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Review Article

From vulnerability to adaptation: A systematic review of land-based economic outcomes of adverse climate events ☆

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HIGHLIGHTS

- Climate adaptation measures reduce economic vulnerability by an average of 7.7%.
- Quasi-experimental evidence exposes sizable heterogeneity in climate impacts.
- Information asymmetries on land hierarchy spur adverse selection exacerbating inequality.
- Policy synergy fosters equitable resilience in land-based climate adaptation.
- Global empirical coverage is uneven, leaving Africa and Latin America understudied.

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ABSTRACT

Cities worldwide are experiencing unprecedented climate pressures that call for evidence-based adaptation planning and design strategies. An active area of research has emerged to explore how various adaptation policies mitigate the adverse economic impacts and help build resilience following adverse climate events. Following the PRSIMA protocol, this review systematically screened extensive relevant literature and ultimately include 108 original papers for bibliometric analysis. We reveal critical gaps in geographical coverage, hazard diversity, property types, and cascading impacts. Furthermore, a random-effects meta-analysis is conducted to compile 44 estimates of treatment effects on property values reported by quasi-experimental studies. We find that magnitude of vulnerability to hazard exposure decreased by 7.7% on average when equipped with adaptation measures. The results are robust to using implementation of adaptation as an alternative treatment definition. However, our review also reveals substantial heterogeneity, and even opposing effects amplifying vulnerability, where adaptation practices can trigger unintended consequences, prove cost-inefficient, or exacerbate preexisting inequalities. By synthesizing these empirical findings, we propose a four-quadrant policy matrix to explain the heterogeneity of adaptation effects, which is informative for policymakers designing concerted policy portfolios. Our review also outlines a roadmap for future research to unpack information channels and the interplay between different climate adaptation activities.

1. Introduction

Evidence for a changing climate is even more compelling than we thought it would be a few years ago. As densely populated and highly structured areas, neighborhoods in cities are emerging as the key battlefields for encountering climate risks (Joshi et al., 2024). Some settlements across the world are already experiencing severe challenges due to the increasing frequency and intensity of extreme climate events. As documented by IPCC (2023), urban areas face compound risks from inland or coastal flooding, storms, wildfires, and heatwaves. Future climate risks are expected to cause severely adverse impacts on land-based assets, and damage key local infrastructure that provides essential services to neighborhoods (Kelly & Molina, 2023). Concurrent with climate change impacts, developers and households continue to locate new properties in the ever-increasing flood-prone areas or wildland-urban interface (WUI) benefiting from value premium derived from

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environmental amenities (Fitch et al., 2023; Peralta & Scott, 2024). The tension between uncertain environmental vulnerabilities and certain land economic benefits presents contemporary challenges for land management and adaptation practices.

Though it is difficult to predict the future climate impacts, there is a wide body of literature to help us understand what happened to neighborhoods and residences exposed to the threats during past serious climate events. Many leveraged the short, extreme events experienced in a given area as identification strategies, typical examples include floods, hurricanes, and wildfires (Akter, 2023; Ellen & Meltzer, 2024). The pre-post change of property value is the most common dependent variable used to indicate the adverse impact and treatment effects. Though there are many other critical dimensions of outcomes such as safety, vitality, well-being, property value still serves as the prime indicator because many other characteristics can be capitalized into the land value through a hedonic model (Breunig et al., 2019). These baseline data and estimates based on rigorous experimental designs provide a credible basis to gauge the land-based economic outcomes from adverse climate event.

Observed impacts from climate events, however, are not distributed evenly among or within urban regions (Indaco & Ortega, 2024). The nature of vulnerability is context specific (Adger, 2006)—households who live in high poverty and socially marginalized areas fare worse than those living in affluent neighborhoods across a wide range of socioeconomic outcomes after the climate shocks and stresses. Such disparities in vulnerabilities are attributed to varying degrees of household socioeconomic status (SES), which low-income or marginalized neighborhoods commonly lack (Lerner & Rottman, 2021). Recent works in urban studies and environmental sciences have employed concepts such as *climate justice* (Long & Rice, 2019) and explored the spatial and societal development factors that drive the disproportional exposure to climate risks (Yang et al., 2021).

In response to climate change and multiple threats, many cities across the world have been considering protective and place-based strategies for adaptation within their communities. Urban planners and landscape architects shape the physical form of cities through decisions about land use patterns, infrastructure placement, green space distribution, and development density. These decisions directly influence both the exposure of communities to climate hazards and their capacity to adapt (Carter et al., 2019; Hudson & Botzen, 2019; Shi & Moser, 2021). Like vulnerability, the capacity for cities and neighborhoods to gather resources for resilience building also varies between and within urban areas. For vast countries like U.S., there are still few national-level regulations or provisions focused on urban adaptation; the initiatives and investments in adaptation are highly localized (Solecki & Rosenzweig, 2022). Even after decades of experience and increasing popularity on adaptation and resilience, empirical research in this area has only recently begun to expand rapidly. A systematic review assessing both the vulnerabilities and the actual effect of adaptation activities is needed to advance understanding of the interaction between climate impact and resilience building. Questions have been raised about *how cities are simultaneously extremely vulnerable to increasingly frequent extreme events yet especially well positioned to adapt and build resilience against environmental threats*.

Prior systematic reviews have primarily focused on the vulnerability side under a single peril, particularly price discounts associated with floodplain locations (Beltrán et al., 2018; Daniel et al., 2009). These studies aggregate empirical evidence (estimates) from previous hedonic price analyses in the U.S. real estate market using meta-regression models; however, neither fully explores the disproportionate climate burdens faced by different neighborhoods. Similarly, Nicholls (2019) extends the risk scope to include additional environmental disturbances such as invasive species and wildfires but identifies only 20 papers in total, limiting the ability to conduct robust statistical analyses or draw strong comparative conclusions. Other reviews have considered broader social consequences, like demographic migrations (Thomas et al., 2022), socio-economic stratification (Lambrou et al., 2023; Rufat et al., 2015), and environmental justice (Allaire, 2018). A key limitation across these reviews is the lack of standardized metrics or composite indices that could systematically capture the outcomes as the measures of social vulnerability vary considerably. To our knowledge, the only existing meta-analysis that maps the socioeconomic outcomes of several climate risks in the housing market is Contat et al. (2024), who also touches upon issues of heterogeneous impacts and climate-induced migration. However, they still does not thoroughly examined the influence of adaptation, except for a brief discussion of insurance, which is likely to become more common in practice under climate change. Furthermore, previous systematic reviews (e.g., Beltrán et al., 2018; Contat et al., 2024) restrict their scope specifically to the US context, which may lead to bias and incomprehensive insights.

In contrast, there is an accumulating body of empirical evidence on various adaptation efforts — from public funded infrastructure defenses to climate risk insurance (CRI) programs — across different communities and regions worldwide (Wannewitz et al., 2024). Beyond compiling recent estimates and frontier findings, our review seeks to bridge the study of vulnerability and adaptation across diverse disaster risks. We emphasize empirical studies that have a quasi-experimental design and find heterogeneous and even opposing effects. Specifically, while most studies report that the adaptation programs have a positive effect on reducing economic losses (Ellen & Meltzer, 2024; Kelly & Molina, 2023), others find that the effect can be negative (e.g., Blackwell et al., 2024; Tanner, 2018). As climate impacts intensify, the traditional planning goals of promoting livability, accessibility, and environmental quality must now integrate resilience as a core objective. Understanding how different planning interventions and landscape modifications translate into measurable economic outcomes provides essential feedback for evidence-based design and policy decisions.

Given the broad range of economic outcomes associated with climate change, let alone long-term transition risks, we restrict the scope of our review to specific fields. First, the central focus is on the effects of exposure to extreme climate events on land parcels and properties, which means the individual-level impacts (e.g., health, well-being, activity), social phenomenon (e.g., crime, education), and macroeconomics behavior (e.g., employment, consumption) do not fall into the rubric, though these works provide valuable insights for our discussion of adaptation policies. Second, we largely concentrate on salient climate event, that may preclude some chronic climate-related pressures like sea level rise, biodiversity loss, which have not formed major catastrophic event. Third, we limit our methodological scope to evidence-based empirical literature, particularly studies that use data and econometric estimators to evaluate interventions related climate events and adaptation policies.

The remainder of the paper is organized as follows. Section 2 provides a theoretical model to understand how climate risk exposures and adaptation activities are simultaneously capitalized into property values. constructs our dataset for systematic review and reports bibliometric analysis results. Section 4 presents our main meta-analysis results and examines disparities in outcomes. Section 5 discusses the basic types of adaptation strategies, their effects and unintended consequences. Finally, we conclude by suggesting a future research agenda.

2. Analytical framework

2.1. Expected utility and hedonic price model

How does the impacts of climate events and their associated risks absorbed into the land economy through spatially embedded properties? To provide an analytical lens, we first adopt an expected utility framework for households or developers making choices when exposed to climate risk (Schoemaker, 1982). The fact that capital invested in land and the built environment is immobilized for long turnover periods makes it sensitive to devaluation under climate change.[1] The effect of the climate impacts on land and property values is often studied using the hedonic price model (HPM), which has been widely applied as a tool for analyzing the relationship between value and characteristics since Rosen (1974)'s seminal work. The basic form of HPM regression mainly concerns endogenously static and spatially rooted characteristics such as property structure, location attributes, and surrounding amenities (Breunig et al., 2019; Law, 2017; Sirmans et al., 2005). In fact, exogenous risk perception significantly influences household-level preferences and aggregate neighborhood attributes. Following the approach of Hallstrom and Smith (2005), who evaluated hurricane risk at the parcel level, we include a generalized perceptive climate-risk term in the valuation[2]:

$$Val_{i,n} = f\left(\boldsymbol{N}, \boldsymbol{h}, p\left(I, Adp\right)\right) \tag{1}$$

where $Val_{i,n}$ is the economic value of the property i in a given neighborhood n, it depends on a series of explanatory variables on the right-hand side of the function. $\boldsymbol{N}$ is a vector of neighborhood attributes, such as environmental quality, access to amenities, and overall safety. Likewise, $\boldsymbol{h}$ is a vector of housing characteristics for property i (including size, age, and number of bedrooms). We add a risk perception term $p(I, Adp)$ which depends on the information about past disaster exposure and external adaptation activities that mitigate risks (e.g., levees, fireproofing, or insurance policies) (Botzen et al., 2019). The estimation could be extended in a semi-loglinear formulation:

$$\log\left(Val_{i,n}\right) = \eta + \boldsymbol{N}_n\gamma + \boldsymbol{h}_i\delta + \theta \cdot p\left(I, Adp\right) + \epsilon_{i,n} \tag{2}$$

Note that the dependent variable becomes the logarithm of property value. γ, δ, and θ estimated coefficients reflecting the marginal effects of neighborhood attributes, property characteristics, and risk perception, η is the intercept term, and $\epsilon_{i,n}$ is the error term.

Next, we consider how households evaluate risk and make property decisions based on utility in pre-disaster and post-disaster states. Assume an expected-utility (EU) model in which all agents (i.e., households) face two potential outcomes contingent on an adverse event occurrence, according to the law of iterated expectations (LIE), that EU (marginal mean) is the sum of both outcomes weighted by their probabilities of occurrence:

$$EU = p\left(I, Adp\right)\cdot U^{post}\left[\boldsymbol{N}, \boldsymbol{h}, C, Loss, \tau\right] + \left(1 - p\left(I, Adp\right)\right)\cdot U^{pre}\left[\boldsymbol{N}, \boldsymbol{h}, C\right] \tag{3}$$

where $U^{pre}[.]$ is the utility living in the pre-disaster state, dependent on neighborhood and housing characteristics, and a composite commodity C (other consumption excluding property), calculated as household income (M) minus property value, $C = M - f\left(\boldsymbol{N}, \boldsymbol{h}, p\left(I, Adp\right)\right)$. In comparison, $U^{post}[.]$ is the utility of living in the post-disaster state, which may directly suffer a short-term economic loss[3] from the climate hazard. τ is the discount weight that multiplicatively discounts post-event utility into pre-event utility. As we are most interested in the difference in household utility before and after the climate event, we take the partial derivative of EU with respect to risk perception p in Eq. (3) and solve for the difference:

$$\begin{aligned} \Delta U &= U^{post} - U^{pre} \\ &= \underbrace{\frac{\partial Val}{\partial p(I, Adp)}}_{\text{IPR}} \cdot \underbrace{\left[p(I, Adp) \cdot \frac{\partial U^{post}}{\partial M} + (1 - p(I, Adp)) \cdot \frac{\partial U^{pre}}{\partial M}\right]}_{\text{EMUI}} \end{aligned} \tag{4}$$

[1] From an urban planning perspective, property values serve as a particularly relevant metric because they reflect the aggregated judgments of how livable and desirable neighborhoods remain under climate pressures. The spatial pattern of property value changes following climate events reveals how risks are distributed across the urban landscape and how adaptation measures reshape neighborhood desirability.

