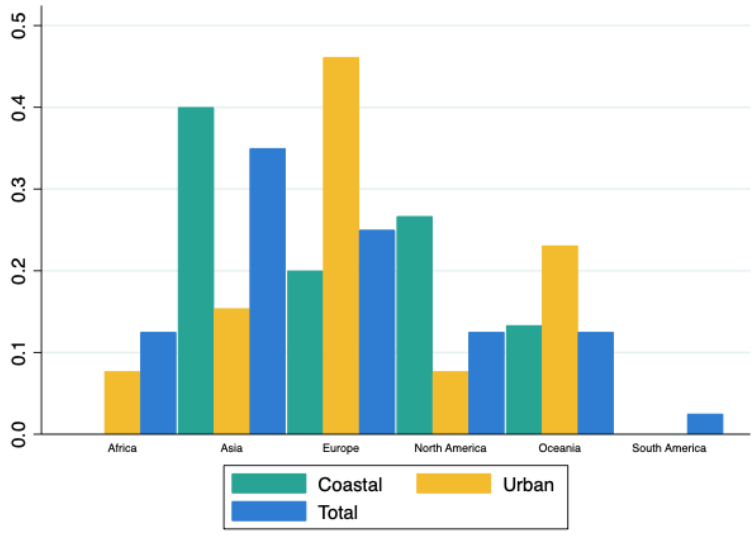

Figure 3. Frequency of areas of study by continent (frequency of coastal areas investigated is reported in green, urban areas in yellow, and total number of locations in blue).

Asia and Europe together account for 60% of the locations investigated in the reviewed studies, with Asia being the predominant continent at 35%. Similarly, when focusing specifically on coastal areas, Asia remains the most represented, comprising 40% of studies on coastal regions, followed by North America and Europe. Conversely, Europe emerges as the primary focus for studies on urban climate adaptation, representing 45% of such research, with Oceania also receiving significant attention at over 20%.

This geographic distribution highlights a surprising lack of representation of Central America and the Caribbean, along with a strong under representation of South America and the Middle East in the studies reviewed. These regions, despite being highly vulnerable to the impacts of climate change, have not been the focus of as much research as might be expected.

3.2. Approach to Cost Estimation

The findings concerning the approaches to cost estimation are presented in Figure 4. This figure illustrates the percentage of studies that adopt each of the concepts or approaches analyzed. It provides a visual representation of how prevalent different methodologies are within the existing literature, highlighting the most and least commonly used strategies in assessing the costs of climate adaptation.

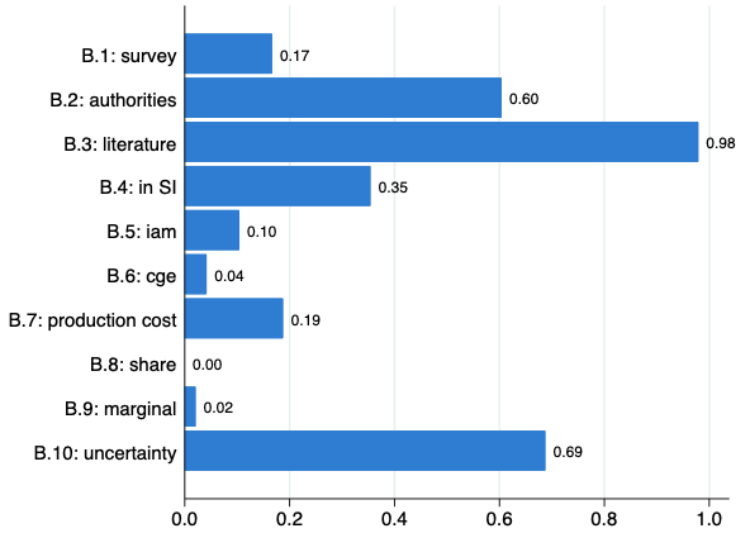

Figure 4. Results in the section on the approach to cost estimation presented as percentage of studies adopting the concept or approach analyzed.

Almost all the studies reviewed rely heavily on secondary data, with 98% deriving information from existing literature and 60% utilizing data from public sources and authorities. In contrast, a very limited number of studies gather new cost data directly through surveys and questionnaires. Additionally, over one-third of the studies include details on cost assessment in the Supplementary Information rather than in the main text, which suggests a lack of emphasis on methodology within the primary discussions of these papers.

The prevalent reliance on secondary data in the studies reviewed may impede the innovation of new methodologies and the validation of existing models, as it largely depends on previously established data frameworks. The limited engagement with primary data collection—evident from the mere handful of studies employing surveys and questionnaires—raises concerns about the robustness and adaptability of findings to evolving economic and policy contexts. Moreover, the tendency to relegate detailed methodological discussions to Supplementary Materials could diminish the transparency and reproducibility of research findings. This practice may limit the utility of these studies for policy-making, where comprehensive and clearly articulated methodologies are crucial for

assessing the applicability and reliability of cost evaluations. Moreover, detailed methodological transparency is essential to ensure the accountability of decision-makers in the public sector.

