Adaptation to Climate Change*

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Mounting costs of anthropogenic climate change reveal that adaptation will be essential to human well-being in coming decades. At the same time, the literature on the economics of adaptation offers relatively little guidance for emerging policy. In this chapter, we review the existing literature, focusing on how it can better inform adaptation policy design and implementation. A simple conceptual model of adaptation decision-making describes two core adaptation channels that we link to two streams of adaptation literature, which have emerged largely in parallel. We outline how insights from these literatures can be used for adaptation policy evaluation, highlight key limitations of public intervention in private adaptation markets, and provide guidance and opportunities for future work.

Keywords: adaptation, climate change, policy intervention

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Introduction

As the impacts of anthropogenic climate change accelerate, adaptation plays an increasingly critical role in shaping human well-being now and into the future. Climate adaptation is generally defined as any behavior, investment or other decision taken in direct response to realized or anticipated changes in the climate. While adaptation often refers to decisions that ameliorate the adverse impacts of climate change, adaptive behavior can also include decisions or changes that allow individuals to exploit beneficial opportunities that arise with an evolving climate. These adaptation decisions occur within a broader socioeconomic fabric, as many environmental, economic, political, and cultural conditions, such as social services, income shocks, and available technologies, shape the constraints and opportunities that individuals, communities, and governments face as they navigate climate change. As a result, conditions exogenous to climate change itself are important in determining the degree and nature of adaptation to climate change.

Unlike mitigation of the greenhouse gas emissions responsible for climate change, adaptation to its impacts is often construed as a set of private decisions. Under perfect market conditions with full information, individuals should make adaptive choices that best respond to short- and/or long-run changes in climatological conditions. Such a setting leaves little room or justification for adaptation policy. Hence, most research in climate economics has focused on quantifying the manner and extent of private adaptation. However, in practice, private adaptation is constrained by many frictions, including imperfect information and inaccurate beliefs, as well as limits to property rights, credit markets, and insurance, which often disproportionately affect low income individuals and countries. Moreover, some adaptation investments have increasing returns to scale or involve public goods and externalities, and cannot or will not be undertaken by individuals. Thus, a critical role for adaptation policy emerges, as intervention can ameliorate climate damages in contexts where market failures preclude individual actors from making optimal adaptive decisions. More broadly, climate change is projected to worsen inequality, due both to the spatial distribution of exposure to climate extremes, and to unequal spending on adaptation. Public policies governed by equity motives may therefore also justify adaptation interventions, even in the absence of market failures.

This chapter reviews the economic literature on climate change adaptation, with a focus on how this body of work can inform adaptation policy. We begin by defining two core channels of adaptation – ex post responses to realized weather shocks and ex ante investments undertaken before weather is experienced – using a simple conceptual model of private adaptation decisions. We demonstrate how the decision environment, including prices, income, and associated markets, shapes adaptation choices and outcomes. We next link these channels to two policy-relevant motivations for studying adaptation, each of which has molded a stream of adaptation literature. The first stream is composed of research quantifying climate damages, which has sought to account for adaptation using a variety of reduced form and structural strategies. The second stream has studied adaptation more directly, aiming to understand the impacts and effectiveness of various adaptation behaviors, technologies and interventions. We review both literatures through a single unifying framework that helps illustrate opportunities for further research progress and synthesis across subfields. Finally, as climate damages mount, so does interest in effective and cost effective adaptation interventions. We therefore discuss frameworks for policy evaluation and conceptual justifications for policy intervention – which are rarely made explicit in existing studies – as well as potential limitations and pitfalls of policy intervention. Throughout the chapter, we highlight weaknesses of current research and opportunities for improvement; we conclude with a final section that summarizes these opportunities and priorities for future work.

1 Defining adaptation: Two channels of adaptive decision-making

The term "climate adaptation" is invoked across the economics literature in various ways with distinct meanings. To clarify definitions and fix ideas throughout this chapter, we categorize uses of the term into two groups, which form two "channels" of adaptation: ex ante and ex post.

We begin by presenting a simplified but general conceptual framework in which decision-makers face exogenous changes in the climate and choose adaptive actions to maximize welfare. The framework encompasses both ex post and ex ante adaptation channels and serves to demonstrate differences between the channels and to elucidate key measurement objectives in the literature. It also highlights the critical role of external factors, which are orthogonal to climate change itself, that shape the adaptation decision environment and therefore influence both channels of adaptation.

Consider an agent facing a simple dynamic utility maximization problem in which she faces exogenous weather realizations, $\boldsymbol{c}_t$ in each period t, that impact her utility. Period t weather $\boldsymbol{c}_t$ is drawn from a steady-state climate distribution $\boldsymbol{C}$, as in Hsiang (2016).[1] For example, one possible functional form linking weather and climate is $\boldsymbol{c}_t = \boldsymbol{C} + \boldsymbol{\varepsilon}_t$, where $\boldsymbol{\varepsilon}_t$ are random, mean-zero, i.i.d. shocks. Other functional forms are possible, but we will assume throughout that the parameters describing the steady state climate reflect expected weather; that is, that $\mathbb{E}[\boldsymbol{c}_t] = \boldsymbol{C}$.

Under a given steady state climate $\boldsymbol{C}$, there are two ways in which the agent can respond to weather-induced utility shocks. First, she can choose from a vector of goods or services $\boldsymbol{b}$ that are available to her as the weather event is occurring or after it has arrived. For example, she may increase energy use to cool her home during a heat wave, increase irrigation water applications to her farm under drought, or switch sectors of employment in response to climate-induced productivity shocks. The choice of adaptive actions $\boldsymbol{b}$ is thus not anticipatory, but instead reactive; we call these adaptive actions "ex post" adaptation, following, for example, Lemoine (2023).

Second, she can choose from another vector of goods or services $\boldsymbol{k}$ that require up front investment before weather realizations occur. For example, if she is a farmer, she must choose which seeds to plant and whether to take up crop insurance before growing season weather is realized. Similarly, if she represents a local government, she must make infrastructure investments, such as bridges and sea walls, in anticipation of future sea levels and storm surges. Her decisions about these durable investments are made based on her information set, which includes her expectations about weather realizations that will occur in the future. In

[1]Weather and climate are denoted as vectors because they can compose many possible variables and moments of the distribution, such as drought, cooling degree days, rainfall, etc.

practice, the relevant time horizon for such expectations depends naturally on the durability of the decision; for example, for a farmer planting annual crops, the relevant horizon is a single year, but for an educational investment the time horizon may be a lifetime. These adaptive actions $\boldsymbol{k}$ we call "ex ante" adaptation.

Here we assume that decisions regarding durable investments $\boldsymbol{k}$ must be made during a single pre-period, before weather is realized and utility is impacted.[2] These durable investments then persist into future periods, but depreciate through time at rate δ. After this pre-period, in each period $t \in [0, ..., \infty)$, the agent then solves:

$$\max_{\boldsymbol{b}_t, w_t} \quad u(\boldsymbol{c}_t, \boldsymbol{b}_t, w_t; \boldsymbol{k}(1-\delta)^t) \quad \text{s.t. } \boldsymbol{p}_t \boldsymbol{b}_t + w_t \leq y_t, \tag{1}$$

where w_t is a numeraire consumption good and y_t is exogenous income. Note that weather $\boldsymbol{c}_t$ is known with certainty before the ex post adaptation choice $\boldsymbol{b}_t$ is made, and that, in contrast, $\boldsymbol{k}$ is taken as given and unchangeable in period t, so that its iterative law of motion is $\boldsymbol{k}_t = \boldsymbol{k}(1-\delta)^t$ for all t. The indirect utility function in period t is therefore $u(\boldsymbol{c}_t, \boldsymbol{b}_t^*, y_t - \boldsymbol{p}_t \boldsymbol{b}_t^*; \boldsymbol{k}_t)$, where we have substituted in the budget constraint and where $\boldsymbol{b}_t^* = \boldsymbol{b}^*(\boldsymbol{c}_t, y_t, \boldsymbol{p}_t; \boldsymbol{k}_t)$ represents the utility-maximizing choice of $\boldsymbol{b}$ in time t.

Now consider the choice of $\boldsymbol{k}$ during the pre-period. The agent must make this choice before knowing the weather realizations $\boldsymbol{c}_t$ in future periods t, but with full knowledge of $\boldsymbol{C} = \mathbb{E}[\boldsymbol{c}_t]$.[3] Suppose for simplicity that prices $\boldsymbol{p}_t$ (the price vector in period t for ex post adaptations) and $\boldsymbol{r}$ (the price vector in the pre-period for ex ante adaptations), as well as income y_t, are deterministic and known with certainty during the pre-period. She then solves:

$$\max_{\boldsymbol{k}} \quad \sum_{t=0}^{\infty} \beta^t \mathbb{E}\left[u(\boldsymbol{c}_t, \boldsymbol{b}_t^*, y_t - \boldsymbol{p}_t \boldsymbol{b}_t^*; \boldsymbol{k}(1-\delta)^t)\right] \quad \text{s.t. } \boldsymbol{r}\boldsymbol{k} \leq \overline{y} \tag{2}$$

where $\mathbb{E}[\cdot]$ indicates expectations over the uncertain weather distribution, given information

[2] The assumption of a pre-period in which durable investments are made is also used in the dynamic framework in Lemoine (2023).