[2] We assume a unitary model (Browning et al., 2006) that views the household as having only one set of preferences to maximize utility under a budget constraint that pools all value and resources.

[3] The short-term impacts include damages to properties and infrastructure, disruption of living conditions, and the extensive health problems.

The difference in utility between pre- and post-event states (ΔU) can serve as an estimate of socioeconomic outcomes of climate impacts, equal to the implicit price of risk (IPR) multiplied by the expected marginal utility of income (EMUI) from the solution. Since EMUI is assumed to be independent of property status and to diminish as wealth or income increases (Layard et al., 2008), the model explains many empirical observations showing that low-income neighborhoods suffer more from extreme climate events.

2.2. Empirical event estimation

When EMUI is held constant, the implicit price of risk is the sole determinant of utility differences, connecting property value to subjective risk perception. We can further decompose IPR into two equivalent expressions:

$$\text{IPR}: \frac{\partial Val}{\partial I} \cdot \nabla_I p \Leftrightarrow \frac{\partial Val}{\partial Adp} \cdot \nabla_{Adp} p \tag{5}$$

As discussed by Kelly et al. (2012), households update their beliefs about climate-risk probabilities through a standard Bayesian learning process based on newly received information. A handful of studies have leveraged surveys or other qualitative approaches to investigate how subjective risk perceptions respond to information about disaster occurrences and adaptation activities (Bakkensen & Barrage, 2017; Bubeck et al., 2012; Ma & Yildirim, 2023). Nevertheless, because risk beliefs involve complex subjective and behavioral elements, it is difficult to quantify their gradients precisely and consistently in the current literature (Rufat & Botzen, 2022). In this review, we primarily focus on the direct value effects of disaster occurrences and adaptation measures, which can be empirically estimated through a natural-experiment setting.

For the sake of exposition, we consider a difference-in-differences-in-differences (DDD) estimator (also known as "triple difference") that accounts for two treatments (hazard exposure and adaptation) across pre- and post-event periods:

$$\begin{aligned} E\left[\ln\left(Val_{i,z,t}\right)\right] =& \eta + \alpha \cdot Evt\_treat_i + \gamma \cdot Adp\_treat_i \\ &+ \beta_1\left(Evt\_treat_i \times Post_t\right) + \beta_2\left(Adp\_treat_i \times Post_t\right) \\ &+ \beta_3\left(Evt\_treat_i \times Adp\_treat_i \times Post_t\right) \\ &+ \delta_{i,z} + \mathcal{N}_z + \varphi_t + \varepsilon_{i,t} \end{aligned} \tag{6}$$

Compared with the basic HPM formulation in Eq. (2), the DDD estimator focuses on quantifying the economic value effects of disaster occurrences and adaptation measures. Here, $Post_t$ is a post-treatment dummy capturing changes attributable to the occurrence of a climate event. $Evt\_treat_i = 1$ if the property is located in an area directly exposed to the natural hazard (e.g. burned or flooded); $Adp\_treat_i = 1$ if the property implemented adaptation measures before the adverse event occured. With this setup in place, we distinguish four groups, as shown in Fig. 1, panel (a) and (b), to enumerate possible counterfactuals and isolate the interactions between these treatments over time.

(i) Group A (Baseline): Households neither exposed to the hazard nor implementing adaptation measures ($Evt\_treat_i = 0, Adp\_treat_i = 0$). These samples provide the baseline control for all subsequent comparisons.
(ii) Group B (Adaptation Only): Households implementing adaptation measures but not exposed to the hazard ($Evt\_treat_i = 0, Adp\_treat_i = 1$). Including them enable the estimation of the independent effect of adaptation measures, unconfounded by direct disaster exposure.
(iii) Group C (Hazard Exposure Only): Households exposed to the hazard but without adaptation ($Evt\_treat_i = 1, Adp\_treat_i = 0$), capturing the direct effect of the climate event on property values.

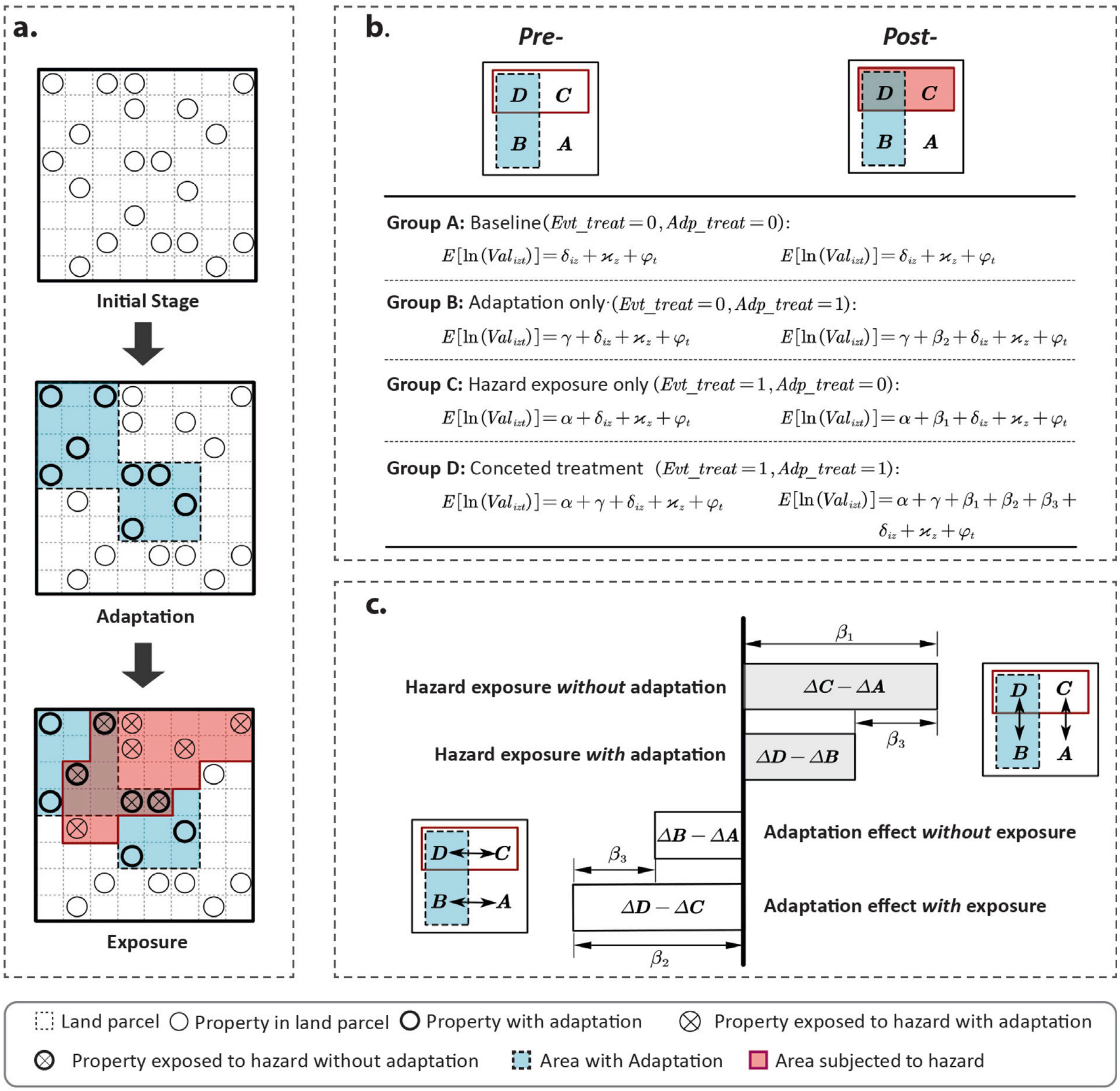


Fig. 1. Empirical estimation for climate hazard exposure and adaptation effects.
Notes: Panel a shows the spatial distribution of households across three stages: initial distribution, adaptation phase, and post-event outcomes. White circles represent initial households, solid black circles indicate households with adaptation measures, and crossed circles denote households exposed to climate events (with and without adaptation). Panel b displays the theoretical decomposition of treatment effects across four groups: baseline (A), adaptation only (B), hazard exposure only (C), and concerted treatments (D). The meaning of each coefficient is shown in Eq. (6). Panel c illustrates the interpretation of combinations of estimated coefficients ($\beta_1, \beta_2, \beta_3$), representing differential impacts across treatment groups.

(iv) Group D (Concerted Treatments): Households exposed to the hazard and implementing adaptation measures ($Evt\_treat_i = 1, Adp\_treat_i = 1$), reflecting the combined and potentially interactive effects of these two treatments.

Recalling from Eqs. (3) and (4) that the outcomes of climate events are determined by the partial derivatives $\partial Val/\partial E$ or $\partial Val/\partial Adp$ while holding EMUI and the risk-perception gradient ∇p constant. These marginal effects are captured directly through the interaction terms in the pre-post event estimation. For ease of exposition, we assume that changes in climate-risk information are solely contingent on hazard exposure (Evt_treat). Therefore, following a disaster, the marginal value effect of disaster occurrence can be expressed as:

$$\frac{\partial Val}{\partial E} = \beta_1 \cdot Val = [\Delta E[\ln(Val)|\mathbb{1}(Group\_C)] - \Delta E[\ln(Val)|\mathbb{1}(Group\_A)]] \cdot Val \tag{7}$$

Hazard exposure introduces new information about the probability and severity of future climate risks, which becomes capitalized into property values through the expected-utility framework. The estimated β_1 (expected to be negative) is thus a direct measure of the IPR for hazard exposure, quantifying how much the market discounts properties based on newly revealed risks from the climate event per se. In the same vein, we can examine the marginal value effect of adaptation, given by:

$$\frac{\partial Val}{\partial Adp} = \beta_2 \cdot Val = [\Delta E[\ln(Val)|\mathbb{1}(Group\_B)] - \Delta E[\ln(Val)|\mathbb{1}(Group\_A)]] \cdot Val \tag{8}$$

Adaptation measures influence property values by signaling reduced vulnerability or enhancing perceived security. A positive β_2 indicates that adaptation measures increase property values, implying market's recognition of reduced risk and improved resilience. While most existing literature adopting a pre-post event estimator focuses on either

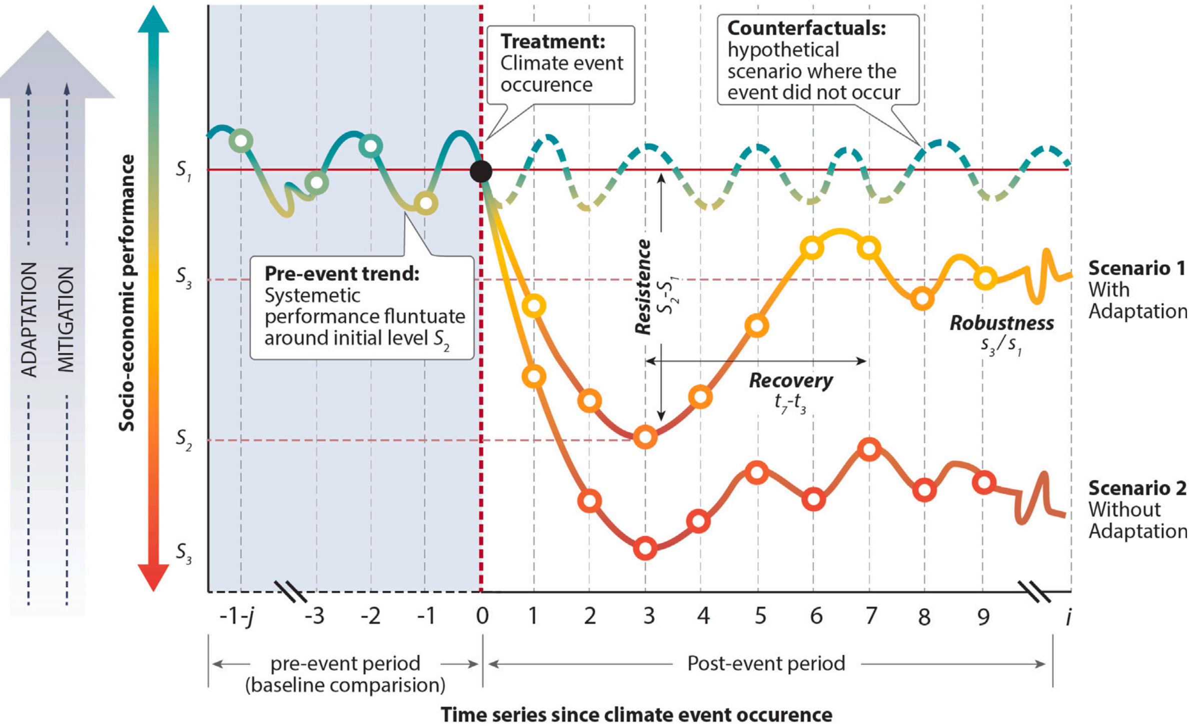


Fig. 2. Resilience framework (3Rs) before and after an adverse climate event.
Notes: Here we show two systemic outcomes with adaptation (Scenario 1) and without adaptation (Scenario 2). The vertical axis measures neighborhood socioeconomic performance (S), with S_1 representing the initial level, S_2 the pre-event baseline, and S_3 the minimum performance level. The horizontal axis shows time periods before ($-j$ to -1) and after (0 to i) the climate event occurrence. Recovery is measured as the time elapsed between t_3 and t_7, while resistance is captured by the performance drop ($S_2 - S_3$). Robustness is calculated as the ratio S_3/S_1. The dashed green line represents the counterfactual scenario (the hypothetical path had the climate event not occurred). The pre-event trend shows systematic performance fluctuations around baseline S_2, serving as the comparison benchmark for post-event outcomes.