Only a handful of studies employ macroeconomic modeling approaches or other methods rooted in economic theory, such as analyses based on marginal costs or production costs. While uncertainty is frequently considered in these studies, the focus predominantly lies on the uncertainties associated with climate-related natural hazards rather than on the economic assessments themselves.

This oversight in assessing economic uncertainties may significantly hinder the development of effective strategies for managing the intrinsic uncertainties associated with the costs of long-lasting infrastructural projects required for climate adaptation. For policymakers, such shortcomings may lead to cost overruns, delays, inadequate resource allocation, and ultimately, a loss of public support for climate adaptation initiatives.

3.3. Focus of Climate Adaptation Efforts

Results highlighting the prevalence of specific efforts and thematic focuses in climate adaptation across the analyzed literature are presented in Figure 5. These results emphasize the substantial interest in supporting economic development through adaptation efforts, as evidenced by references in 75% of the studies. Additionally, almost two-thirds of the studies focus on infrastructure adaptation, which is probably envisioned as a critical mechanism for preserving the potential for economic development.

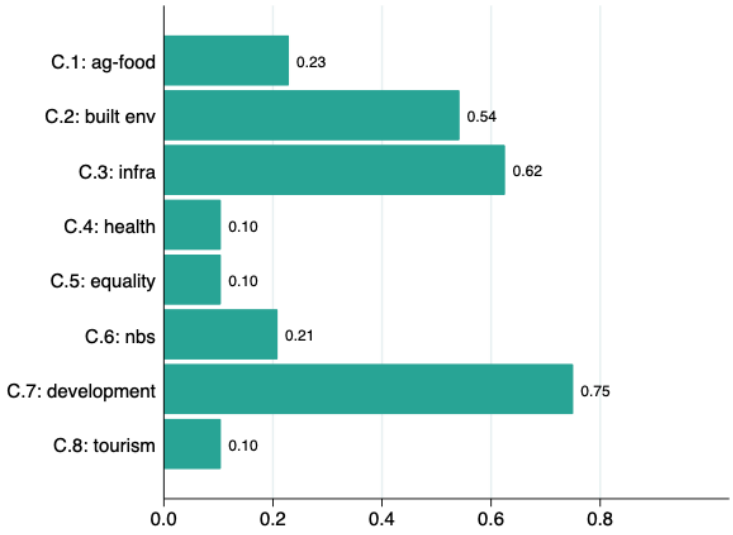

Figure 5. Percentage of reviewed studies that adopt various concepts or approaches concerning the focus of climate adaptation efforts.

Over half of the studies reviewed focus on the built environment and strategies to protect it. Additionally, 21% of the studies explore the potential of relying on nature-based solutions, indicating a growing interest in sustainable and ecological approaches to adaptation. Agriculture and food systems are also prominently featured (23%). In contrast, health implications, issues of equality, and tourism receive considerably less attention, suggesting that these areas may be underrepresented in current research and approaches on climate adaptation.

The emphasis on economic development suggests a necessity for policymakers to garner support for climate adaptation initiatives by demonstrating that the economic benefits outweigh the costs (see also below on CBA). However, this focus on adaptation efforts with positive economic outcomes restricts the range of methodologies employed for cost assessments. Such methods, in fact, are seldom applied or developed to evaluate

initiatives primarily aimed at adapting to climate change with different objectives, such as those seeking positive impacts on health and social equity.

3.4. Methodological Use of Cost Estimation

As previously discussed, the intended use of cost assessments can significantly influence the selection of the analytical approach to cost estimation. Therefore, we analyze the prevalence of various methods utilizing cost estimations across the reviewed literature. The results are presented in Figure 6, which depicts the percentage of studies employing different methods and indicators. To provide a more detailed perspective, Figure 7 specifically focuses on the subset of studies that utilize CBA. This figure reports the indicators most frequently associated with such analyses, offering insights into the common metrics and considerations that accompany the application of CBA of climate adaptation interventions.