[3] Of course, in practice durable investments can be made at any time, and agents must decide as the climate changes continuously when, if at all, to invest in long-run adaptive capital. To maintain tractability, we abstract from this timing decision here, but point readers to Fried (2022); Bilal and Rossi-Hansberg (2023); Krusell and Smith (2022), among others, where it is handled explicitly.

available in the pre-period, and $\overline{y}$ indicates income available in the pre-period (noting that all other future variables, such as prices and income, are deterministic). The agent's decision over $\boldsymbol{k}$ influences her utility in all future periods $t = 0, ..., \infty$, due to its durability. Her optimal choice $\boldsymbol{k}^*(\boldsymbol{C}, \overline{y}, y_{t=0,...\infty}, \boldsymbol{p}_{t=0,...\infty}, \boldsymbol{r}; \delta)$ represents the value of $\boldsymbol{k}$ that maximizes her expected stream of utility over all periods. Note that $\boldsymbol{k}^*$ depends not on the weather, but on the climate (i.e., expected value of the weather in all t), as this ex ante decision must be made before weather is realized.

We are interested in assessing the impacts of climate change. Following the literature (e.g., Hsiang, 2016; Deryugina and Hsiang, 2017; Lemoine, 2023; Rudik et al., 2024), we consider the steady-state impacts of changing the climate, evaluated in a future period t, after ex post adaptations have taken place and allowing for ex ante adaptations to adjust in expectation of a new climate. This mirrors the empirical literature reviewed in Section 2.1, much of which seeks to estimate the total damages from climate change in a given year — for example, the year 2100. Recall that the steady-state climate is $\boldsymbol{C}$, from which all weather realizations $\boldsymbol{c}_t$ are drawn. Since each period's decision problem for t is a static problem with optimal actions that satisfy the first-order conditions from Equation (1), the expected impact of climate change in t is simply the total derivative of the expected value of the indirect utility in period t, i.e., $u_t = u(\boldsymbol{c}_t, \boldsymbol{b}_t^*, y_t - \boldsymbol{p}_t\boldsymbol{b}_t^*; \boldsymbol{k}_t)$, with respect to the steady-state climate:

$$\frac{d\mathbb{E}[u_t]}{d\boldsymbol{C}} = \underbrace{\frac{\partial u_t}{\partial \boldsymbol{c}_t}\frac{d\boldsymbol{c}_t}{d\boldsymbol{C}}}_{\substack{\text{direct effect of} \\ \text{weather}}} + \underbrace{\frac{\partial u_t}{\partial \boldsymbol{b}_t}\frac{\partial \boldsymbol{b}_t^*}{\partial \boldsymbol{c}_t}\frac{d\boldsymbol{c}_t}{d\boldsymbol{C}}}_{\substack{\text{ex post response} \\ \text{to weather}}} + \underbrace{\frac{\partial u_t}{\partial \boldsymbol{k}}\frac{d\boldsymbol{k}^*}{d\boldsymbol{C}}}_{\substack{\text{ex ante adaptation} \\ \text{to climate}}} \tag{3}$$

where all partial derivatives are evaluated at $\boldsymbol{c}_t = \mathbb{E}[\boldsymbol{c}_t] = \boldsymbol{C}$ and expectations are formed using information available in the pre-period.[4] The expression in Equation (3) makes clear that the overall impacts of climate change (lefthand side) can be decomposed into the direct

[4]Evaluating the derivative of payoffs at mean weather is equivalent to evaluating the derivative of expected payoffs over the full distribution of weather only under the functional form assumptions detailed in Mérel et al. (2024) – i.e., that actions $\boldsymbol{b}_t$ and $\boldsymbol{k}$ interact linearly with weather within $u(\cdot)$. Like Lemoine (2023), Deryugina and Hsiang (2017), Carleton et al. (2022) and many others, we make that assumption here in order to simplify the notation of the stylized framework we present. This assumption does not have bearing on the qualitative interpretations of Equation 3 made throughout the chapter.

effects of changing weather realizations, holding fixed all adaptive decisions (first term), and two terms capturing the impacts of the two channels of adaptation: one for ex post decisions (second term) and one for ex ante (third term). We discuss each of these channels in turn below, as well as the importance of exogenous conditions (e.g., income y and prices $\boldsymbol{p}$ and $\boldsymbol{r}$, as well as market structure, information, and other factors) that shape adaptation choices and thus the impacts of climate change.

Before considering each channel of adaptation, we note that this framework is highly stylized and therefore omits many key features of adaptation. For example, the dynamic decision problem in Equation 2 involves no savings nor credit constraints, and both ex post and ex ante decisions are assumed to be made under perfect information regarding the weather, the impacts of weather on utility, and the steady state climate. Additionally, the object of interest is assumed to be utility itself, in which case the Envelope Theorem implies that $\frac{\partial u_t}{\partial \boldsymbol{b}_t} = \frac{\partial u_t}{\partial \boldsymbol{k}} = 0$ in Equation (3) and the two adaptation terms drop out (Guo and Costello, 2013; Hsiang, 2016; Deryugina and Hsiang, 2017). In contrast, most applied work investigates a component of utility or profits that is impacted by the weather, such as crop yields or human health, rendering the two latter terms on the righthand side of Equation (3) nonzero and critical for assessing climate change impacts. Throughout the remainder of the chapter, we highlight literature that empirically and/or theoretically expands upon this simplified framework to investigate more complex models of adaptation.

1.1 Channel 1: Ex post response to a climate shock

Ex post adaptation is perhaps the simplest channel of climate adaptation, as individuals, households, or governments respond to weather realizations either as they are occurring or after they arrive. The role of ex post adaptation in shaping welfare under climate change can be seen in the second term on the righthand side of in Equation (3). This effect includes three components.

The vector of partial derivatives $\frac{\partial \boldsymbol{b}^*}{\partial \boldsymbol{c}}$ captures any behavior changes taken in response to the weather. To the extent that these partial derivatives are non-zero, they reflect ex post adaptations agents pursue to respond to the weather shocks they experience. When empirical papers investigate the adoption and use of ex post adaptation technologies – for example, how much irrigation water is applied during drought events or how much energy is used during heat events – they are assessing this partial derivative. How such adaptations influence utility is captured in $\frac{\partial u}{\partial \boldsymbol{b}}$. We note that this effect can be composed both of direct utility benefits or harms from changing decisions $\boldsymbol{b}$, as well as utility benefits that arise from lowering the welfare effects of an adverse weather shock. Studies that assess impacts of adaptation decisions on welfare-relevant outcomes, such as agricultural profits or consumption, are either quantifying this term alone, or this term in combination with how the adoption decision changes with the weather, i.e., $\frac{\partial \boldsymbol{b}^*}{\partial \boldsymbol{c}}$. Finally, $\frac{dc}{d\boldsymbol{C}}$ captures how weather changes due to climate change. Studies that investigate ex post adaptation under the current climate distribution do not account for this final term, although its inclusion is critical to making insights regarding adaptation relevant to the future under long-run climate change.

1.2 Channel 2: Ex ante investment based on beliefs

Many adaptive decisions are anticipatory, requiring an ex ante adjustment before weather realizations occur. Thus, agents must choose the optimal vector of durable goods $\boldsymbol{k}^*(\cdot)$ to maximize the expected stream of discounted utility, facing unknown future weather realizations. This uncertainty arises because weather is inherently unpredictable, even when the climate distribution itself is known. However, in many settings, particularly with rapidly evolving climate change, the climate distribution from which weather is being drawn may also be uncertain. In either case, ex ante decisions must be made based on agents' expectations, as long as adaptation technologies or investments are long-lived. The effects of ex ante adaptation on welfare under climate change can be seen in the last term on the righthand side of Equation (3), which is composed of two parts.

First, the vector of partial derivatives $\frac{d\boldsymbol{k}^*}{d\boldsymbol{C}}$ captures ex ante behavior changes taken in response to changes in the expectation of future weather realizations. If such derivatives are non-zero, they reflect ex ante adaptations. As detailed throughout the chapter, these decision adjustments made in response to changing expectations are assessed both implicitly and explicitly in existing literature. How these adaptations influence utility is captured by $\frac{\partial u}{\partial \boldsymbol{k}}$, which, like for ex post adaptation, will include both direct effects of adaptive investments on utility, as well as any benefits realized through reducing harms from adverse weather.

In Section 2, we describe how some subsets of the literature successfully identify ex ante adaptation and/or its influence on climate damages. We also highlight how difficult accounting for ex ante adaptation can be and therefore we identify many gaps in the literature. We discuss how ex ante adaptation decisions also affect the set of feasible ex post adaptations (as seen in the decision problem in Equation (1)), which complicates separation of the two channels in some empirical settings.