β_1 (the pure hazard impact) or β_2 (the information channel for adaptation), some studies also investigate the concerted effect (Ellen & Meltzer, 2024), denoted by the coefficient β_3 of the triple-interaction term in Eq. (6). The measure has a straightforward interpretation, allowing us to separate the additional value impact beyond the sum of independent effects; it can also be written as the second-order partial derivatives $\beta_3 = \frac{\partial^2 ln(Val)}{\partial I \cdot \partial Adp}$. In Fig. 1, panel (c), we show four possible combined effects and their interpretations with coefficients.

2.3. Urban resilience (3Rs) framework

The directional shifts in the frequency and magnitude of the extreme climate events prompt cities to invest in adaptation measures in response to the profound uncertainty. Differences in available services and the extent of adaptation efforts lead contemporary cities to exhibit increasing variability in resilience after experiencing devastating climate events (Grafton et al., 2019). Observations of disparate socioeconomic outcomes among neighborhoods raise the natural question of how to explain and describe such responsive performance. Urban resilience provides a conceptual framework for understanding the systemic performance of a city or neighborhood before and after various shocks and stresses. The concept first emerged in the ecological disciplines and later extended broadly to human ecosystems, referring to the capacity of complex systems to absorb, recover from, and adapt to exogenous disturbances while maintaining functionality (Pickett et al., 2014; Zhou et al., 2021).

We apply the resistance-recovery-robustness (3Rs) resilience framework of Grafton et al. (2019) to the context of urban socioeconomic system under climate threats. Suppose a well-established neighborhood under normal conditions operates as a homeostatic system in which the SES maintains a stable level. An adverse climate event serves as an exogenous shock (i.e., 'treatment' in the event study estimation) that affects the operation of the neighborhood's core functional and structural system. After the disruptions, the potential effects of external drivers may follow several trajectories that translate into systemic performance changes and generate transitions, as shown in Fig. 2.

3. Methods and materials

We followed the general reporting guidelines for systematic literature review outlined by Sohrabi et al. (2021) PRISMA statement 2020, including systematic reviews (SRs) and meta-analyses (MAs) to get down to the nitty-gritty in the empirical findings and insights within the database. We also conducted a bibliometric review to reveal the subjects, time trends, and case locations from existing body of publications. The purpose of our review is to comprehensively map the charted territory and identify research gaps. In doing so, a four-step method (Fig. 3) for the search and identification process was adopted first.

3.1. Systematic review method

3.1.1. Step 1: Identification and inclusion

The search for relevant papers was conducted across six databases: Web of Science (WoS), Scopus, Science Direct, Sage, Taylor and Wiley. Among these, WoS and Scopus were selected as primary sources due to their extensive literature coverage and high-quality classification indexing, ensuring comprehensive and reliable results (Pranckutė, 2021; Wang & Waltman, 2016). We established three keyword categories to guide our search (i.e., search terms in title, topic and abstract) within databases to include papers addressing adverse climate events, their

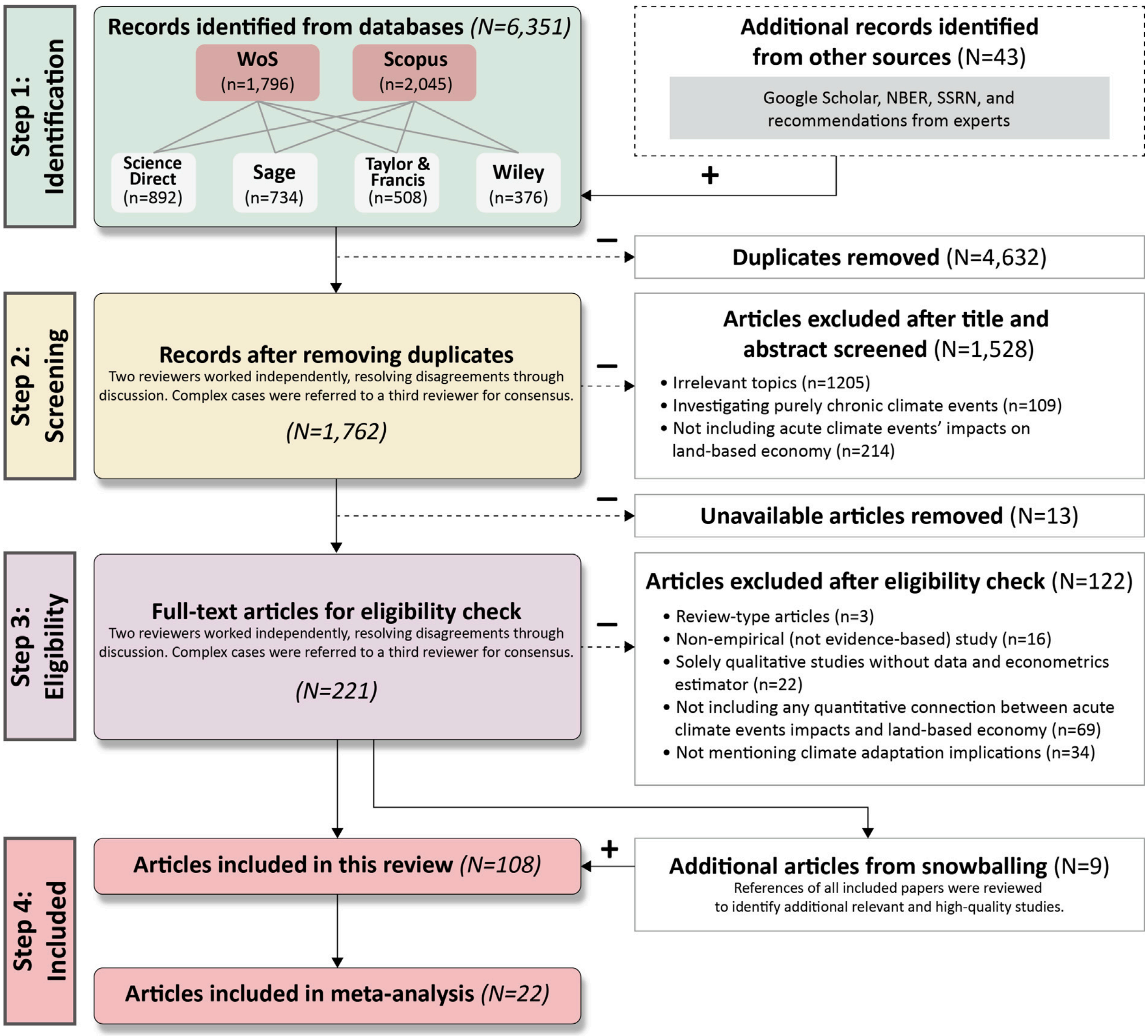


Fig. 3. Workflow of systematic literature scoping following the PRISMA framework.

economic outcomes and the methodologies employed (see Table 1). In addition, to further enrich the search results, we included other databases, such as Google Scholar, NBER and SSRN, along with recommendations from experts in this field. These databases offer access to high-quality preprints and conference papers. We imposed no restrictions on the publication year and only papers written in English were included. As a result, 6351 papers were extracted, with 4632 duplicates subsequently removed.

3.1.2. Step 2: Screening according to title and abstract

During the screening process, two reviewers independently screened the titles and abstracts of the retrieved records. Any disagreements were initially resolved through discussions between the two reviewers. For more complex cases, a third reviewer was consulted to reach consensus (Page et al., 2021). We applied the following criteria to filter articles: (a) articles focusing on irrelevant topics were excluded, such as pandemic, agroecosystem and solar plants (1,205 papers were excluded); (b) articles should zero in acute climate events rather than purely chronic climate processes, such as global warming, sea-level rise and air pollution (109 papers were excluded); (c) articles should include the impacts of adverse climate events on land economy. Therefore, papers that separately discuss these two sides without addressing the mutual relationship should be excluded (214 papers were excluded). We then conducted a full-text review, with one researcher carrying out the process. Any ambiguous items were further discussed with another researcher to ensure the accuracy of the dataset. After these filtering processes, 1762 papers were selected for the fine screening.

3.1.3. Step 3 and 4: Eligibility check and inclusion

These steps aim to slim down the remaining large dataset through an eligibility check. The method used to determine whether a study met the inclusion criteria was consistent with Step 3.1.2. The following inclusion criteria were applied: (a) articles should not be review type (3 excluded); (b) articles should be empirical evidence-based studies (16 excluded); (c) articles should not be purely qualitative studies without data and econometrics estimators (22 excluded); (d) articles should include at least one econometric model linking the impacts of adverse climate events to land-based economic outcomes (9 excluded); (e) articles should mention climate adaptation measures (34 excluded). Subsequently, to further refine the dataset, we employed a technique known as backward snowballing, reviewing the references of all included papers to identify additional relevant, high-quality studies, which resulted in the inclusion of nine papers (Cooper et al., 2018). A total of 108 papers were included in bibliometric analysis. A more limited set of criteria filtered 31 papers in meta-analysis in Section 4.

Table 1
Search query from academic literature database.

Category	Query keywords	Search syntax
Adverse climate event	Flood*, inundat*, hurricane, storm*, heat*, wildfire, smoke, drought, sandstorm, “sand storm*”, “dust storm*”, climate	TS=(flood* OR inundate* OR hurricane OR storm* OR heat* OR wildfire OR smoke OR drought OR sandstorm OR “sand storm*” OR “dust storm*” OR climate) OR TI=(flood* OR inundate* OR hurricane OR storm* OR heat* OR wildfire OR smoke OR drought OR sandstorm OR “sand storm*” OR “dust storm*” OR climate) OR AB=(flood* OR inundate* OR hurricane OR storm* OR heat* OR wildfire OR smoke OR drought OR sandstorm OR “sand storm*” OR “dust storm*” OR climate) AND
Land-based economy	“propert* value$”, “propert* price$”, “real estate”, “household finance”, “hous* value$”, “hous* price$”, “hous* market”, rent$, mortgage$	TS=(“propert* value$” OR “propert* price$” OR “real estate” OR “household finance” OR “hous* value$” OR “hous* price$” OR “hous* market” OR rent$ OR mortgage$) OR TI=(“propert* value$” OR “propert* price$” OR “real estate” OR “household finance” OR “hous* value$” OR “hous* price$” OR “hous* market” OR rent$ OR mortgage$) OR AB=(“propert* value$” OR “propert* price$” OR “real estate” OR “household finance” OR “hous* value$” OR “hous* price$” OR “hous* market” OR rent$ OR mortgage$) AND
Methods	Quantitative, econom*, “difference-in-differences”, regression, “quasi-experiment”, estimator, hedonic, empirical	TS=(quantitative OR econom* OR “difference-in-differences” OR regression OR “quasi-experiment” OR estimator OR hedonic OR empirical) OR TI=(quantitative OR econom* OR “difference-in-difference$” OR regression OR “quasi-experiment” OR estimator OR hedonic OR empirical) OR AB=(quantitative OR econom* OR “difference-in-differences” OR regression OR “quasi-experiment” OR estimator OR hedonic OR empirical)