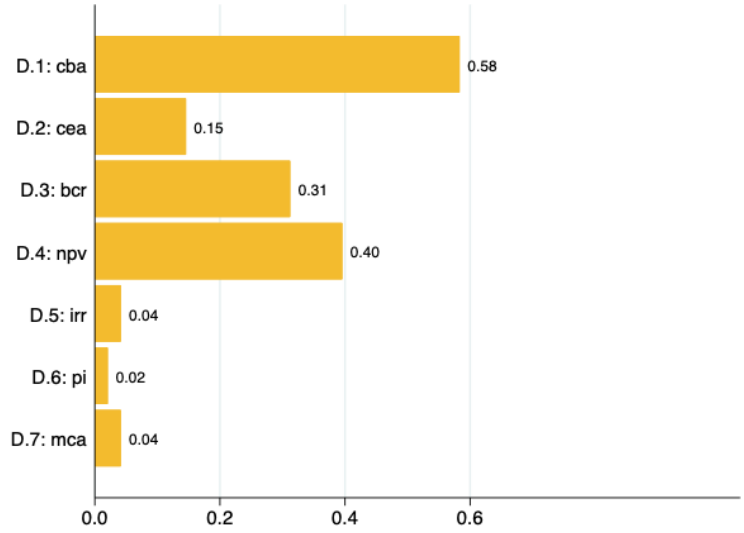

Figure 6. Percentage of reviewed studies employing various methods and indicators based on the assessed climate adaptation costs.

The majority of studies, almost 60%, employ cost estimates primarily to conduct CBA. Additionally, a significant proportion of studies, about 40%, compute net present values, thereby incorporating a multi-temporal perspective into the assessment of the costs—and potentially the benefits—of climate adaptation.

However, approaches that include non-economic dimensions for decision-making, beyond just costs and economic benefits, appear to be underutilized. This is evidenced by the rarity of studies referring to multi-criteria analysis (MCA), which would typically encompass a broader range of decision-making factors, including environmental, ecosystems, social, fairness, and governance aspects.

This complements the observations made in the preceding section regarding the scope of adaptation initiatives considered. Cost assessments are primarily confined to the economic dimension, thereby excluding various other dimensions that could influence public support and decision-making. This approach may also overlook potential indirect costs, such as those arising from the appropriation of natural resources and ecosystem services.

Of the studies focusing on CBA, over half utilize the benefit-to-cost ratio to support decision-making on adaptation strategies. This metric is frequently chosen due to its straightforwardness in evaluating the economic efficiency of investments in adaptation. However, the profitability of these investments is less frequently considered. This is evidenced by the low prevalence of metrics such as the IRR and the profitability index (PI) in the broader research (Figure 6) and specifically among those studies employing CBA (Figure 7).

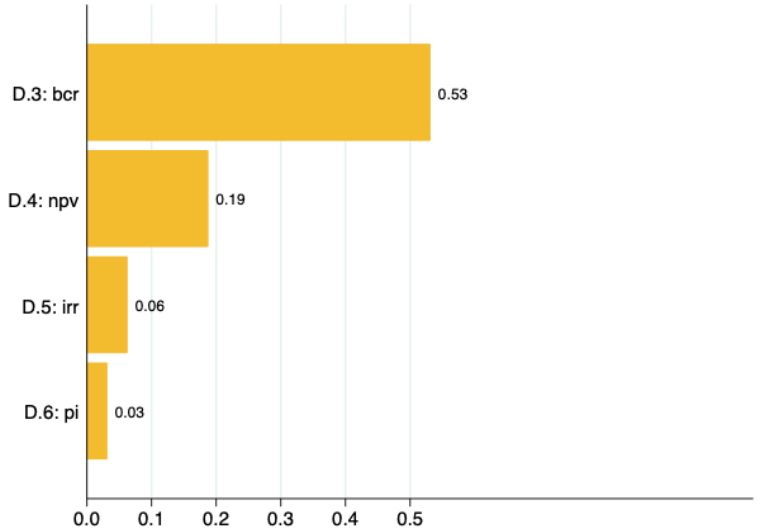

Figure 7. Percentage of studies employing various indicators within those that use CBA based on the assessed climate adaptation costs.

4. Discussion and Conclusions

We have systematically explored the current methodologies and approaches in the field of climate adaptation costs through a detailed review of the recent literature. Our findings highlight several key trends and gaps that have significant implications for future research and policy-making.

One of the main findings from our review is the broad range of cost estimates, methodologies, and focal areas identified across the studies. This diversity reflects the inherently varied details and needs of adaptation efforts across different contexts. In other words, this variety is beneficial as it allows for tailored approaches to unique regional and sectoral challenges, even though it may complicate assessments from a global perspective. However, our work also brings to light several concerns that need further exploration.

One of the initial findings highlighted above is the significant geographical disparity in the focus of the studies, particularly the underrepresentation of regions such as Central America, the Caribbean, and the Middle East. Similarly, research on coastal and urban adaptation is not evenly distributed, with many areas of the world either ignored or insufficiently studied. This uneven distribution can lead to underrepresentation and lack of analytical capability, which may impede effective climate adaptation strategies in areas that are significantly vulnerable to climate impacts.