1.3 Exogenous conditions governing the decision environment shape both channels of adaptation

A diverse set of conditions unrelated to climate change itself governs the adaptation decision problems in Equations (1) and (2), influencing choices $\boldsymbol{b}^*$ and/or $\boldsymbol{k}^*$. These external factors include changes in adaptation prices p and r, income y, as well as information, market structure, and any market frictions. To see how such features shape adaptation and the impacts of climate change, consider an exogenous change in the budget constraint y_t in period t. A loosening of the budget constraint changes optimal ex post adaptations $\boldsymbol{b}^*(\boldsymbol{c}_t, y_t, \boldsymbol{p}_t; \boldsymbol{k}_t)$, where $\frac{\partial \boldsymbol{b}^*}{\partial y_t} \geq 0$ for normal goods. The effects of such reoptimization on the impacts of climate change can be seen by taking the derivative of Equation (3) with respect to y_t:

$$\frac{d^2\mathbb{E}[u_t]}{dy_t \boldsymbol{d}C} = \frac{\partial u_t}{\partial \boldsymbol{b}_t} \frac{\partial^2 \boldsymbol{b}_t}{\partial y_t \partial \boldsymbol{c}_t} \frac{d\boldsymbol{c}_t}{d\boldsymbol{C}}, \tag{4}$$

where all variables are defined as in Equation (3).[5] The middle term on the righthand side of Equation (4) quantifies how a marginal relaxation of the budget constraint changes the optimal ex post adaptation actions $\boldsymbol{b}$ in response to weather $\boldsymbol{c}$. When multiplied by $\frac{\partial u_t}{\partial \boldsymbol{b}} \frac{d\boldsymbol{c}_t}{\boldsymbol{C}}$, this indicates how this change in the budget constraint modifies the welfare effects of climate change.[6] An analogous expression can be derived for a change in pre-period income $\overline{y}$, which will alter optimal ex ante adaptation $\boldsymbol{k}^*$. Similarly, changes in prices $\boldsymbol{p}$ and $\boldsymbol{r}$, shifts in

[5]In Equation (4) we assume the cross-partials $\frac{\partial^2 u_t}{\partial y_t \partial \boldsymbol{c}_t}$ and $\frac{\partial^2 u_t}{\partial y \partial \boldsymbol{b}}$ are both zero. These are relatively innocuous assumptions – they imply that income has no influence over the direct effects of weather and that income itself does not change the efficacy of the adaptation actions within the vector $\boldsymbol{b}$.

[6]Note that an increase in income changes the welfare effects of climate change both by relaxing the budget constraint, as discussed here, and by raising the lower bound of consumption under a bad weather realization. The importance of the latter channel depends on the shape of the utility function.

expectations $\mathbb{E}[u_t]$, changing preferences $u_t(\cdot)$, and any other features of the decision problem may change adaptation choices and ultimately the welfare effects of climate change.

In discussing the empirical literature on the adoption and efficacy of adaptation strategies in Section 2.2, we use E to indicate an intervention that changes any aspect of the adaptation decision environment, including changes in: prices $\boldsymbol{p}$ and $\boldsymbol{r}$; income y; and any other frictions or market conditions. Here we briefly preview how they interact with the ex post and ex ante adaptation channels articulated above.

(i) First, prices $\boldsymbol{p}$ and $\boldsymbol{r}$ affect adaptation decisions and outcomes. If adaptation goods are normal goods, $\frac{\partial b_j^*}{\partial p_j} \leq 0$ for any element j of the vector $\boldsymbol{b}$ (or, analogously, for $\boldsymbol{k}$). Price changes induced by the market, by public policies, or by innovation therefore affect adaptation decisions and resulting climate change damages inclusive of ex post and ex ante decisions. Relatedly, technological innovation can introduce new elements into the vectors $\boldsymbol{b}$ and $\boldsymbol{k}$, effectively reducing their prices from infinite to nonzero, leading to substitution and income effects that reshape adaptation decisions.

(ii) Second, adaptation decisions over $\boldsymbol{b}$ and $\boldsymbol{k}$ will depend on the tightness of the budget constraint y, independent of weather realizations or expectations of future climate. Specifically, demand for adaptation goods that are normal and deliver positive utility will increase with income, even for a given climate. For example, India is projected to see expansive growth in air conditioning installations, regardless of how future climate change unfolds (Birol, 2018). Greater coverage of air conditioning is likely to lower mortality risks from climate change by mitigating the risk of death on extremely hot days. Relatedly, social programs may reduce variability in income, as opposed to its overall level, with corresponding influence over adaptation choices and outcomes, particularly in dynamic settings.

(iii) Finally, a wide array of frictions, including behavioral biases, incomplete information, market structure (e.g., trade costs), and other barriers to optimal adaptation, including credit and financial constraints, influence adaptation decisions. These various frictions are regularly influenced by government policy and they modify adaptation decisions and resulting climate change damages.

A growing body of literature leverages variation in conditions *(i)*, *(ii)*, and/or *(iii)* to identify the adoption and/or efficacy of both ex post and ex ante adaptation decisions. We review this literature in detail in the next section.

2 Why study adaptation? The evolution of the adaptation literature and its policy motivations

The economics literature on adaptation to climate change has emerged largely through two distinct streams, each of which is motivated by very different aims. One body of work emerging largely within environmental economics, but interacting with a broader interdisciplinary scientific community, has focused on quantifying the expected damages from long-run climate change, which has required attention to the costs and benefits of adaptation. The motivating principle in this literature is that accurately assessing the future impacts of climate change requires accounting for the adaptive actions that agents are likely to take as the climate warms. This literature is designed to inform mitigation policy by generating estimates of policy-relevant objects like the social cost of carbon (Carleton and Greenstone, 2022).

A second stream of literature growing out of both development and environmental economics has focused on identifying the particular interventions that facilitate adaptation to climate change. The motivation in this literature is generally that policy interventions, sometimes directly targeting adaptation, can enable welfare improvements under climate variability and change. This literature seeks to inform adaptation policy by providing insight into what does and does not enable individuals, firms, or local governments to suffer less under climate change.

In this section, we provide a brief intellectual history of each stream of literature and review the methods employed and findings uncovered in each. We show that these two literatures place different emphasis on each of the terms in Equation (3), thus providing distinct insights into the role of adaptation in shaping welfare under climate change. While we highlight weaknesses and strengths of the existing literature throughout the section, recommendations on how the two bodies of work can learn from one another can be found later in Section 4.

2.1 The study of adaptation to inform mitigation policy

One branch of literature studying climate change adaptation is motivated by the goal of estimating the total effect of climate change on a welfare-relevant outcome (e.g., agricultural profits, economic output, health, etc.). This literature is thus focused on quantifying the lefthand side of Equation (3), $\frac{d\mathbb{E}[u_t]}{d\boldsymbol{C}}$. It has long been acknowledged that doing so accurately requires accounting for the adaptive actions that agents will undoubtedly take as climate change gradually unfolds (Schlenker et al., 2005; Deschênes and Greenstone, 2007). Thus, while a growing body of empirical work has quantified the short-run direct effects of weather (previously reviewed in, e.g., Dell et al., 2014; Carleton and Hsiang, 2016; Auffhammer, 2018; Kolstad and Moore, 2020), these studies are of limited relevance for understanding the effects of long-run climate change if people, governments, and firms make adaptive investments or undertake behavior changes in order to cope with a gradual, expected shift in the climate. That is, estimates of the total derivative in Equation (3) must account for both adaptation terms on the righthand side of the expression.[7]

In its pursuit to measure the impacts of climate change inclusive of adaptation, this literature faces a core challenge: the vectors $\boldsymbol{b}$ and $\boldsymbol{k}$ are composed of myriad adaptive actions, many of which are difficult to observe and measure. To confront this challenge, some studies develop methodological and/or theoretical innovations that, under key assumptions, allow climate impacts estimates to *implicitly* account for all unobservable adaptive changes to choices $\boldsymbol{b}$ and $\boldsymbol{k}$ without enumerating adaptive margins individually. To do so, these studies generally rely on the assumption that agents perfectly optimize their adaptation choices, facing no frictions, distorted incentives, or incomplete information. Other studies *explicitly* model specific elements of the $\boldsymbol{b}$ and/or $\boldsymbol{k}$ vectors that are likely to be first-order in terms of their impacts on climate change damages (e.g., international trade, migration, infrastructure investments). While these studies by construction omit many plausible adaptive margins, they enable researchers to investigate the welfare implications of particular adaptation actions, as well as the barriers and frictions impeding the deployment of those adaptations.

[7]As mentioned in Section 1, when the outcome of interest is an optimized quantity, there are conditions under which the Envelope Theorem can be applied such that the adaptation terms in Equation (3) need not be directly estimated in order to recover accurate estimates of the long-run impacts of climate change (Hsiang, 2016).

Here we review three sets of methods that contribute to our understanding of climate change damages inclusive of adaptation, each of which navigates this fundamental challenge in a distinct way. First, in Section 2.1.1, we describe reduced form econometric approaches to estimate the damages from climate change. These studies generally take the implicit approach to solving the challenge of many unobservable adaptive actions: their goal is not to identify which specific elements of $\boldsymbol{b}$ or $\boldsymbol{k}$ are used or are most effective in mitigating damages, but instead to produce estimates of climate change damages that include all adaptive responses. Second, in Section 2.1.2, we outline a growing set of quantitative general equilibrium models designed to estimate the aggregate damages from climate change. These analyses enumerate specific ex post and/or ex ante adaptation decisions, such as trade and migration, that modify climate damage projections. Finally, in Section 2.1.3, we summarize the body of work using integrated assessment models (IAMs) and process-based models to estimate climate change damages, the social cost of greenhouse gases, and/or optimal carbon taxes. These studies present a mix of implicit and explicit modeling of adaptation. In each section, we describe the methods used to identify adaptation and highlight the key findings on adaptation that have emerged to date.

2.1.1 Reduced form econometric approaches to account for adaptation in climate damage estimation

A rapidly expanding applied econometrics literature has uncovered a multitude of ways that the weather shapes social and economic activity. Increasingly, such analyses are being combined with climate model-generated projections of future weather under climate change to estimate the long-run impacts of climate change. As discussed above, this literature has long endeavored to ensure such estimates account for both ex post and ex ante adaptation channels, largely through attempts to implicitly embed such adaptive actions in empirical estimation, rather than to enumerate adaptive margins explicitly. Here, we outline the key methodologies developed in this space, roughly in chronological order (while acknowledging that different approaches have emerged independently and simultaneously). We then summarize the central findings regarding the nature and extent of adaptation across the applied econometric literature. Throughout, we focus on adaptation methods and results; more comprehensive treatments of the large climate econometrics literature can be found in Chapter 2 of this Volume by Hogan and Schlenker (2024) and in prior reviews (e.g., Auffhammer and Schlenker, 2014; Dell et al., 2014; Carleton and Hsiang, 2016; Auffhammer, 2018; Massetti and Mendelsohn, 2018; Kolstad and Moore, 2020).