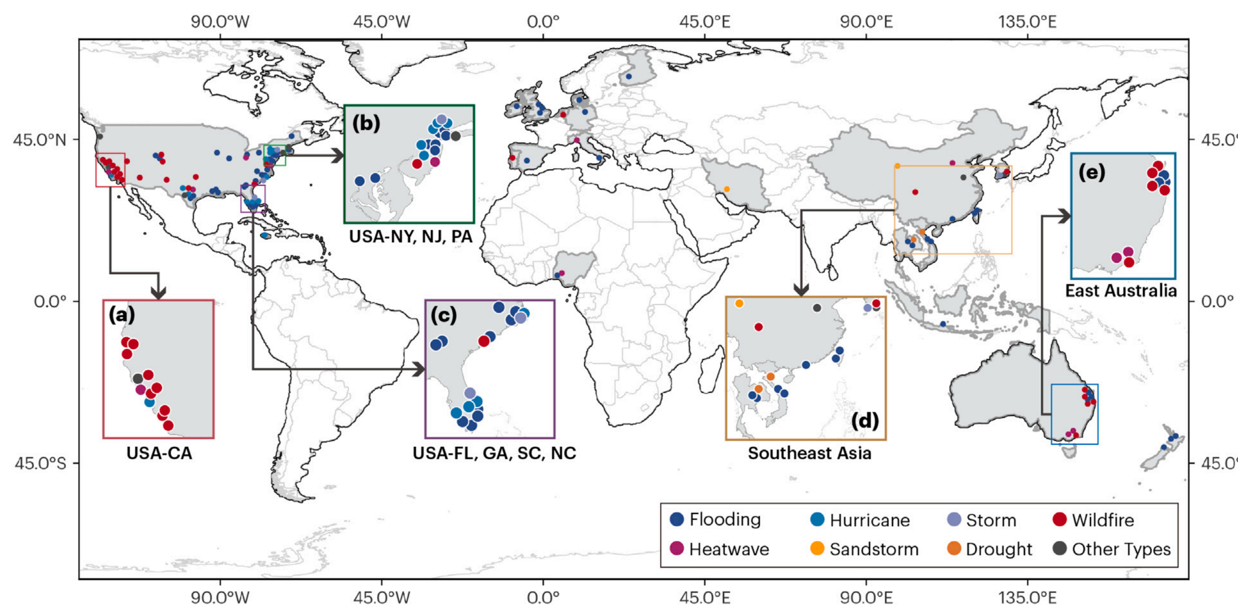


Fig. 4. Geographical distribution of cases in the selected literature.
Notes: This figure plots the locations of 131 documented case studies across various climate-related hazards, color-coded by event category. Areas with stronger data infrastructure and greater research funding (United States, parts of Europe, and urban centers in East Asia) exhibit higher concentrations of empirical analyses. Large regions, including Africa and parts of Latin America, remain underrepresented and thus present opportunities for future study.

3.2. Bibliometric analysis

We first examined the geographical locations of the empirical cases in the selected literature. Essentially all the papers include at least one case, and some compare up to five. Taken together, Fig. 4 displays 131 cases spanning different categories of climate events around the globe. What we observe overall is a pronounced clustering of studies in a handful of regions with well-developed data infrastructure and robust funding for climate research. As shown in Fig. 5, the United States accounts for the largest share of documented empirical applications, owing to the relatively rich availability of property-level records and hazard mapping. Western Europe also features prominently, with numerous multi-country comparisons that exploit standardized data on floods, wildfires, and heatwaves. Within Asia, most attention focuses on China and Southeast Asia, regions undergoing rapid urbanization, albeit with varying degrees of institutional capacity to measure and address climate-related risks.

Despite these concentrations, the map makes it clear that large portions of the globe remain understudied. In particular, Africa, Latin America (beyond a few cases in Brazil and Mexico), and most island nations in the Pacific have contributed far fewer empirical studies to this scholarship. The deficit could stem from multiple factors, including limited access to georeferenced data, institutional constraints on research funding, and the higher cost of conducting fieldwork in remote or low-resource settings. Yet these regions often face heightened vulnerability to climate extremes, suggesting an opportunity for future inquiries. Deepening the geographical scope of empirical evidence could illuminate whether the findings from well-studied regions generalize or whether distinct local conditions — such as governance, socioeconomics, and infrastructure — produce different outcomes when confronted with comparable climate risks.

Beyond the exponential growth in scale over the last three decades, there has also been a discernible shift in both research methods and materials over time. Fig. 5, panel (a), shows that the share of studies

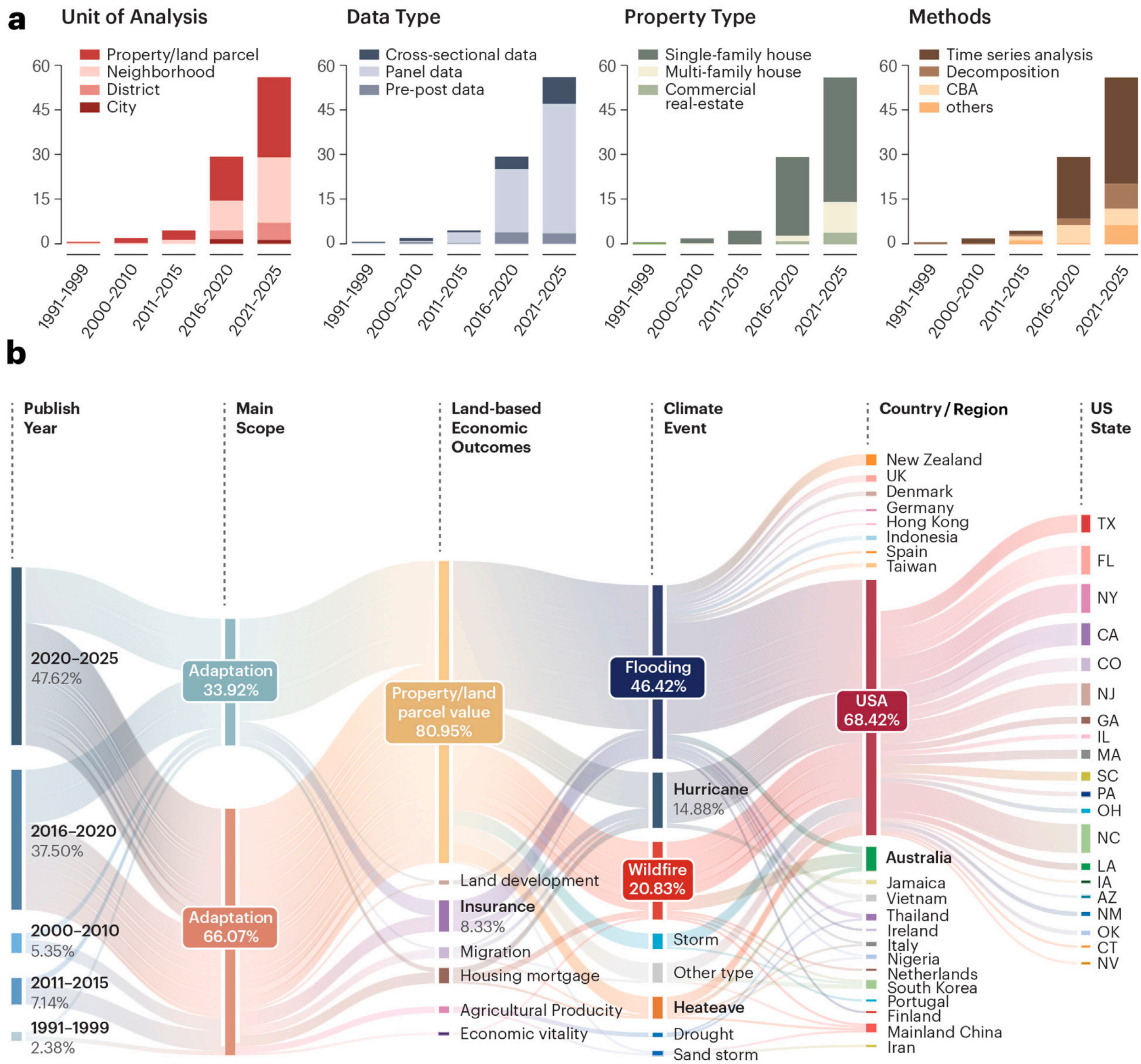


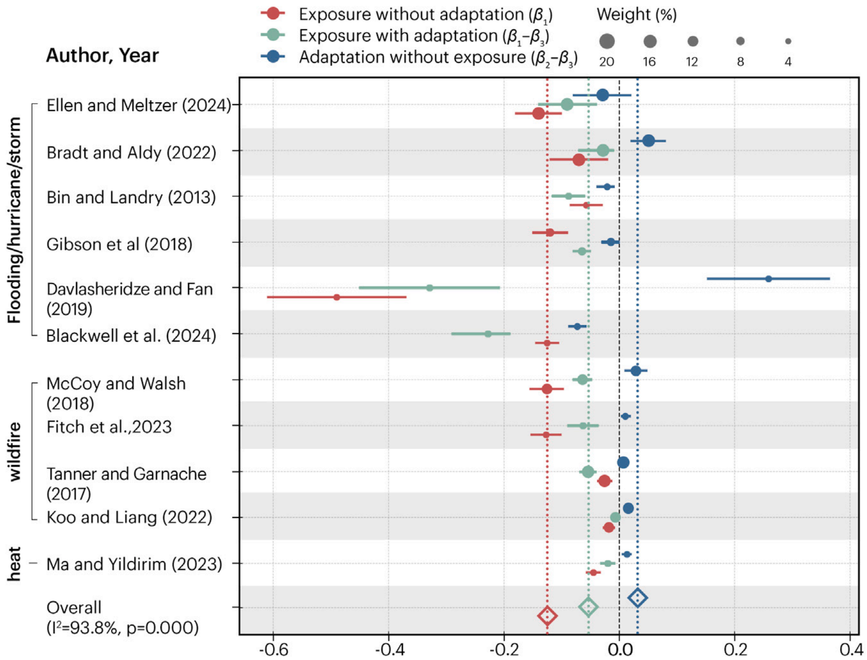
Fig. 5. Bibliometric analysis of research trends and characteristics.
Notes: Panel a uses stacked bar plot to track shifts in unit of analysis, data, property, and methods over time. Panel b depicts a Sankey diagram linking publication year, research scope, land-based economic outcomes, climate event, and country or region. Flooding and wildfire remain the two most frequently studied hazards, while U.S. states dominate the empirical landscape.

analyzing property- or land-parcel-level data grew sharply after 2015, whereas earlier works tended to focus on aggregated areas such as districts or cities. This micro-level shift coincides with a broad surge in the use of panel data and pre-post estimators, reflecting the increasing availability of high-resolution spatial datasets and the growing appetite for causal identification strategies. Indeed, the methods chart shows that time-series and decomposition approaches, once prevalent, have been complemented or superseded by more quasi-experimental designs, especially in studies published since 2016. As researchers have increasingly tapped into controlled experiment, the unit of analysis become progressively more granular—mostly using land-parcel or neighborhood level data.

4. Meta-analysis results: Aggregate empirical estimations

In our review database for bibliometric analysis, we include literature employing a wide range of quantitative methods; however, all studies selected for the final meta-analysis adopt *ex post* natural experiments with rigorous difference-in-differences econometric estimators. Twenty-two research articles complied with this strict rubric after our final identification step (Fig. 3). The key dependent variable (i.e., property value) is generally transformed into a semi-loglinear form so that the coefficient can be interpreted as indicating a percentage change. While all estimators control for fixed effects, the size of coefficients varies depending on the specific context the choice of identification and modeling strategies.