Similarly, sectoral representation is incomplete. It is evident that industries dependent on natural resources are more exposed to natural hazards; however, there is still a significant gap in our understanding of how their adaptation costs compare to those of other industries, which may have been less exposed to such 'emerging' natural risks.

Another key issue that emerged in our analysis concerns data sources. The prevalent reliance on secondary data, primarily sourced from existing literature and, to a lesser extent, public sources, could potentially limit the novelty and precision of cost estimates. Primary data collection through surveys and direct assessments is significantly underutilized. From a broader perspective, the focus on data sources is insufficient, problems related to the attribution of spending to climate adaptation purposes are not adequately discussed, and consequently there are no evident proposals to improve data collection methods emerging from these studies.

The consequences of lack of methodological focus extend to the conceptualization and quantification of uncertainty. While uncertainty is occasionally addressed, the focus is narrowly placed on climate as the source, given the uncertain nature of natural hazards. Considering the inherent uncertainties in climate-induced scenarios is indeed crucial for

climate adaptation; however, we argue that cost estimates themselves are inherently uncertain and imprecise. A key advancement in methodology would, therefore, be to integrate a robust assessment of their accuracy through enhanced uncertainty quantification.

Along the same lines, the long-term lifecycle and impacts of climate adaptation efforts are still not fully grasped. Only a significant minority of the reviewed studies utilize cost assessments to develop a NPV of adaptation investments. Failure to capture the inherently multi-temporal nature of these efforts could potentially lead to inaccurate assessments of both benefits and costs.

Besides the use of NPV, our review reveals that the methods for utilizing assessed costs do not significantly influence upstream cost assessment approaches. However, in practical applications, there is considerably less variety, with almost two-thirds of studies relying on CBA. This uniformity has two important consequences. First, there is a notable gap in non-economic assessments, as evidenced by the extremely limited use of MCA approaches. This gap results in the underconsideration of social, environmental, and ethical dimensions, both as costs and benefits.

Second, the focus on CBA, rather than on other economic approaches, constrains the analysis to project approval rather than broader financial viability. In fact, CBA supports decisions between adaptation efforts aimed at managing a specific natural hazard but does not facilitate decision-making when multiple (often interdependent) natural risks are considered. Furthermore, the lack of emphasis on profitability concepts (e.g., IRR, PI) limits the ability to compare these investments with others, potentially hindering the prioritization of adaptation investments and the building of consensus about their value.

In the literature reviewed, the predominant focus on direct economic impacts and costs, along with the neglect of cost uncertainty and the adaptation effort life-cycle, highlights significant limitations in applying the existing methodologies for policy-making. To address these gaps, scientific innovations are needed that extend cost analyses and adaptation efforts to other domains, such as health, ecosystems, and social equity. Such expansions would enable a more comprehensive understanding of both indirect costs and benefits. Additionally, there is need for distinguishing cost uncertainties from those associated with natural hazards and adopting a multi-temporal perspective capable to address the adaptation life-cycle. These policy needs should guide future approaches to the scientific assessments of adaptation costs.

As a final methodological note, we adhered to the PRISMA standardization [13], which defines three phases: identification, screening, and analysis. We enhanced the analysis stage with the aid of the tool prismAId [14]. This enhancement effectively substitutes the traditional ones by teams of individuals with a formalized assessment by a model. This model is a state-of-the-art generative AI capable of understanding human texts. The formalization comprises the project configuration we developed, which specifies model parameters and prompt engineering. This latter aspect precisely defines the information sought and provides the model with all necessary instructions to execute the task.

The analysis has been faster and accurate, as confirmed by manual verification checks against the reviewed studies. For human analysts, the process of reviewing multiple studies can be error-prone and attention-demanding. By meticulously defining concepts, the AI-enhanced analysis achieves greater consistency and homogeneity than traditional methods conducted by research teams. These teams, in fact, often face challenges in developing and sticking to a uniformly shared understanding of the definitions and boundaries of various analytical concepts.

Finally, the AI-enhanced analysis can be replicated by anyone in a matter of minutes. It can also be quickly extended to study different time periods by simply changing the set of studies considered. Furthermore, the analysis can be expanded by adding or substituting information pieces to be analyzed. Overall, the AI-enhanced analysis represents a promising advancement in protocol-based literature reviews, significantly enhancing several Open Science features.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cli12080116/s1, Seven project configuration files ('.toml' extension); File with full results from AI-enhanced analysis: 'results.csv'.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
BCR	Benefit-to-Cost Ratio
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CGE	Computable General Equilibrium Model
IAM	Integrated Assessment Model
IRR	Internal Rate of Return
MCA	Multi-Criteria Analysis
NBS	Nature-Based Solutions
NPV	Net Present Value
PI	Profitability Index
SI	Supplementary Information

Appendix A

Table A1. List of Reviewed Studies [17–64].

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