Methodologies Here we identify the key methodologies used in the climate econometrics literature to assess damages inclusive of ex post and/or ex ante adaptation. With few exceptions noted below, these methods all implicitly account for adaptation, instead of enumerating specific adaptive margins. The benefit of this approach is that the many adaptive actions individuals, communities, firms, and governments take do not need to be identified and measured directly. The key drawback is that each methodology relies on assumptions regarding adaptive behavior that are often difficult to validate empirically. These assumptions are described within each methodology below.

Long-run climate variation in cross-sectional regression

The first reduced form econometric estimates of the impacts of climate change utilized cross-sectional variation in the long-run climate. This approach, referred to as the "Ricardian" method, estimates the equilibrium (i.e., long-run) effects of climate change on an outcome, just as other forms of hedonic analyses recover the value of nonmarket attributes by leveraging variation in the market price of an asset. If one assumes that agents have chosen all $\boldsymbol{b}$ and $\boldsymbol{k}$ values so as to optimize the outcome under the current climate, comparisons of outcomes across climates are inclusive of all ex post and ex ante adaptive actions (i.e., the total derivative on the lefthand side of Equation (3)). In its first application, Mendelsohn et al. (1994) regress U.S. farmland values, reflecting the discounted stream of expected future land rents, on long-run average climate conditions to recover estimates of climate damages on agriculture, accounting for adaptation.[8]

While the Ricardian approach implicitly accounts for all adaptive margins under quite general assumptions, it faces two shortcomings that have limited its continued use in the lit-

[8]See Mendelsohn and Massetti (2017) for a review of the results of cross-sectional climate impact studies on agriculture around the world. The authors conclude that the relationship between farmland value or net revenue and temperature, inclusive of adaptation, is concave, such that the marginal impact of warming is beneficial in cold places and harmful in hotter locations.

erature. First, correlated unobservables pose a considerable threat – many factors correlate spatially with climate and also influence outcomes of interest.[9] Second, an implicit assumption of these hedonic analyses is that the economic assets used as outcome variables (e.g., land values) do not capitalize future climate change, but instead reflect historical climates only. Severen et al. (2018) show that the forward-looking nature of asset markets leads to a misspecified standard Ricardian approach since assets capitalize available information on future climate change, inducing another form of omitted variables bias that they show to be large in the context of U.S. agriculture.

Short-run weather variation in panel fixed effects regressions

To address omitted variables bias concerns in Ricardian analyses, panel data methods were developed to isolate plausibly random variation in the weather by including time- and location-specific fixed effects (Deschênes and Greenstone, 2007; Schlenker and Roberts, 2009). This approach effectively eliminates the influence of omitted time-invariant characteristics and common time trends by using fixed effects (Ortiz-Bobea, 2020), but such regressions only capture agents' short-run responses to realized weather shocks at a particular point in time, thus accounting for ex post (second term in Equation (3)), but not ex ante (third term in Equation (3)) adaptation.[10] These estimates may overstate the total damage associated with climate change if omitted ex ante adaptations successfully reduce long-run damages (Deschênes and Greenstone, 2007), although long-run damages may be underestimated if ex post responses cannot be sustained indefinitely. For example, Blanc and Schlenker (2017) discuss how groundwater pumping might temporarily offset water deficits, but cannot be sustained in the long-term due to resource depletion. The tension between the benefit of low-frequency variation accounting for ex ante adaptation (as in the Ricardian approach) and the cost of less credible identification relative to the panel fixed effects method has been

[9] For example, access to irrigation shapes agricultural outcomes and correlates with the long-run climate, as has been shown in the U.S. (Schlenker et al., 2005), China (Wang et al., 2009), and Africa (Kurukulasuriya and Mendelsohn, 2008). To partially remedy this challenge, researchers can sometimes leverage longer time series to observe the same spatial unit under different long-run climate regimes in a "repeat-Ricardian" model (Buck et al., 2014; Bareille and Chakir, 2023a).

[10] In non-linear panel models with higher-order polynomials of weather variables, some ex ante adaptation is also implicitly incorporated, by accounting for mean weather (see McIntosh and Schlenker (2005); Lobell et al. (2011); Schlenker (2017); Mérel et al. (2024) for additional methodological details).

called the "frequency-identification trade-off" (Hsiang and Burke, 2014; Hsiang, 2016).

In some settings, short-run weather variation exploited in panel fixed effects regressions can generate climate damage estimates inclusive of both ex post and ex ante adaptation. As mentioned in Section 1, when agents are optimizing adaptation decisions in a static environment, both adaptation terms in Equation (3) drop out due to the Envelope Theorem and the impacts of short-run weather are identical to impacts of long-run climate change, inclusive of adaptation (Guo and Costello, 2013; Hsiang, 2016; Deryugina and Hsiang, 2017). For this conclusion to hold, however, the outcome of interest must be an optimized quantity (e.g., profits), adaptive actions $\boldsymbol{b}$ or $\boldsymbol{k}$ must be continuously differentiable with respect to the weather $\boldsymbol{c}$, markets and information must be perfect, and agents must rationally optimize without frictions. When adaptation technologies are discontinuous and the choice variables are discrete (e.g., long-lived infrastructure), outcomes of interest are not optimized quantities (e.g., health), and/or frictions impede optimal decision-making, reduced form panel fixed effects regression results no longer reflect long-run impacts of climate change inclusive of ex ante adaptation. Additionally, Mérel et al. (2024) show that restrictions are needed on the functional form of ex ante adaptation in order for standard implementations of the insights from Deryugina (2017) and Hsiang (2016) to appropriately capture adaptation. Thus, while some papers assume that the conditions necessary to invoke the Envelope Theorem hold, the vast majority of panel fixed effects climate regressions generate climate change impact estimates that do not account for ex ante adaptation.

While most reduced form econometric methods only implicitly account for adaptation, panel fixed effects estimates are used in some cases to *explicitly* identify ex post adaptation. This is done by using a specific adaptive margin as the outcome variable, thus estimating the extent to which a particular form of ex post adaptation responds to short-run weather shocks. These studies identify *adoption* and *use* of ex post adaptive behaviors and/or technologies (i.e., $\frac{\partial \boldsymbol{b}^*}{\partial \boldsymbol{c}}$), but generally do not identify the *effectiveness* of these ex post adaptive measures in mitigating climate damages (i.e., $\frac{\partial u}{\partial \boldsymbol{b}}\frac{\partial \boldsymbol{b}^*}{\partial \boldsymbol{c}}$). For example, Deschênes and Greenstone (2011) show that state-level energy demand responds to heat shocks, but do not link this adaptive behavior directly to its heat-related health benefits. Besides energy use, other ex post adaptation responses that have been investigated via weather dose-response functions include: human migration (e.g., Cai et al., 2016; Benveniste et al., 2020); time use (e.g., Graff Zivin and Neidell, 2014; Rode et al., 2022); changes in supply-chain relationships (e.g., Balboni et al., 2024; Pankratz and Schiller, 2024); firms' location choices (e.g., Indaco et al., 2021; Jia et al., 2022; Castro-Vincenzi, 2023); and use of agricultural inputs, such as pesticides and fertilizers (Jagnani et al., 2021), land adjustments (Aragón et al., 2021), irrigation investments (Taraz, 2017), and soil and water conservation practices (Tambet and Stopnitzky, 2021).

Heterogeneous short-run weather impacts based on long-run climate

A newer set of approaches aims to leverage plausibly random weather variation while also accounting for ex ante adaptation. Perhaps the most common method is to estimate heterogeneous treatment effects of within-location weather variation across different long-run baseline climates in each location. The intuition is that ex ante adaptive investments are made based on the expectations people form over their location's weather distribution (as reflected in the decision problem in Equation (2)). Therefore, differences in the marginal effects of a short-run weather shock across distinct climates are assumed to reflect differential adaptive investments made by individuals, firms, and local governments located in different equilibrium climates. Econometrically, this is often implemented as an interaction between a long-run climate variable, which proxies for expectations of local agents, and a short-run weather shock. One of the first applications of this methodology was in the study of temperature's influence over GDP growth (Dell et al., 2012), but the approach has also been applied to tropical cyclone damages (Hsiang and Narita, 2012) and the impact of heat on: agriculture (Butler and Huybers, 2013; Hultgren et al., 2022); mortality (Heutel et al., 2021; Carleton et al., 2022); energy consumption (Rode et al., 2021); and labor supply (Rode et al., 2022). This approach can also be implemented via a two-step estimation in which the first equation identifies the short-run relationship between weather and the outcome separately for a set of locations via many subsampled panel fixed effects regressions (capturing ex post adaptation). The second, cross-sectional, equation then estimates how the location-specific response to weather varies across space as a function of the long run climate (capturing ex ante adaptation). This two-step method is implemented in Auffhammer (2022) for temperature impacts on electricity consumption in California.