The primary reason preventing us conducting a full-fledged meta-regression, as in Daniel et al. (2009) and Beltrán et al. (2018), which focused exclusively on flood vulnerability, is that the sample of estimates in our investigation differs in risk type and adaptation approach rather than consisting of a large volume of highly comparably structured estimators. Therefore, we consider a more qualitative synthesis using a forest plot (Borenstein et al., 2009) given our broader focus on diverse event types, adaptation approaches, and geographical contexts. Moreover, as discussed in the 3Rs framework, the estimated effects of climate events on economic performance appear to vary with the time horizon: short-run effects (estimated within two years after an event) are larger in magnitude than long-run effects (over horizon exceeding



Study Effect Size (95% CI)

β_1	β_1–β_3	β_2–β_3
−0.140 [−0.180, −0.100]	−0.090 [−0.140, −0.040]	−0.030 [−0.080, 0.020]
−0.070 [-−0.120, −0.020]	−0.035 [-0.070, -0.010]	0.050 [0.020, 0.080]
−0.057 [−0.085, −0.029]	−0.088 [−0.116, −0.060]	−0.130 [−0.08, 0.02]
−0.065 [−0.080, −0.050]	−0.015 [−0.030, 0.010]	-0.120 [−0.150, −0.090]
−0.490 [−0.610, −0.370]	−0.329 [−0.450, −0.208]	0.259 [0.153, 0.365]
−0.125 [−0.145, −0.105]	−0.228 [−0.290, −0.190]	−0.078 [−0.112, 0.048]
−0.126 [−0.155, −0.097]	−0.064 [−0.080, −0.048]	0.029 [0.010, 0.048]
−0.127 [−0.153, −0.101]	−0.060 [−0.089, −0.037]	0.013, [0.008,0.020]
−0.024 [−0.031, −0.017]	−0.055 [−0.058, −0.052]	0.007 [0.003, 0.011]
−0.017 [−0.021, −0.013]	−0.009 [−0.012, −0.006]	0.016 [0.013, 0.019]
−0.045 [−0.057, −0.033]	−0.020 [−0.032, −0.008]	0.013 [0.005, 0.021]
−0.125 [−0.146, −0.084]	−0.048 [−0.076, −0.021]	0.031, [0.009,0.042]

Fig. 6. Forest plot of vulnerabilities and adaptations of climate event studies.
Notes: This figure presents a forest plot of estimated effects from 11 empirical studies examining property value changes due to climate events and adaptation measures between 2013 and 2024. Effect sizes represent percentage changes in property values with 95% confidence intervals shown in brackets. Red circles (β_1) indicate the effect of hazard exposure without adaptation; green circles ($\beta_1 - \beta_3$) show the combined effect of exposure with adaptation measures; and blue circles ($\beta_2 - \beta_3$) represent the effect of adaptation measures in the absence of hazard exposure. Circle sizes correspond to study weights in the meta-analysis, determined by the inverse variance method. The dotted vertical lines represent the pooled estimates for each effect type. The diamond markers at the bottom show the overall random-effects estimates, with $I^2 = 92.8\%$ indicating substantial heterogeneity across studies. Studies are grouped by climate hazard type and ordered chronologically within each group. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

five years). In other words, after a major climate event occurs, the magnitude of vulnerabilities tends to diminish. Therefore, when researchers have conducted DID analysis with multiply time periods, we collect the estimates corresponding to the most robust effects.

4.1. Vulnerability with and without adaptation

We begin with a random-effects model[4] by Borenstein et al. (2010) in the meta-analysis of the 11 event studies that included both vulnerability and adaptation effects. The forest plot in Fig. 6 reveals substantial heterogeneity: the magnitude of property value effects varies markedly, with flooding and hurricane events generating the largest negative impacts (−6.5% to −49.0%) compared with wildfires (−1.7% to −12.7%) and heatwaves. Furthermore, the variance in effect sizes is notably larger for flood-related studies, implying that local contexts and specific adaptation approaches may play a more crucial role in determining outcomes for flood hazards than for other climate events.

The efficacy of adaptation measures in mitigating negative economic impacts varies considerably across studies, though most find that adaptation attenuates value depreciation, with the average mitigation effect (β_3) of 7.7%. The difference between exposure effects with and without adaptation ($\beta_1 - \beta_3$) ranges from −32.9% to −0.9%, with larger mitigation effects observed in flooding contexts. However, several studies document cases where adaptation measures counterintuitively amplify negative impacts. Good intentions notwithstanding, Bin and Landry (2013) find that flood map updates lead to greater value depreciation (−8.8%) compared to pure exposure effects (−5.7%), attributable to enhanced public risk awareness. Similarly, Blackwell et al. (2024) document that home elevation in Charleston paradoxically increases the rate of lost appreciation after flooding events, with elevated properties experiencing a −22.8% effect compared with −12.5% for non-elevated properties.

One likely explanation for these contradictory findings is that the outcomes of the climate events are not always objective or predictable but contingent on how people perceive or evaluate potential climate risks in the future (Bakkensen & Barrage, 2017). Individuals choose whether to move or locate within areas in proximity to floodplain or wildland–urban interface (WUI) zones based on how climate risk information is perceived. In this vein, if climate risk has been internalized in advance, the negative impact from foreseeable hazards could be ameliorated (Ellen & Meltzer, 2024). It is also possible that people find it difficult to evaluate the risk from highly stochastic climate events, despite the ongoing reality of climate change, making most households less likely to be concerned when presented with relatively small risk probabilities (e.g. a one-in-a-hundred-year flood) (Gibson et al., 2018). Under such circumstances, the market may not value adaptation (i.e., flood map) as an effective mitigation approach.

Most adaptation measures enhance property values even without a crisis occurrence, as the estimate in the absence of hazard exposure ($\beta_2 - \beta_3$) yields predominantly positive values, lying between 0.7% to 25.9%. Hard infrastructure protection, such as levees, has a positive land-value capitalization effect even without surges, reflecting reduced subjective risk perception and promoting moral hazard. In contrast, soft adaptation may produce negative effects as households gain more awareness of actuarial risk levels at parcel level. For instance, properties within designated high-risk zones, such as FEMA flood maps or Fire Hazard Severity Zones, frequently experience value depreciation

[4] The model assumes that the true effects being estimated differ from each other; therefore, the pooled effect is a weighted average of study-specific effect sizes. The weights assigned to each study are based on the inverse of the variance of the study's effect size plus an additional variance term that represents heterogeneity.

(−13.0% in Bin and Landry (2013); −12.0% in Gibson et al. (2018)) even without direct exposure to hazards. Formal risk designation may serve as a negative signal to potential buyers, reflecting the capitalization of perceived risk into property values independent of actual crisis events.

4.2. Pure adaptation treatment effect

We now consider the robustness of the above-reported findings on adaptation effects. So far we have focused on quasi-experimental studies where the climate event is the external intervention applied to separate the treatment and control groups. A different form of empirical estimator is the "pure adaptation effect" which identifies the completion or implementation of adaptation policies or programs as the primary treatment in a DID framework. The meta-analysis includes 11 empirical investigations, most of which evaluate programs designed to mitigate flood-related hazards. In each study, treatment properties are those that directly benefit from an adaptation policy whereas control properties remain unaffected by the intervention. As shown in Fig. 7, panel a, the estimated policy effects on property values range from −0.14 to +0.57, with a pooled mean of +0.10 (95 percent confidence interval $[0.02, 0.20]$). Once again, we observe prominent heterogeneity across studies, suggesting that local context and policy design play critical roles in determining market responses (Benetton et al., 2023; Pecharroman, 2023).

A majority of investigations report statistically significant, positive effects on property values upon the completion of adaptation measures. For instance, Pecharroman (2023) show that communities participating in the Community Rating System (CRS) achieve marked price appreciation — close to +0.57 — likely driven by reduced flood insurance premiums and heightened public awareness of safety measures. Similar but less dramatic gains arise in settings where structural defenses have been implemented, such as Miami-Dade County, where Kelly and Molina (2023) document about a +0.05 improvement in housing prices surrounding new flood-control infrastructure. Such evidence aligns well with the broader hypothesis that credible, visible flood-protection systems act as a signal of lower disaster risk, thereby bolstering demand for properties within the safeguarded areas (Qiu & Gopalakrishnan, 2018).

Not all adaptation programs necessarily produce straightforward value premiums. Several studies have uncovered muted or even negative impacts, especially when the policy in question places restrictions on property use or signals high residual risk. Hashida and Dundas (2023) find a −0.14 effect for a coastal buyout and acquisition program, suggesting that the prospect of being "bought out" can lead to declines in the perceived stability of local real estate markets. A related study by Shr and Zipp (2019) documents that flood-hazard map updates, which designate new high-risk zones, can depress property values as buyers weigh higher insurance costs against uncertain protection benefits. In the same vein, Häse and Hirte (2023) observe that while public HIQ100 flood protection measures in Europe offer long-term safety advantages, they may also temporarily increase building code stringency, causing transitional market dips in at-risk municipalities.

To assess robustness beyond these individual effects, the funnel and Galbraith plots in Fig. 7, panel (b) and (c), show no conclusive evidence of severe publication bias but reveal considerable variance in standardized effect sizes. In this respect, adaptation should not be viewed as a monolithic solution: for some interventions, larger structural footprints translate into readily observable benefits, fostering trust among potential homebuyers (Druckenmiller et al., 2024; Kim et al., 2020). Yet, in other contexts, newly implemented measures carry regulatory or financial costs (for example, mandated retrofits or elevated insurance premiums) that may outweigh the perceived advantages. Indeed, the extreme dispersion — ranging from negative double-digit shifts to substantial price appreciation — reinforces the notion that localized factors, such as pre-existing infrastructure, hazard salience, and socioeconomic conditions, can shape market responses as strongly as the adaptation measure itself (Blackwell et al., 2024). This is evident in home-buying choices, when households trade off the normal benefits of waterbodies or forests against the negative outcomes from a small probability of flooding or wildfire (McCoy & Walsh, 2018). They tend to favor a sure gain from natural amenity (i.e., landscape) over a probabilistic loss from severe hazard.

Taken together, the assembled evidence supports a nuanced interpretation of "pure adaptation effects" on property values. Some measures — such as beach nourishment (Qiu & Gopalakrishnan, 2018) or expanded urban canopy (Han et al., 2024) — appear to generate unambiguous gains by upgrading local amenities while mitigating environmental risk. Others, like federal dune construction or green infrastructure programs, tend to provide modest though statistically significant improvements in property values (Dundas, 2017; Hashida & Dundas, 2023), reflecting the interplay of risk reduction and aesthetic co-benefits. In contrast, regulatory strategies that rely on hazard-zone demarcations or voluntary buyouts may improve long-run safety but can experience short-run discounts as households re-sort across the urban landscape (Benetton et al., 2023). In light of these findings, we concluded that adaptation policies should be tailored not only to specific hazard contexts but also to broader economic and social environments, lest measures intended to strengthen climate resilience inadvertently engender unintended economic repercussions.

4.3. Disparities in socioeconomic outcomes across neighborhood

One important limitation of meta-analysis is its neglect of heterogeneity, as it often pools point estimates of the effect of interest (Balima & Sokolova, 2021). In fact, urban neighborhoods are not homogeneous with regards to social strictures based on race, gender, and class, which result in disproportionate outcomes (Solecki & Rosenzweig, 2022). A smaller but growing body of literature offers insights into how heterogenous households with different SES levels sort themselves accoding to specific neighborhood characteristics (e.g. amenities, social demographics, environmental quality), thereby reinforcing fixed socioeconomic patterns (Graff Zivin & Neidell, 2013; Kuminoff & Mathes, 2024). Under the escalating climate risks, households are more likely to move or be displaced because extremely severe events cause irreversible disruptions and damage to properties and critical infrastructure.

Understanding the heterogeneity of short- and long-term climate impacts across neighborhoods and groups is emerging in current scholarship. This literature must first grapple with the question of whether the burdens of environmental harms and adaptations are equitably distributed. Wealth is an important factor in communities' capacity to adapt. Individuals who live in low-income areas fare worse than those in affluent neighborhoods when facing catastrophic climate events (Billings et al., 2022). Limited financial resources hinder their ability to prepare ahead of time, cope with disruptions, and build long-term resilience. Ellen and Meltzer (2024) found evidence that, after Hurricane Sandy, neighborhoods in FEMA flood zones with pre-existing adaptive measures such as insurance experienced smaller housing price declines, whereas poorer areas without adaptation suffered persistent devaluation. Wealthier communities, in contrast, tend to rebound more rapidly due to better adaptive investments and financial reserves, which contribute to the perpetuation of disparities.

Climate gentrification can occur in several ways, as documented in numerous studies (De Koning & Filatova, 2020; Gould & Lewis, 2018; Keenan et al., 2018) undertaken thus far. These include wealthy residents moving out of high risky areas, or residents unable to afford higher premiumss from climate adaptation measures. In the case of green infrastructure regeneration in Brooklyn, Gould and Lewis (2018) find the transformation of hazardous floodplain exacerbates sociodemographic inequalities by attracting wealthier households. Similarly, in New Orleans, higher-elevation neighborhoods disproportionately attracted investment after Hurricane Katrina, driving gentrification in

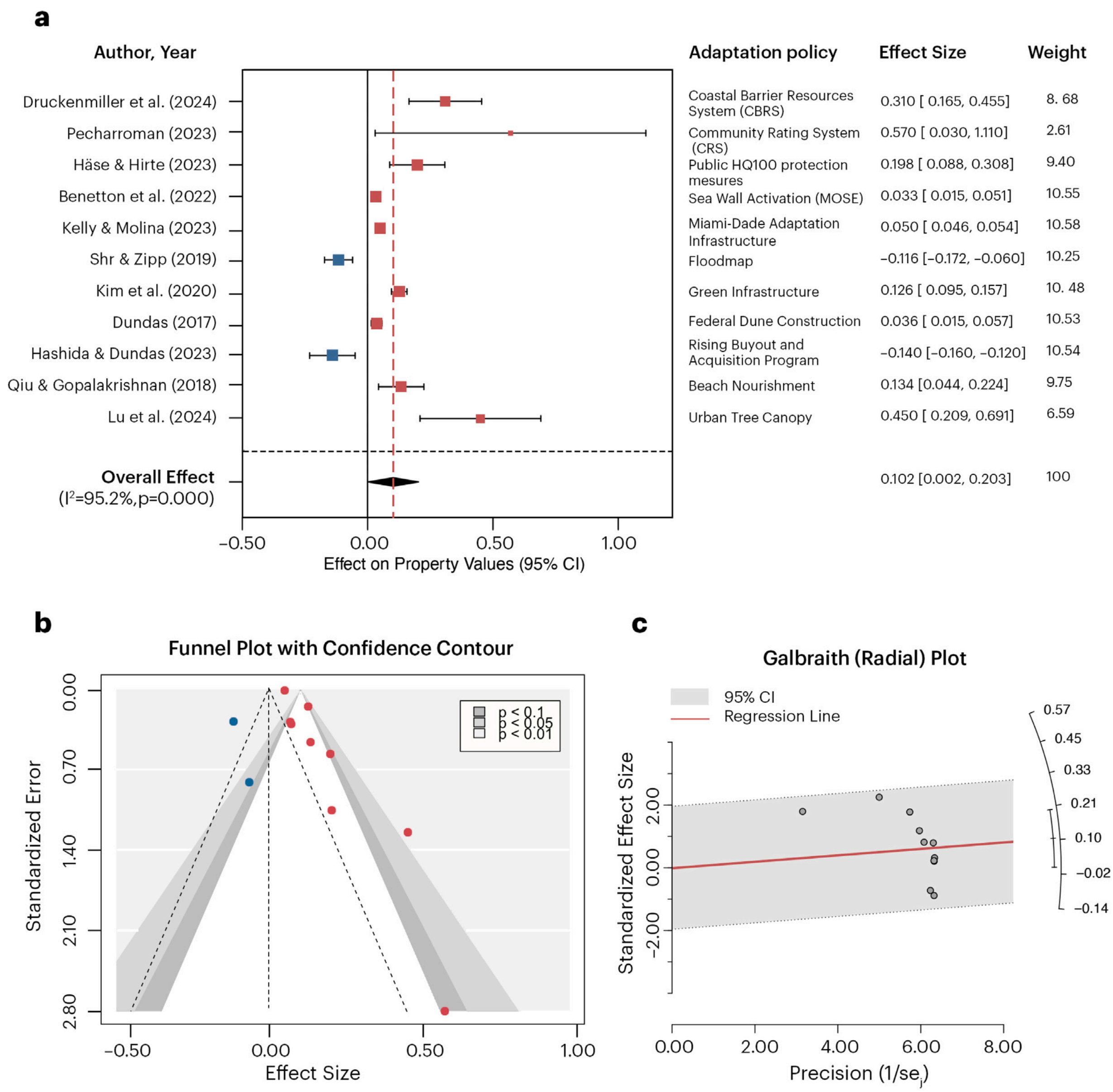


Fig. 7. Meta-analysis of the pure adaptation effect on property value.
Notes:: This figure summarizes the results of a meta-analysis on the impact of adaptation policies on property values, as estimated from eleven quasi-experimental studies. Panel a presents a forest plot of the adaptation effect, where each point represents the estimated change in property value due to specific adaptation interventions, such as flood control infrastructure or regulatory changes. The red squares indicate point estimates, with horizontal lines indicating 95% confidence intervals. The black diamond represents the pooled effect, calculated using a random-effects model. Panel b shows a funnel plot with confidence contours, which tests for potential publication bias in the studies included in the analysis. Finally, panel c shows a Galbraith plot, illustrating the standardized effect size versus its precision. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

areas less susceptible to flooding (Aune et al., 2020). These unintended processes reflect broader patterns where adaptive investments and disaster recovery resources are unequally distributed, reinforcing systemic disparities in urban resilience. Conversely, degentrification can occur in climate-vulnerable zones as affluent residents retreat, leaving behind economically marginalized populations. Ratnadiwakara and Venugopal (2020) report that flood-affected areas often experience drops in property values, subsequently attracting less affluent and more credit-constrained homeowners, a trend described as "filtering" of the housing stock. Meanwhile, post-wildfire reconstruction in California revealed cost-burden gentrification, where rebuilding efforts focused on higher-value properties, marginalizing lower-income residents (McConnell & Braneon, 2024). These dual trajectories underscore the heterogeneity of climate outcomes across neighborhoods, shaped by local governance, market dynamics, and the socio-ecological context. Addressing these environmental justice concerns demands concerted land-use policy interventions that integrate climate adaptation with inclusionary zoning and equitable urban planning.

5. Implications: place-based adaptation policies

Dread and despair need not impede commitment, action, or innovation. There is substantial evidence showing promising efforts to mitigate and adapt to our new reality of a warmer planet (Wannewitz et al., 2024). There is little controversy over whether climate adaptation raises land-based values. There is substantial debate, however, over the policy prescriptions of which adaptation programs and to what extent should government devote. For our purpose, we conceptually divide place-based adaptations along two dimensions: (1) how adaptation is delivered and (2) how it is funded and implemented.

5.1. Hard defense: Public and private invest infrastructure

Public investment in climate adaptation infrastructure has become increasingly vital as communities worldwide face escalating climate-related risks. Policymaking encompasses the strategic allocation of public resources to develop and maintain infrastructure systems that help communities cope with and become more resilient to hazards. There are two main categories: gray (human-engineered) infrastructure and green (nature-based) infrastructure. Gray infrastructure refers to engineered solutions, such as sea walls, levees, dikes, storm drains, and pumping stations, typically constructed using concrete, steel, and other manufactured materials against specific climate hazards (Siegel, 2020). Despite their precise control and measurable performance metrics, these mega infrastructures have high construction and upkeep costs yet limited flexibility under changing conditions (Bradt & Aldy, 2025; Fan, 2024). In contrast, green infrastructure leverages natural systems and processes to provide adaptation benefits. These include constructed wetlands or dunes, bioswales, urban greenery, green strips, and restored coastal ecosystems, which can effectively manage stormwater, reduce urban heat, and protect against coastal flooding while providing additional ecosystem services (Dundas, 2017; Han et al., 2024; Hashida & Dundas, 2023).

Many publicly invested infrastructures for climate adaptation, unlike environmental amenities (i.e., clean air and scenic vistas), are not pure public goods whose benefits and services can be shared by everyone.[5] Even when they are shown to be valuable for neighborhoods and property values, there is no clear capitalization mechanism to signal scarcity unless climate events occur frequently and are widely recognized (Kelly & Molina, 2023). Therefore, it is not financially viable for markets to provide such adaptation services because of the free-rider problem, especially given the high up-front costs and uncertain future returns (Davlasheridze & Fan, 2019). Moreover, people tend to be overly optimistic about their ability to overcome environmental risks, which inadvertently undermines efforts to regulate climate risks and build resilience in a sustained way. Recent research has demonstrated the extremely high costs of constructing and maintaining these infrastructures if they fail or degrade (Shi & Moser, 2021). Fan (2024) find that poor maintenance leads to a higher probability of levee failures, reducing housing values in affected areas by 3%–9%. In turn, declining property values reduce local tax revenues, constraining future investments in infrastructure maintenance and creating a self-reinforcing “doom loop" of development.[6]

Is the economic outcome of the public investment desirable from the standpoint of society as a whole? There is no straightforward answer to this question. A key consideration for local government is whether, and to what extent, to invest in adaptation infrastructure based on a full cost–benefit analysis (CBA). Under neoclassical economic theory, governments should proceed with adaptation actions and public investments only if the expected benefits exceed costs, yeilding a positive net present value (Brzozowska, 2007).[7] A handful of empirical studies assess adaptation policies by calculating aggregate costs and benefits. For example, Kelly and Molina (2023) uses over 400,000 property transactions to assess 162 fixed infrastructure in Miami designed to combat flooding. Although three-quarters of the projects yield positive net benefits, the analysis changes starkly when negative externalities on surrounding residential land not protected by adaptive infrastructure are taken into account. Another novel recent study by Bradt and Aldy (2025) provides a quasi-experimental analysis of levee benefits, examining positive spillovers to market prices, mitigation of flooding losses, and other valuation methods, comparing these benefits against the costs of levees—e.g. construction and maintenance inputs, negative spillovers to unprotected neighborhoods, etc. They find that the majority of the 37 USACE-constructed levee projects have benefit-cost ratios below 1, meaning that the monetary costs exceed the value of the benefits in most cases. Similar ancillary impacts are observed in natural infrastructures such as dunes (Dundas, 2017), where positive capitalization effects may be offset by reductions in environmental amenities.

In contrast with public infrastructure, privatly invested adaptation infrastructure exhibits two noteworthy differences. First, private adaptation infrastructure typically operates at a much smaller spatial scale, focusing on individual properties or parcels, resulting in fragmented protection and reduced overall community resilience (Toole et al., 2016). Second, private infrastructure investments are characterized by significant variances in both implementation quality and timing, driven by individual households' varying risk perceptions, willingness to pay, and technical expertise (Derkzen et al., 2017). Studies have documented a range of structural fortification approaches, including elevation of buildings, flood barriers, fireproof materials, and defensive space creation, with installation costs typically borne by individual property owners but capitalized into property values under climate change (Blackwell et al., 2024; Champonnois & Erdlenbruch, 2021). However, unlike public infrastructure projects that undergo standardized planning and engineering processes, private adaptations often lack consistent technical oversight and may not adhere to optimal design standards (Wamsler, 2016). Moreover, this favors individual property protection over broader public interests and encourages rebuilding in the same places with elevated building structures, creating an unsustainable cycle of repetitive loss and redevelopment that cannot be financed in the long term (Kayden, 2015). These challenges raise critical issues regarding the coordination between public and private adaptation efforts.

5.2. Soft protection: Insurance programs and land-use regulation

The types of adaptation approaches reviewed above are known as hard defense in that they are tangible infrastructure in nature. Adaptation has also taken the form of intangible “soft protection” programs — ranging from climate insurance, and risk-treatment initiatives to land-use regulations — that play an important role in building neighborhood resilience (Carter et al., 2019; Netusil et al., 2021). Unlike large investments in public infrastructure, soft adaptation is more flexible and grants greater discretion to individual households (Tan-Soo et al., 2023). Therefore, a central goal of these policies lies in understanding the reward structure of the stakeholders, so that the adaptation efforts provide effective incentives or restrict certain behaviors that collide with households' long-term benefits in climate vulnerable areas, even if they are not fully recognized (Parton & Dundas, 2020).

For private investment protection, the literature examines property owner's willingness to pay as climate risks escalate and how this influences market behavior. Under wildfire risks, Issler et al. (2020) develop a game theory decision model in which households face two binary decisions (to insure their properties or not) to evaluate the utility considering both housing quality and neighborhood externalities. The payoff matrix, in the absence of wildfire, ends up with “prisoner's dilemma” where both households have a dominant strategy

[5] This does not preclude the use of the public goods framework, as climate adaptation can be locally non-rival and non-excludable within a community or district.

[6] For most U.S. cities, local revenue streams rely heavily on property taxes. When climate events cause land-value declines, local financing is affected accordingly, further diminishing the capacity to provide public adaptation measures. This creates a critical feedback loop between land values, fiscal capacity, and resilience that planners must navigate.

[7] More recently, public economists have used more sophisticated welfare analysis tools, such as the Marginal Value of Public Funds (MVPF), to compare long-run policy effectiveness across multiple publicly funded programs (Finkelstein & Hendren, 2020).