This method faces two challenges. First, the measures used as proxies for climate expectations are not exogenous and only vary cross-sectionally, making it difficult to determine whether the recovered coefficients reflect ex ante adaptation or are simply jointly co-determined by a third unobserved factor. Second, and related, ex ante adaptation is identified using heterogeneity in weather responses across space, under the implicit assumption that preferences and technology are constant across space, so that differences reflect only different choices of $\boldsymbol{b}^*$ or $\boldsymbol{k}^*$, as opposed to differences in utility functions or available technologies. This is an analogous problem to the Lucas critique (Lucas Jr, 1972). A partial solution is to exploit, when available, temporal variation in climatic trends by replacing the time-invariant climate variable with a rolling climatic average, which may mitigate omitted variables bias and ensure that preferences and/or technologies are more comparable between long-run climates (Mérel et al., 2024). Direct measurement of individual beliefs about the weather distribution – instead of the use of climate variable proxies for expectations – could also help mitigate both challenges, but these beliefs are also likely correlated with unobservables and are themselves seldom observable.

Partitioning long-run climate and short-run weather variation in a single equation

An alternative set of approaches to account for ex post and ex ante adaptation emerged in parallel to the heterogeneous weather effects methods described above. These "partitioning variation" methods combine variation in weather and climate in a jointly estimated equation to decompose meteorological conditions into a component associated with a long-run climate mean (the response to which is presumed to be inclusive of ex ante adaptation) and a component associated with deviations from it (the response to which is presumed to include only ex post adaptation) (Kelly et al., 2005; Kolstad and Moore, 2020).

This method takes multiple forms. Mérel and Gammans (2021) introduce a "climate penalty" to a panel fixed effects regression, which measures the distance between contemporaneous weather and a location's long-run average climate. Just as in the heterogeneous weather effects models described above, this allows for weather shocks closer to average conditions to differentially impact outcomes relative to shocks that are more unusual (and therefore less expected). Schlenker (2017) adopts a slightly more general approach in which the "climate penalty" reflects the distance between contemporaneous weather and a measure of expectations that is endogenously estimated and may differ from the long-run climate mean. Both Moore and Lobell (2014) and Bento et al. (2023) include 30-year moving averages of climate variables in a panel fixed effects regression alongside weather deviations from those averages to jointly estimate long- and short-run responses to changes in the climate.[11] The authors interpret differences between those responses as an empirical measurement of adaptation. However, this approach has identification challenges and, as implemented in Moore and Lobell (2014), is conceptually inconsistent, as the estimated long-run response does not represent the outer envelope of the short-run response (Mérel and Gammans, 2021). Moreover, it is unclear why the long-run climate would *directly* impact annual outcomes; in other approaches, the long-run climate shapes beliefs and expectations, which influence ex ante adaptive decisions that lower or raise responses to short-run weather shocks.

Long differences

A relatively recent method aimed at combining the benefits of both the panel fixed effects model and the Ricardian approach uses medium- to long-run climate trends as a source of identification. Using a sufficiently long time series of weather observations, the "long differences" approach estimates the relationship between a time trend in an outcome of interest (e.g., crop yields) and the corresponding trend in climate (e.g., temperature) over the same period, generally leveraging cross-sectional variation in these trends (Burke and Emerick, 2016; Dell et al., 2014).[12] Because the variation is medium- to long-run, ex ante adaptations that are undertaken in response to gradually changing climatology are accounted for.

Results from this approach are often compared against estimates from a short-run weather panel data model (inclusive of only ex post adaptation) to draw conclusions regarding the extent of ex ante adaptation taking place (see, e.g., Dell et al. (2012) for an application to

[11] There are multiple differences between estimation methods in these two papers, but a notable one is that Moore and Lobell (2014) do not include panel unit spatial fixed effects, implying both cross-sectional and temporal variation influence estimated parameters.

[12] In long enough time series, changes in the trend itself within a location can be exploited; this is called a "panel" of long differences (Waldinger, 2022).

economic growth and Burke and Emerick (2016) for an application in agriculture).[13] While generally used to implicitly characterize ex ante adaptation, this approach is also used to explicitly identify specific ex ante adaptive actions by placing adaptation choices on the lefthand side of the regression. Analogous to how panel fixed effects models can identify the adoption of ex post adaptive behaviors, these studies identify the adoption of ex ante adaptation (i.e., $\frac{d\boldsymbol{k}^*}{d\boldsymbol{C}}$), but generally cannot identify the *effectiveness* of such behaviors in lowering climate damages (i.e., $\frac{\partial u}{\partial \boldsymbol{k}}\frac{d\boldsymbol{k}^*}{d\boldsymbol{C}}$). For example, Cui (2020) and Cui and Zhong (2024) show that cropping patterns respond to long-run trends in temperature in the U.S. and China, respectively, suggesting (but not directly showing) that crop migration and switching may be an important margin of agricultural adaptation. Similarly, Liu et al. (2023) show that long-run increases in temperature restrict labor mobility across sectors in India — a result which contrasts sharply with documented increases in sectoral reallocation following short-run temperature shocks (Colmer, 2021).

This method has two key drawbacks. Most importantly, any unobservable that is correlated with trends in weather and also influences trends in the outcome will bias identification. That is, climatic trends must be spatially randomly assigned, conditional on regression controls. Second, results may be sensitive to how the "difference" is computed between the start and end of the period;[14] to avoid this, recent papers estimate trends using all observations over the sample period (e.g., Burke and Tanutama, 2019).

Quasi-random spatial variation in long-run climate

To mitigate the challenge of non-random variation in long-run climate trends (long differences) or levels (Ricardian approach), a set of recent methodologies has emerged to isolate plausibly random spatial variation in the long-run climate. First, the "spatial first differ-

[13] Hsiang (2016) recommends exploiting climatic variations at many different temporal frequencies and comparing estimated coefficients to those from long differences and from the cross-section. Lemoine (2023) shows that long difference estimates are also identified off of differences in the sequences of transient weather shocks which might also conflate differential rates of climate change. Whether divergent estimates from the long difference and panel estimates are driven by ex ante adaptation or other unobserved factors is a topic of ongoing debate.

[14] Long differences in climate and outcome variables are generally computed as $\frac{1}{n}\sum_{t\in a} x_t - \frac{1}{n}\sum_{t\in b} x_t$, where a and b are multi-period ranges spanning n time periods, with b representing the end of the sample and a the beginning (e.g., in the annual analysis in Burke and Emerick (2016), $n = 5$, a includes years 1978-1982 and b includes years 1998-2002). If there is substantial inter-period variability in climate and/or outcome variables, the choice of n, a, and/or b can influence estimates.

ences” (SFD) method regresses the difference in the long-run average of the outcome between two geographically-adjacent locations on the corresponding spatial difference in the long-run average climate (Druckenmiller and Hsiang, 2018). In essence, this approach substitutes the temporal difference in a classical “first difference” approach with its spatial analog. By limiting cross-sectional variation to spatially adjacent pairs of locations, SFD relies on less restrictive identifying assumptions than the pure cross-section, yet still accounts for ex ante adaptation if agents adapt to their local climatology. However, this approach can suffer from limited variation at higher spatial resolutions where its key identifying assumption becomes more plausible. Moreover, this approach may be subject to violations of the stable unit treatment value assumption (SUTVA) since flows of goods, people, and capital are often inversely related to distance, although models accounting for spatial lags may help allay such concerns (Druckenmiller and Hsiang, 2018). SFD has been applied in agricultural settings in the U.S. (Druckenmiller and Hsiang, 2018; McFadden et al., 2022) and to assess temperature’s influence over global economic activity (Linsenmeier, 2023).

Second, a few studies have generated climate impacts estimates inclusive of ex ante adaptation by exploiting quasi-random spatial variation in geologically determined access to groundwater (Blakeslee et al., 2020; Hornbeck, 2012; Hornbeck and Keskin, 2014), and spatial discontinuities in water supplies (Hagerty, 2022). This approach is generally well-identified, but is less generalizable – it relies on context-specific availability of plausibly random spatial variation in climatic conditions.

Accounting for weather forecasts

A causal interpretation of the panel fixed effects models described earlier requires the assumption that short-run weather variation is plausibly randomly assigned. However, in practice, individuals often access weather forecasts, which can facilitate ex ante adaptation to weather, undermining the assumption of unanticipated random shocks. A growing number of studies, which we further discuss in Section 2.2.2, show, across diverse settings, that short-run forecasts do influence behavior and thus induce short-run ex ante adaptation.[15] If individuals

[15] The role of forecasts has been documented in several sectors, including agriculture (Rosenzweig and Udry, 2013; Burlig et al., 2024; Du Puy and Shrader, 2024), health (Shrader et al., 2023), labor supply (Downey et al., 2023; Song, 2024), and financial markets (Schlenker and Taylor, 2021; Lemoine and Kapnick, 2024). Here, we discuss the studies that focus on quantifying climate damages, deferring a discussion of the

adjust their behavior in response to forecast information, climate damage estimates that do not account for forecasts represent biased estimates of direct climate effects ($\frac{\partial u}{\partial \boldsymbol{c}}$), as they include some ex ante adaptation effects ($\frac{\partial u}{\partial \boldsymbol{k}} \frac{d\boldsymbol{k}^*}{d\boldsymbol{C}}$) resulting from forecasted weather. The solution proposed in the literature is straightforward – simply add controls for forecast information into a standard panel fixed effects weather regression (Lemoine, 2023). For example, Shrader (2023) adds El Niño Southern Oscillation (ENSO) forecasts to a regression of commercial fishing output on the ENSO index, showing that ex ante adaptive actions taken in response to forecasts substantially reduce direct damages from ENSO. This approach allows researchers to isolate unexpected shocks in realized weather from forecasted weather events that may induce ex ante adaptation, providing valuable information on the nature and extent of adaption.