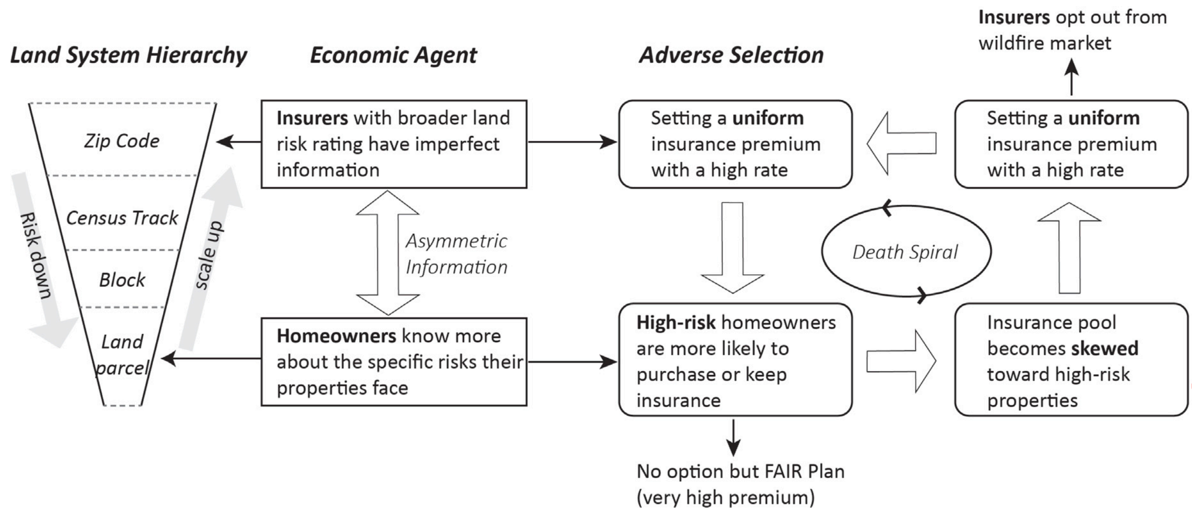


Fig. 8. Adverse selection in wildfire insurance with asymmetric risk information on land hierarchy.
Notes: This figure illustrates how information asymmetry in land system hierarchy leads to adverse selection in climate insurance markets. The left panel shows the hierarchical structure of land risk information from zip code to individual parcel level. The middle panel demonstrates the asymmetric information between insurers and homeowners, where insurers rely on broader geographic risk ratings while homeowners possess more granular parcel-specific risk information. The right panel depicts the resulting adverse selection dynamics: high-risk homeowners' disproportionate participation in insurance markets leads to a "death spiral" of increasing premiums and market exit by insurers. The FAIR Plan represents a last-resort option for high-risk properties, typically offering coverage at substantially higher premiums. The figure draws on evidence from California's wildfire insurance market documented in Boomhower et al. (2024).

not to insure, though this is not the socially optimal outcome (Blanco et al., 2020). Nevertheless, the Nash equilibrium[8] changes in favor of insurance for both homeowners when disaster strikes. These herding conclusions hold only if the exact payoffs of household utility in the absence and presence of climate events are known, a condition unlikely in real-world settings, where payoffs are heterogenous within and across neighborhoods and determined by individual attitudes, land characteristics, and financial standing (Auer & Hexamer, 2022; Lee et al., 2022).

Another challenge in prompting soft adaptation involves trade-offs between time and risk. Adaptation activities are always associated with up-front costs and delayed benefits: for instance, households must pay extra premiums for stand-alone climate insurance, but the benefits only materialize after a disaster occurs (Netusil et al., 2021). The framing effect, in psychology terms, has prevented many households from adopting risk aversion attitudes when deciding whether to buy climate insurance or undertake other risk-mitigation strategies[9] (Bradt, 2022; Robinson et al., 2021). That explains why take-up rates of disaster insurance remain low even in areas facing substantial climate risks (Choi et al., 2024). Moreover, asymmetries in land-risk information lead to adverse selection, as households possess hidden information about parcel-level risks and decide whether to participate in insurance programs accordingly. This occurs in California's wildfire-insurance market where Boomhower et al. (2024) document that insurers with less granular parcel-level risk data suffer from severe adverse selection, as insurance pools become skewed toward high-risk properties. The *death spiral* (Fig. 8) increases market concentration and premiums until insurers cease offering coverage, eventually collapsing the market. For example, the 2025 Los Angeles Palisades Fire, projected to cause up to $150 billion in damages, has led major insurers like State Farm and Allstate to stop issuing new policies in high-risk areas, leaving homeowners with limited and costly options such as the California FAIR Plan (Reed, 2025).

One solution to move markets plagued by adverse selection toward efficiency is to replace private programs with government backed ones. In the United States, the long-standing National Flood Insurance Program (NFIP) transfers household's financial risk to the federal government (Carter et al., 2019; Kousky, 2018). Since 2021, NFIP has introduced Risk Rating 2.0, an actuarially fair pricing system that evaluates flood risk at the individual property level, to address adverse selection (Nayak et al., 2025). Nevertheless, this reform can also lead to moral hazard, despite its smoothing effect on property values, by encouraging homeowners or developers to (re)build properties in close proximity to water. Peralta and Scott (2024) aggregates community-level insurance coverage map data and population flow from the last twenty years, finding that population levels in NFIP communities increased by approximately 5%, with greater effects in historically flood-prone locations. Similarly, Ding et al. (2023) quantitatively examine the linkage between levee construction and urban sprawl in floodplains. They conclude that publicly funded adaptation projects often inadvertently create moral hazard by encouraging new development in high-risk areas, thereby exacerbating inefficiencies and fiscal burdens. Baylis and Boomhower (2022) note that subsidized wildfire suppression disproportionately benefits low-density developments in fire-prone regions, as homeowners and developers rely on public protection rather than investing in private adaptation measures such as fireproof materials or defensible space, as discussed in hard defense section.

For comprehensive government-backed adaptation program, financial risk transfer is only part of the story, the overarching goal is to mitigate and reduce the physical risk of climate change on land ecosystems (Browne et al., 2024). For instance, NFIP has developed and implemented a series of floodplain land management system, including risk communication through flood-hazard mapping, community land-used regulation and building-code standards (Carter et al., 2019). At the local level, municipal governments hold primary authority to regulate land use through zoning overlays or special ordinances in floodplain

[8] A Nash equilibrium is a stable state in a game where no player can improve their outcome by changing their strategy, provided that the other players' strategies remain unchanged.

[9] Basic insurance theory rest on the assumptions that households demand full insurance to smooth consumption across states of the world, that is, shifting consumption from the positive state of the world (when they pay only premiums) to the negative state of the world (when they receive benefits). Current stand-alone climate insurance is perceived more as an added loss than as protection, encouraging risk-seeking behavior and undermining full consumption smoothing.

and WUI, restricting new development in high-risk areas (Bell & Morrison, 2015). Another tool leveraged by NFIP to promote adaptation at the local level is the Community Rating System (CRS), which incentivizes neighborhoods to adopt proactive management strategies that mitigate flood risk (Sadiq et al., 2020). However, existing literature have shown ambiguous and sometimes contradictory relationships between CRS participation and economic outcomes (Highfield & Brody, 2017; Pecharroman, 2023). Furthermore, some studies reveal that barriers like administrative disputes and unequal resource distribution limit CRS participation, particularly in under-resourced communities, suggesting a need for reforms to enhance equity and efficiency (Gourevitch & Pinter, 2023; Landry & Li, 2012).

Public provision of soft protection programs must also strike a balance between cost and benefit; however, CBA is more complex than public-investment infrastructure because evaluating hidden losses and gains requires a more subtle exercise. In a review paper by Hudson and Botzen (2019), the authors find that land-use regulations generally yield positive economic returns, with median and mean benefit-cost ratios (BCRs) of 1.09 and 2.2 respectively, for zones within the one-hundred-year floodplain. However, when considering all floodplains, the overall median BCR drops to 0.79, implying that targeted rather than broad-based zoning policies tend to be more economically viable.

5.3. Equity in adaptation: Winners and losers

As we mentioned before, because neighborhoods vary greatly in their economic and social circumstances, any adaptation programs, even even when applied uniformly, will unavoidably impose a "disparate impact" across different neighborhoods. Dispite recent advances in empirical climate adaptation research, notable opportunities remain focus on equity considerations. Decision-making in the investment and provision of adaptation projects often raises concerns about "narrow bracketing" (Rabin & Weizsäcker, 2009), meaning that households or neighborhoods design adaptation plans focused narrowly on localized benefits while failing to consider broader spatial and social interdependencies. Indaco and Ortega (2024), demonstrate that investments in flood barriers, elevated buildings, and resilient utilities tend to preserve or increase property values in at-risk areas, particularly in dense urban environments with high residential capital. This "infrastructure-value feedback loop" enables more affluent populations to remain in or move to hazard-prone locations while potentially displacing lower-income residents who cannot afford rising housing costs or insurance premiums (De Koning & Filatova, 2020; Li & Grant, 2022).

The challenges of climate adaptation inequality are particularly salient in insurance programs, where low- and moderate-income (LMI) households are more likely to be uninsured or underinsured (Kunreuther, 2018). Actuarial fair premiums or mandatory coverage requirements may be sufficient to cover program costs but are often beyond the willingness to pay (WTP) for most LMI households (Kousky, 2018; Netusil et al., 2021). This undoubtedly weakens their resistance capacity and prolongs recovery after extreme climate events (Auer & Hexamer, 2022). Subsidies targeted toward underserved populations, such as means-tested or income-based programs, can promote affordability for LMI households, yet few studies have examined the effects of progressive climate subsidies on property owners.

In some cases, government-backed approaches ensure a more equitable distribution of adaptation benefits but do not necessarily address externalities (Billings et al., 2022; Fitzgerald, 2022). On-site publicly funded adaptation infrastructures that considers only narrow interests may leave adjacent households or neighborhoods worse off due to negative spillover effects. Although many studies find that the overall economic benefits of these adaptation projects outweigh their costs based om CBA analysis (Kelly & Molina, 2023), Bradt (2022) argue that accounting for negative spillovers to "outsiders" (i.e., less protected neighborhoods) can reverse this conclusion. Significantly, rigorous cost–benefit analysis accompanied by impact statements can place marginalized community in a stronger negotiation position to demand adaptation subsidies. As cities enter an era of increasing local fiscal autonomy, it is theoretically feasible to propose transfer programs from the neighborhoods protected by adaptation measures to those worse off (Fitzgerald, 2022). In practice, such compensation is difficult because identifying who the losers are, how much they lost, and how far the effects extend is highly complex. Local government may be better positioned to provide the specialized expertise needed for such analyses.

6. Discussion

6.1. General trends of empirical studies

Early research in this field generally centered on a single hazard, particularly coastal flooding. Over time, however, there has been growing recognition that communities face multiple, and sometimes overlapping, threats from a broadening set of climate-related perils. Wildfires, flash flooding, sandstorm and heatwaves have entered the empirical landscape in recent years, with mixed evidence on their impacts. Compared with discrete hazards, chronic events pose greater identification challenges because their effects permeate entire regions, leaving no clear control areas. At the same time, attention has shifted from merely documenting the damage caused by acute physical risks toward examining how adaptation measures alter these outcomes. This shift allows researchers to identify both the vulnerability and mitigation effects.

Another major development is the growing recognition that "one-size-fits-all" assumptions about vulnerability overlook the substantial heterogeneity across neighborhoods and demographic groups. Early analyses often assumed uniform household responses to climate shocks, yet more recent studies find significant variation depending on baseline income, urban density, and existing adaptive capacity. This shift underscores the need for finely grained data, as ongoing scholarship increasingly exploits parcel-level records and high-frequency observation windows, enabling more precise causal inference. Indeed, as difference-in-differences estimators and other quasi-experimental approaches become more common, researchers can better isolate market responses induced by climate events or adaptation programs.

6.2. A four-quadrant policy matrix for climate adaptation

Based on the synthesis of empirical evidence, we develop a comprehensive, organizing taxonomy matrix to help policymakers at both local and national levels design effective policies for promoting climate adaptation. As discussed in Section 5, two key distinctions — how adaptation is delivered and the way in which the program is funded — lead to four major climate adaptation types, as shown in the four-quadrant matrix (Fig. 9). More precisely, the separation between columns reflects the dichotomy between hard infrastructural defenses and soft place-based policies, while the separation between rows indicates whether the adaptation initiatives are funded by public or private sources. We categorize various adaptation activities identified in the reviewed literature and fit them into each quadrant of the framework.