This approach relies on the assumption that individuals perfectly observe publicly available, and thus measurable, forecasts. Any wedge between individuals' expectations and forecasted meteorological conditions can introduce measurement error into the quantification of ex ante adaptation through forecast control variables. Moreover, while this approach is helpful for identifying climate damages inclusive of short- and medium-run ex ante adaptation, to date this method has not been used to assess ex ante adaptation to longer-run climate change projections.

Accounting for dynamics in adaptive investments

Most formalizations of adaptation used to inform climate econometric models rely on a static maximization problem in which agents choose adaptive actions in each period with no dynamic linkages (e.g., Hsiang, 2016; Deryugina and Hsiang, 2017; Carleton et al., 2022).[16] However, many ex post and ex ante decisions influence a capital or natural resource stock, implying that decision-making is inherently dynamic. For example, using groundwater for irrigation in response to a heat shock today lowers the stock of groundwater available for adaptation tomorrow. A small set of recent papers propose approaches to incorporate dynamic considerations into reduced form econometric estimation of climate damages and

rest of the literature on forecasts to Section 2.2.2.

[16]Note that Guo and Costello (2013) study adaptation within a dynamic optimization framework, but do not link their model to an estimable reduced form regression method.

adaptation, though these methodologies have not yet been widely applied.

First, Lemoine (2023) develops a dynamic optimization model in which ex post and ex ante adaptation influence a capital or resource stock, showing that short-run panel fixed effects models fail to reflect long-run climate impacts, inclusive of adaptation, when such dynamics are ignored. Lemoine (2023) proposes an indirect least squares (ILS) estimator which maintains the same identification strategy as the common panel fixed effects specifications, but can disentangle the direct effects of the weather ($\frac{\partial u}{\partial \boldsymbol{c}}$) from ex post and ex ante adaptation ($\frac{\partial u}{\partial \boldsymbol{b}}\frac{\partial \boldsymbol{b}^*}{\partial \boldsymbol{c}}$ and $\frac{\partial u}{\partial \boldsymbol{k}}\frac{d\boldsymbol{k}^*}{d\boldsymbol{C}}$) without needing to observe either the ex ante adaptation capital stocks or actions. However, without forecast data, this method only captures the dynamics of ex post adaptations, not ex ante.

Second, Rudik et al. (2024) focus on ex ante adaptation in a dynamic setting, reconciling measurements of adaptation from a dynamic spatial general equilibrium model (reviewed in Section 2.1.2) with a reduced form approach. The authors develop a novel dynamic Envelope Theorem method to measure welfare impacts accounting for specific ex ante adaptations (trade and labor reallocation) and apply their method to climate impacts on the U.S. economy.

Accounting for adaptation costs

All of the methods discussed above aim to recover the benefits of ex post and/or ex ante adaptation (i.e., the second two terms of Equation (3)). However, such benefits come at a cost. In some cases, this cost may manifest as a reduction in the average outcome level – for example, many heat-resilient crop varieties perform suboptimally under average climate conditions, creating a mean-variance trade-off (Schlenker et al., 2013). In other cases, this cost is simply pecuniary, as agents pay for investments or technologies that lower the damages from adverse weather. Generating climate change impact estimates that account only for the benefits, but not the costs, of adaptation will systematically underestimate total damages (Schlenker et al., 2013; Mérel et al., 2024; Carleton et al., 2022).[17] As discussed above, ex post adaptation is generally embedded implicitly within reduced form econometric estimates

[17] As previously discussed, only when the outcome variable of interest is an optimized quantity (e.g., profits, utility) and the change in the climate is marginal, can the Envelope Theorem be invoked to assume that the benefits of adaptation exactly equal its costs, and neither need to be explicitly measured.

of climate damages, such that neither benefits nor costs of such adaptations are explicitly identified in the literature. In contrast, a set of studies have developed revealed preference based methods to estimate costs of ex ante adaptations.

Schlenker et al. (2013) first quantified ex ante adaptation costs by showing that the lower sensitivity of U.S. maize yields to extreme temperatures observed in hotter locations (documented in Butler and Huybers (2013) and presumably reflecting ex ante adaptation) comes at the cost of lower average yields. The authors add these average yield "costs" of adaptation in to climate change impact estimates to show that total effects of climate change on yields rise substantially. Carleton et al. (2022) build on thus intuition and the theory from Guo and Costello (2013) to develop a revealed preference approach to infer adaptation costs associated with the mortality risk from climate change. Adaptation is assumed to be undertaken up to the point where marginal adaptation benefits, obtained from empirical estimates of how the long-run climate impacts mortality's sensitivity to temperature, equal marginal adaptation costs. Total costs of adapting to non-marginal climate change are then calculated by integrating marginal adaptation costs over time, and they include any level effects of the climate on mortality, as well as the value of pecuniary expenditures. The authors find that estimated costs of adaptation are a meaningful share of overall climate change damages and that they are incurred disproportionately by the world's wealthier populations.

These reduced form econometric approaches to assessing adaptation costs rely on strong assumptions regarding agent behavior and the nature of adaptation technologies. Most approaches do not take dynamics into account. Moreover, results from an enumerative approach – in which specific adaptation expenditures are measured and studied directly (e.g., Rode et al., 2021; Auffhammer, 2022; Du Puy and Shrader, 2024) – have yet to be directly compared with the adaptation cost estimates recovered from the revealed preference methods described here. These two approaches are complementary and much could be learned from combining insights from both methods.

Key findings A growing set of reduced form econometric analyses use the methods articulated above to quantify climate impacts either inclusive of ex post adaptation or of both ex post and ex ante adaptation. Ex post adaptation is implicitly accounted for in nearly all reduced form estimates of climate damages, but isolating its effect from direct climate impacts is generally impossible (i.e., separating the first two terms on the righthand side of Equation (3) is rarely feasible as observable short-run variations in outcomes always include ex post adaptations).[18] In contrast, the methods detailed above often enable researchers to isolate ex ante adaptation effects, shedding light on the extent and economic importance of such preemptive adaptation. Here, we summarize the key findings on ex ante adaptation from this literature; quantitative estimates are provided in Table 1.

Key finding # 1: Ex ante adaptation in U.S. agriculture is minimal, but in global agriculture is substantial

Much of the reduced form econometric literature has focused on U.S. maize yields, and Table 1 shows that these studies generally present minimal evidence of within-crop ex ante adaptation. That is, while crop switching and/or crop migration are likely important margins of ex ante adaptation (Cui, 2020), and total agricultural GDP in the U.S. exhibits large benefits from ex ante adaptation (Mérel et al., 2024), it appears that farmers can do to little to lower U.S. maize yield losses from heat (Schlenker and Roberts, 2009; Schlenker et al., 2013; Burke and Emerick, 2016; Druckenmiller and Hsiang, 2018).[19] In contrast, in settings with greater geographical scope, ex ante adaptations appear to substantially reduce crop-specific losses from climate change. For example, Hultgren et al. (2022) show that accounting for ex ante adaptation benefits reduces aggregate global yield losses from climate change by 47%.

Key finding #2: Ex ante adaptation in aggregate economic output is likely minimal

Comparisons of climate change impacts on aggregate GDP derived from methods that do (e.g., long differences) versus do not (e.g., panel fixed effects) implicitly account for ex

[18]There are two important exceptions to this claim. First, Lemoine (2023) uses a theoretically-derived indirect least squares estimator to document that ex post adaptations substantially lower climate damages to U.S. county incomes. Second, Bareille and Chakir (2023b) pair a panel fixed effects method with a structural model to show that ex post adaptive use of fertilizer and pesticide on French farms mitigate between one-quarter and two-thirds of the negative impacts of warming on yields.

[19]An exception to this finding is Butler and Huybers (2013), who use the response heterogeneity approach to uncover evidence of substantial ex ante adaptation within U.S. maize. To our knowledge, this finding has not been reconciled with evidence from other methods indicating that ex ante adaptation is minimal.

ante adaptation suggest that the benefits from adaptation are minimal. Dell et al. (2012) do not find heterogeneous responses of country-level annual GDP to temperature shocks across distinct baseline climates. They also show that long differences and panel fixed effects approaches recover similar estimates, and that responses to temperature do not become less severe over time in a long panel. Burke et al. (2015b) reach a similar conclusion, also studying country-level GDP responses to temperature and showing limited evidence of ex ante adaptation using variation over time and across space. Burke and Tanutama (2019) use subnational GDP data from 37 countries to show that short-run panel estimates of GDP-temperature relationship are *smaller* than those recovered with long differences, a result that is inconsistent with any substantial ex ante adaptation effects.

Two exceptions suggest that ex ante adaptation may be more substantial than these earlier studies suggest. Kalkuhl and Wenz (2020) use sub-national economic output data across 77 countries and find that projected climate change damages based on panel estimates are about twice as large as those based on cross-sectional ones, suggesting that ex ante adaptation may be considerable in magnitude. However, omitted variables bias in the cross section renders such a comparison difficult to interpret. Kahn et al. (2021) regress country-level economic growth on a measure of weather deviations from baseline climate to show that varying the time interval over which the baseline climate is computed changes output losses from climate change. This suggests ex ante adaptations taken in response to a shifting long-run climate are considerable. To our knowledge, these findings have not been reconciled with earlier work, leaving uncertainty regarding the extent to which ex ante adaptation has and will continue to mitigate aggregate economic losses from climate change.

Key finding #3: Ex ante adaptation is substantial in nearly all settings outside agriculture and aggregate economic output

Ex ante adaptation is found to have large impacts on climate damages in nearly all settings other than agriculture and aggregate economic output. This finding is consistent across various econometric methods. Results from papers leveraging the two-stage approach (Auffhammer, 2022), response heterogeneity method (Carleton et al., 2022; Heutel et al., 2021), or from those partitioning the variation in long run climate and weather deviations

(Bento et al., 2023) and leveraging forecasts (Shrader, 2023) conclude that accounting for adaptation substantially alters estimates of climate damages across a wide range of outcomes, including mortality, energy consumption, labor disutility, ozone concentrations, and fishery output. The magnitude of welfare benefits from ex ante adaptation in these settings is estimated to be large, ranging from 17% in a study of global labor disutility (Rode et al., 2022) to 44% in a study of the elevation of U.S. ozone concentrations in response to temperature (Bento et al., 2023). One important exception to this conclusion is the study of crime, conflict, and suicide. Burke et al. (2018) and Carleton (2017) show that short-run variation in temperature has similar impacts on suicide rates across different temporal and spatial subsamples in Mexico, the U.S., and India, while reviews of the large crime, conflict, and temperature literature similarly show limited evidence of ex ante adaptation (Burke et al., 2015a; Carleton et al., 2016).

Key finding #4: Ex ante adaptation costs are estimated to be large

While only a few studies aim to account for ex ante adaptation costs alongside ex ante adaptation benefits, their findings show that such costs dramatically change total climate damage estimates. Three studies in Table 1 provide such estimates — Schlenker et al. (2013); Carleton et al. (2022) and Hultgren et al. (2022) – and all conclude that while adaptation benefits are substantial, they come at a high cost. This implies that studies accounting only for ex ante adaptation benefits will underestimate the welfare effects of climate change and adds urgency to the need for improved methodologies for estimating ex ante adaptation costs.

Table 1. Ex ante adaptation in reduced form econometric climate impact studies

Reference	Estimating equation general form	Sector	Geographical scope	Spatial resolution	Impact of ex ante adaptation
Short-run weather variation in panel fixed effects regressions					
Schlenker and Roberts (2009)	$y_{it} = f(c_{it}; \beta) + \alpha_i + h(t) + \varepsilon_{it}$	Agriculture	U.S.	ADM-2	Accounting for ex ante adaptation has little to no effect on crop yield impacts of climate change
Dell et al. (2012)	$y_{it} = f(c_{it}; \beta) + \alpha_i + h(t) + \varepsilon_{it}$	Income per capita	World	ADM-0	Accounting for ex ante adaptation has no statistically distinguishable effect on aggregate output impacts of temperature
Burke et al. (2015b)	...	Income per capita	World	ADM-0	Accounting for ex ante adaptation has no statistically distinguishable effect on aggregate output impacts of temperature
Deryugina and Hsiang (2017)	...	Income per capita	U.S.	ADM-2	Accounting for ex ante adaptation (via nonlinearities within a temperature bin and urban-rural heterogeneity) reduces net present value of income losses from climate change by 51%
Burke and Tanutama (2019)	...	Income per capita	World	ADM-1/ ADM-2	Accounting for ex ante adaptation (via long differences) increases climate damages
Kalkuhl and Wenz (2020)	...	Income per capita	World	ADM-1/ ADM-2	Accounting for ex ante adaptation (via cross sectional regressions) reduces climate damages by 50%
Heterogeneous short-run weather impacts based on long-run climate					
Butler and Huybers (2013)	$y_{it} = f(c_{it}, \mathbf{C}_i; \beta_C) + \alpha_i + h(t) + \varepsilon_{it}$	Agriculture	U.S.	ADM-2	Accounting for ex ante adaptation reduces maize yield impacts by 57%
Schlenker et al. (2013)	...	Agriculture	U.S.	ADM-2	Accounting for ex ante adaptation reduces maize yield impacts by 8%
Heutel et al. (2021)	...	Health	U.S.	ZIP code	Accounting for ex ante adaptation reduces mortality impacts of climate change by 30%
Rode et al. (2021)	...	Energy consumption	World	ADM-2	Accounting for ex ante adaptation reduces energy expenditure impacts of a 1°C increase in global mean surface temperature in 2100 by 39%
Carleton et al. (2022)	...	Health	World	ADM-2	Accounting for ex ante adaptation benefits reduces mortality impacts of climate change by 30%; accounting also for ex ante adaptation costs (via a revealed preference approach) reduces impacts by 19% [1]
Hultgren et al. (2022)	...	Agriculture	World	ADM-2	Accounting for ex ante adaptation and economic development reduces crop yield impacts of climate change by 47%
Rode et al. (2022)	...	Labor disutility	World	ADM-2	Accounting for ex ante adaptation reduces labor disutility costs of climate change by 17%
Mérel et al. (2024)	$y_{it} = f(c_{it}; \beta_{C_{i,t}}) + \gamma z_i c_{it} + \alpha_i + h(t) + \varepsilon_{it}$	Agriculture	U.S.	ADM-2	Accounting for ex ante adaptation reduces agricultural GDP impacts of climate change by 9-28%
Auffhammer (2022)	(i) $y_{it} = f(c_{it}; \beta_i) + \alpha_i + h(t) + \varepsilon_{it}$ (ii) $\widehat{\beta}_i = f(C_i; \gamma) + \mathbf{X}'_i + \varepsilon_i$	Energy[2]	California (U.S.)	ZIP code	Accounting for ex ante adaptation increases electricity consumption impacts of climate change by 50%
Long differences					
Burke and Emerick (2016)	$y_{it} - y_{i,t-\tau} = f((c_i - c_{it-\tau}); \beta) + (\varepsilon_{it} - \varepsilon_{it-\tau})$	Agriculture	U.S.	ADM-2	Accounting for ex ante adaptation has no statistically distinguishable effect on the maize yield impacts of heat exposure
Partitioning long-run climate and short-run weather variation					
Moore and Lobell (2014, 2015)	$y_{it} = f((c_{it} - C_{ip}); \beta) + g(C_{ip}; \gamma) + \alpha_i + h(t) + \varepsilon_{it}$	Agriculture	Europe	ADM-2	Accounting for ex ante adaptation reduces yield impacts of climate change by 7% (wheat), 32% (barley), and 89% (maize)
Bento et al. (2023)	$y_{it} = f((c_{it} - C_{ip}); \beta) + g(C_{ip}; \gamma) + \alpha_i + h(r) + \varepsilon_{it}$	Ozone concentration	U.S.	Ozone monitors	Accounting for ex ante adaptation reduces the ozone impacts of climate change by 44%
Quasi-random spatial variation in long-run climate					
Druckenmiller and Hsiang (2018)	$y_{it} - y_{jt} = f((c_{it} - c_{jt}); \beta) + (\varepsilon_{it} - \varepsilon_{jt})$	Agriculture	U.S.	ADM-2	Accounting for long-run versus medium-run ex ante adaptation has no statistically distinguishable effect on the maize yield impacts of heat exposure
Accounting for weather forecasts					
Shrader (2023)	$y_{it} = f(c_t; \beta) + h(\widehat{c}_t; \gamma) + \alpha_i + h(p) + \varepsilon_{it}$	Fisheries	North Pacific Ocean	N/A[3]	Accounting for short-run ex ante adaptation reduces fisheries output impacts of El Niño Southern Oscillation by 31%

Notes: The "Estimating equation general form" column reports a stylized representation of the main empirical specification adopted in each paper, where three dots indicate the same specification as the preceding row. $f(\cdot)$ represents a general functional form of the weather and/or climate variables in the estimating equation, such as high-order polynomials or bins. c_{it} represents weather, C_i represents climate (long-run average weather), i indicates location, and t indicates time. τ is the time interval over which differences are taken in the "long differences" approach. p indicates a weakly larger level of temporal aggregation than t (used in the "partitioning variation" and "accounting for forecasts" approach), and r a one-level higher aggregation in time than p (used in the "partitioning variation"). The "Spatial First Difference" approach (Druckenmiller and Hsiang, 2018) takes the difference on both left- and right-hand side of the estimating equation with j,the unit immediately adjacent in space to i. "Accounting for forecasts" also includes $\hat{c}_t$, which indicates weather forecasts available at time t. Each equation estimates coefficients β and/or γ. α_i indicates unit fixed effects and $h(\cdot)$ indicates a general function of time (t, p or r), which can include spatially explicit time trends and/or time fixed effects. In the "Spatial resolution" column, ADM-0 indicates country, ADM-1 indicates the first administrative unit (e.g., a U.S. state), and ADM-2 indicates the second administrative unit (e.g., a U.S. county).

[1] We compare the global estimates of the benefits of climate adaptation in 2100 under RCP8.5 in deaths/100k to a counterfactual that accounts for benefits of income growth only (see Table II in Carleton et al. (2022)).

[2] Auffhammer (2022) uses an ex post adaptation margin, residential electricity consumption, as the outcome variable in estimating equation (i). Thus, accounting for ex ante adaptation (i.e., adoption of energy technologies like air conditioning) *increases* use of electricity as an ex post adaptation strategy under climate change.

[3] The unit of analysis in Shrader (2023) is vessel-month-year. The estimating equation accounts for vessel-, month-, and year- fixed effects, but the ENSO forecasts and realizations do not vary across space.