The policy matrix offers a conceptual framework for characterizing adaptation policy portfolio across different contexts. Each approach can independently yield substantial reductions in expected damage, however, it may also lead to unintended consequences and challenges due to misaligned incentives. Moral hazard represents onr of the most common challenges in publicly backed adaptation programs, wherein individuals may engage in riskier land-use behaviors (e.g. rebuilding in floodplains) and have weaker incentives to protect themselves from climate-related hazards. Scholars continue to cast doubt on the net benefits that cities reap from investing in large-scale adaptation infrastructure or public financial assistance. Critics also contend that public adaptation programs are more likely to rife inefficiency and allow

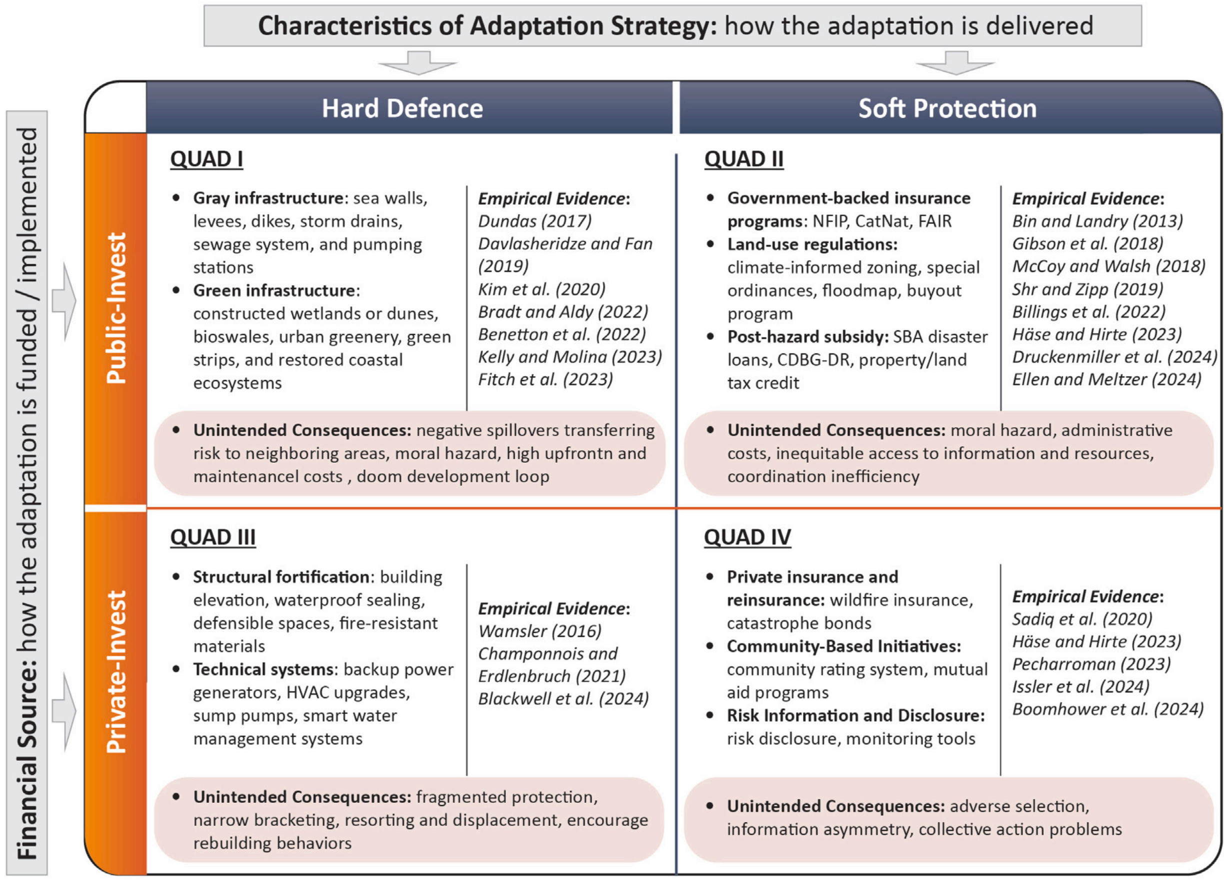


Fig. 9. Four-quadrant policy matrix for place-based climate adaptation activities.
Notes: The matrix categorizes climate adaptation strategies along two dimensions: delivery method (hard defense vs. soft protection) and funding source (public vs. private investment). Each quadrant presents specific adaptation approaches, relevant empirical evidence from the literature, and associated unintended consequences. Quad I covers public infrastructure investments; Quad II includes government-backed programs and regulations; Quad III encompasses private structural adaptations; and Quad IV contains market-based and community initiatives. The matrix synthesizes findings from 21 empirical studies published between 2016 and 2024, documenting both intended effects and negative externalities of various adaptation strategies. Hard defense refers to physical infrastructure and structural modifications, while soft protection includes policy instruments and risk management programs.

bureaucracy to grow as there is no competitive pressure to keep it in check.

On the flip side, the private marketplace faces the unraveling of insurance coverage: even when households are willing to pay premiums exceeding the expected property loss incurred by natural hazards, the market does not necessarily supply such insurance. Accordingly, middle-ground solutions like public–private risk sharing mechanisms are needed to expand policy coverage, reduce market imperfections, and ensure that adaptation benefits reach LMI households in need. As more joint evidence accumulated in the literature, the matrix will evolve from one with sharply delineated to more porous boundaries. It bears emphasis that the scope and relative emphasis of each quadrant may vary across implementation stages so that concerted efforts are both common and encouraged to sustain long-term climate action.

6.3. Research gaps for future studies

6.3.1. Risk belief and information channel

The diversity of various adaptation portfolios, their complex interdependencies, and disproportionate outcomes highlight the need to investigate local adaptation responses from a dynamic perspective. Future studies could focus on behavioral tendency whereby households' subjective risk perceptions evolve based on adaptation implementation, hazard experiences, and social surroundings (Cuni-Sanchez et al., 2025). In practice, understanding how residents perceive climate risk before and after major events helps policymakers anticipate decisions on construction, relocation, and adaptation, which is crucial for designing suited policies (Kettle & Dow, 2016). As our review indicates, failing to account for shifting sentiments and anticipate preference reversals has led to misaligned incentives underlying many land-use conflicts over climate risk (Ackerschott et al., 2023; Krawchenko & Tomaney, 2023). Consistent with our model in Eq. (5), climate change complicates policymakers' ability to predict and model homeowners' risk gradients to natural disasters when determining appropriate measures.

Information channels play a critical role in resilience building as well: households often underestimate climate risks until hazards occur. Conversely, households may overestimate future risks even under modest exposure or by seeing negative shocks from nearby climate events. This generates a cascade of follow-on effects that ultimately result in much larger economic impacts. This phenomenon is well documented in areas not directly affected by flooding but located near damaged neighborhoods where stories of the event are repeatedly shared (Klenk, 2018). While the availability heuristic[10] produces extensive vestigial

[10] The availability heuristic in climate risk perception refers to people's tendency to judge the likelihood and severity of climate risks based on how easily they can recall related examples or experiences (Sunstein, 2006). They often rely on memories of recent or vivid climate-related events rather than statistical data or long-term trends.

effects on long-term socioeconomic outcomes, monitoring risk perceptions and fostering public engagement in the planning process can help policymakers identify which program activities align with current priorities (Reja et al., 2023). Whether and how risk conveyance tools and participatory process like scenario planning foster long-range resilience remain empirical questions that future research can explore.

6.3.2. Interplay between joint adaptation efforts

Quantitative research has provides limited evidence on how different adaptation activities interact within the overall policy portfolio (Fig. 9). While each measure aims to reduce climate risk exposure from a particular channel, their relationship exhibits complex complementarity and substitution effects that warrant careful examination (Browne et al., 2024). Many adaptation programs have not fared as well as expected because policymakers failed to give adequate deliberations on the chain reactions triggered by new initiatives. This lack of understanding of coordinated mechanisms has led to persistent underestimations of the extent and influence of resilience practices over time. For example, recent work by Ziff and Vinnakota (2022) leveraging variation in levee construction and accreditation timing, find that levee provision reduces flood insurance take-up by approximately 16%, indicating that households view levees as partial substitutes for insurance-based adaptation. This finding has significant policy implications, as public agencies have become increasingly critical of large subsidized adaptation projects, scrutinizing their associated cost-benefit ratios.

Furthermore, if public–private joint ventures are recognized as tools to address structural problems underlying many climate adaptation programs, the need for overall evaluation becomes pressing. However, few detailed economic assessments encompassing both public and private sides have been conducted to date. For example, the levee effect can also encourage new construction and development if not in tandem with appropriate land-use regulation restriction (Georgic & Klaiber, 2022). Future empirical investigations should focus on the intersections of different adaptation policy portfolios, specifically on how risk-prone land management can mitigate moral hazards induced by incentives schemes. Understanding these causal interactions can help governments step in and design targeted policies and planning interventions to alleviate unintended consequences and improve equity.

6.3.3. Other limitations

The full impacts of climate hazards often exceeds the sum of immediate injuries, damages, and losses from a single disaster. Failure to factor in cascading impacts on households' dynamic decisions and long-run neighborhood transitions can lead to underestimate of consequences and misjudgment of appropriate management or adaptation response (Lawrence et al., 2020). As research on climate shockss remain affixed on how single perils associated with specific events shape real-estate markets, many questions remain clouded regarding how compound risksor cascading effects that are part of a broader cycle of climate change effect local economies.

Our intention to generalize the findings could also be hindered by geographic coverage. Regions like Africa, parts of Latin America, and smaller island nations show relatively limited coverage in our system-level review. Such omissions may stem from data constraints, underfunded research infrastructures, or simply historical precedent in focusing on developed economies. As climate risks grow and diversify, expanding the empirical frontier to include these understudied domains will be essential for testing whether current findings generalize or whether new hazard contexts and institutional frameworks yield diverging results. Regarding property typologies, prior event studies concentrated in the U.S. context largely focus on single-family housing, whereas empirical investigations of multi-family housing or other land-based assets (e.g. commercial properties, informal settlements) are sparse and evolving. The primary challenges — as Contat et al. (2024) previously noted — may attributed to the limited availability of highly granular data, however, much can still be learned by broadening the research scope to capture greater geographical and typological diversity. From a global perspective, many of the most pressing land management challenges arising in advent of climate change exist in the high-density urban areas, especially in developing nations experiencing rapid rural-to-urban migration.

7. Conclusion

Irreversible urbanization and intensifying population growth are making urban neighborhoods increasing vulnerable to unprecedented climate challenges. In response to these risks, decision-makers worldwide have been proactively seeking strategies to build resilience through climate adaptation. Certainty may arrive too late, only after a climate calamity has occurred, to commence on designing optimal responses. Unbundling climate risks into manageable proportions is essential for local policymakers when making specific interventions and investments. To allocate the public funds more efficiently and equitably, we need to understand how different place-based adaptation policies translate into land-market outcomes. Property and land values thus serve as important metrics, directly affecting municipal tax revenues, which, in turn, constrain or enable local governments' capacity to invest in adaptation infrastructure and maintain urban services. Our theoretical guided, systematical review aims to synthesize such empirical evidence from prior literature.

Nearly 80% of empirical studies documented in the literature underscore how climate adaptation programs help households resist the negative shocks associated with acute hazards. The strong record offers tangible evidence that climate adaptation activates enhance property and land values compared with those counterparts without adaptation. In average, adaptation programs mitigate adverse shocks to property values by roughly 7.7 percentage points. Importantly, this magnitude may be overstated, as interdependence among different types of adaptation activities likely dampens isolated effects. Our review also reveals broad heterogeneity and even detrimental effects of some programs, where adaptation practices can trigger unintended consequences, prove cost-inefficient, or exacerbate preexisting inequalities. Evaluating model that consider only the benefits to targeted groups while ignoring externality costs risk misrepresenting long-run resilience outcomes.

When assessing the effects of government interventions, urban planners and policymakers must recognize that every program entails both direct and indirect effects. Across the wide spectrum of climate adaptation options, there is growing recognition that interdependencies among different measures, and the distribution of protective benefits across disparate neighborhoods, should be incorporated into project design from the earliest stages. Our results suggest that successful climate adaptation calls for carefully coordinated portfolios of interventions. No isolated strategy can eliminate the impacts of climate change; instead, multiple strategies must operate synergistically to reduce economic losses. The four-quadrant matrix we propose provides a structured framework for evaluating policy combinations while remaining attentive to equity considerations.

Several promising directions for future research emerge from our analysis. First, further work is needed to understand how risk beliefs and information channels mediate adaptation outcomes, particularly given evidence that heightened risk awareness can sometimes works against adaptation goals. Second, the interactions between different adaptation measures deserve closer empirical scrutiny, as our review suggests both complementarities and substitution effects that remain poorly understood. Finally, expanding the geographical and typological scope of empirical work could illuminate whether the patterns observed in relatively high-income contexts generalize to other regions — and to different property types — where data constraints and governance structures differ markedly. Research integrating multiple data sources, including fine-grained spatial records and novel identification strategies, would greatly clarify how households respond to compound climate risks. Such a broadening in scope could also help scholars detect equity trade-offs more precisely, shedding light on whether new place-based adaptation policies inadvertently reinforce local inequalities and thereby challenging policymakers to design more inclusive approaches.

CRediT authorship contribution statement

Yihao Wu: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Jinpeng Yang:** Visualization, Data curation. **Zhenhua Li:** Writing – review & editing.

Data availability

Data will be made available on request.

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