2.1.2 Adaptation in quantitative general equilibrium models

An expanding literature in trade, macroeconomics, and related fields assesses climate change damages using quantitative general equilibrium models that explicitly enumerate key ex post and ex ante adaptation margins. Such studies are generally focused on informing mitigation policy by estimating aggregate welfare damages from climate change, but their enumerative approach to adaptation also elucidates when and where specific margins of adaptation, or barriers to those margins, are critical to shaping welfare under climate change. To maintain tractability, these models generally focus either on adaptation over time (e.g., durable investments) or adaptation margins that link spatial units (e.g., international trade or migration). Here, we review the key findings from this literature, first summarizing insights from studies modeling adaptation over time, and second from those modeling adaptation over space. We highlight the papers that embed both features in dynamic spatial general equilibrium models. Table 2 summarizes key findings on adaptation from this literature. We note that a comprehensive review of the methods employed in these studies is beyond the scope of this chapter; we focus here on results.

Adaptation over time This strand of literature develops macroeconomic quantitative models that focus on intertemporal adaptation margins. These models do not account for spatial links across geographical units, but they often study different adaptation strategies within one paper, enabling cost-effectiveness comparisons across adaptive strategies (e.g., comparing ex post and ex ante margins, or comparing public to private adaptation options). This provides a rich analysis of adaptation trade-offs that to date has not been feasible in the reduced form approaches outlined above. Simulations are generally conducted using a calibrated model to draw these conclusions, allowing a wide range of counterfactual analyses, but coming at the cost of structural assumptions that cannot always be verified with appropriate data and empirical evidence. Only few studies, notably Bakkensen and Barrage (2018), bridge the reduced form-structural gap by combining both approaches to study tropical cyclones.

A first group of papers assesses the macroeconomic effects of natural disasters, often focusing on disaster-prone countries like small island nations, and using either a dynamic small open economy model or a dynamic stochastic general equilibrium (DSGE) model. Together, these papers point to large benefits from intertemporal ex ante adaptation. Marto et al. (2018) study the impact of cyclones in Vanuatu through a dynamic small open economy model, highlighting the trade-off between investing in ex ante resilient capital and spending on ex post international aid after a disaster takes place – they find that ex ante investments are 10% less costly. Cantelmo et al. (2023) reach a similar conclusion in a DSGE model, with ex ante public investment in resilient capital across disaster-prone developing countries being 30% more cost-effective than ex post international aid at reducing welfare losses. Corugedo et al. (2023) expand these approaches with a DSGE model which includes incomplete markets, financial frictions with collateral constraints (which limits borrowing for ex post reconstruction), and a full set of fiscal policy instruments and find modest long-run gains from ex ante adaptation. Bakkensen and Barrage (2018) combine a rich econometric analysis with a stochastic growth model calibrated for 40 vulnerable countries to quantify macroeconomic welfare impacts of cyclone risk accounting for adaptation via changes in savings and investment. In a global sample, Hong et al. (2023) introduce learning and adaptation into a continuous-time stochastic general equilibrium model with disaster risks, showing that adaptation changes as society learns about climate change and demonstrating that optimal adaptation involves a mix of private adaptation at the firm level and public spending. Finally, Fried (2022) uncovers adaptation benefits of 11% in a dynamic general equilibrium model in the context of severe storms in the U.S., where benefits are derived from both private ex ante adaptation capital investment and public ex post adaptation through U.S. federal disaster policy.

A second stream of papers focuses on adaptation through financial instruments. Early contributions develop stylized dynamic small open economy models with a representative agent. Borensztein et al. (2017), Mallucci (2022) and Phan and Schwartzman (2023) study adaptation to climate change in sovereign bond markets, where adaptation is represented as purchasing bonds with disaster clauses (called CAT bonds). These papers highlight the importance of financial frictions, as CAT bonds are highly effective at mitigating welfare effects of hurricanes, but are not readily available in all vulnerable nations. More recently, Bakkensen et al. (2023) integrate heterogeneous beliefs and learning as drivers of adaptation to sea level rise where agents make adaptation decisions regarding mortgage leverage and maturities in the collateralized debt market. More pessimistic buyers are more likely to leverage and use longer maturity mortgage contracts to finance the purchase of properties exposed to sea level rise risk.

An important feature that only few papers consider – but which we revisit in detail in Sections 2.2 and 3 – is the role of wealth and income heterogeneity in determining adaptive responses and resulting welfare effects of climate change. Van Der Straten (2023) studies the implications of sea level rise and floods on household wealth and welfare in the Netherlands accounting for adaptation through home ownership and investment in home protection (e.g., stilts). The author introduces credit constraints for low-income households and shows that climate change worsens wealth inequality when adaptation is less accessible for credit-constrained households. Fried (2024) highlights the importance of income inequality in determining U.S. climate damages induced by higher temperatures, as wealthier individuals can invest more heavily in energy and equipment for heating and cooling. She finds that aggregate welfare losses induced by climate change accounting for income heterogeneity are almost four times larger than in a representative agent simulation.

Adaptation over space Recent advances in spatial general equilibrium modeling have enabled investigations into margins of adaptation to climate change that reallocate economic activity across space, such as migration, trade, and knowledge spillovers. These models have progressively implemented more realistic and detailed embeddings of empirically-grounded spatial relationships, and some also include temporal dynamics. As with the models discussed in the previous subsection, the use of counterfactual simulations that restrict or constrain particular margins of adaptation enable insights into the welfare implications of adaptation that are generally infeasible in reduced form approaches. Of course, these models also require structural assumptions that may be difficult to evaluate, particularly at global scale. Here we review key findings from these analyses as they pertain to adaptation, summarizing results in Table 2. We refer the reader to Desmet and Rossi-Hansberg (2023) for a comprehensive review.

There are three major differences in scope between these analyses and the structural literature modelling adaptation only over time (see second two panels in Table 2). First, while the intertemporal adaptation literature has focused on natural disasters, most of the spatial studies rely on temperature as the major climate shock, with some notable exceptions that include sea level rise (Desmet et al., 2021; Burzyński et al., 2022), storms (Burzyński et al., 2022), and heat waves (Bilal and Rossi-Hansberg, 2023). Second, most of the studies have a global geographical scope, although the spatial unit of analysis varies from country (Nath, 2023; Costinot et al., 2016; Gouel and Laborde, 2021) to grid cell level (Conte et al., 2021; Desmet et al., 2021; Burzyński et al., 2022). Third, these papers introduce sectoral heterogeneity, although often only differentiating between agriculture and non-agriculture.

The first contributions in this literature focused on migration. For example, Desmet and Rossi-Hansberg (2015) introduce dynamic and spatial linkages into a general equilibrium model to quantify the adaptive role of migration, as well as trade and innovation, in a one-dimensional model that focuses on global warming across latitudes. To our knowledge, this was the first paper to document the welfare consequences of restricting the adaptive margins of migration and international trade under climate change. Importantly, the approach includes general equilibrium forces – wage adjustments and agglomeration economies – that render the direction of such restrictions on welfare under climate change ambiguous. On average, the authors find that enabling individuals to move away from the regions most impacted by climate change dominates general equilibrium feedbacks, and that welfare effects of unrestricted adaptive migration are net positive.

More recent work on migration shows conflicting estimates of the magnitude of adaptive gains from migration. While Desmet and Rossi-Hansberg (2015) find that imposing restrictions on migration raises the welfare costs of warming temperatures by 1.7% globally, Rudik et al. (2024) find smaller values for the U.S. Shayegh (2017) models the effect of climate change on fertility rates, income inequality, and human capital accumulation in developing countries with skill-heterogeneous migration as the ex ante adaptation margin. Output per capita increases by 3% when skilled and unskilled migration is allowed. When modeling a broader suite of climate shocks, Burzyński et al. (2022) uncover migration benefits of 6% globally, while Desmet et al. (2021) find very large (21%) global benefits of migration in the case of sea level rise. In the case of storms and heat waves, Bilal and Rossi-Hansberg

(2023) find a limited effect of ex ante anticipation and migration on aggregate U.S. losses from climate change, but a sizeable effect on welfare dispersion across counties, particularly for capital owners whose capital stock cannot move. In Africa, migration restrictions are found to increase welfare losses from climate change by 8% (Conte, 2023).

A second focus in this literature has been on agriculture. These models aim to assess how crop choice and international trade in agricultural products influence projected damages from climate change, as existing reduced form analyses ignored both margins of adaptation (Costinot et al., 2016; Gouel and Laborde, 2021). Estimated benefits from these adaptive margins differ across studies. While Costinot et al. (2016) find that shutting down crop switching raises the agricultural welfare losses from climate change by 300%, trade in agricultural goods is shown to be unimportant as an adaptive margin. In contrast, Gouel and Laborde (2021) find that free trade lowers agricultural damages from climate change by 27%, on par with the effects of crop switching.[20] In more recent work, Nath (2023) accounts for non-homothetic preferences and low substitutability between agricultural and non-agricultural production and recovers large adaptive benefits from trade in agriculture that reduce welfare losses from climate change by 22%. However, other recent work on agriculture recovers small (<1%) adaptive benefits from trade within Africa(Conte, 2023).

A third group of recent studies examines the welfare consequences of specific margins of adaptation that involve a spatial dimension at the firm level. These adaptation strategies include plant location choices (Castro-Vincenzi, 2023) and sourcing decisions from suppliers (Balboni et al., 2024; Castro-Vincenzi et al., 2024) in the case of floods globally, in India, and in Pakistan, respectively. These papers tend to find modest (1-6.5%) gains from adaptation, but these aggregate figures mask substantial heterogeneity recovered across regions.

Because these studies differ in many dimensions, including spatial extent, sectoral disaggregation, and approaches to empirical calibration, it is difficult to decompose the sources of such large differences in estimated adaptive benefits. As we discuss below in Section 4, such a decomposition would have enormous value for informing emerging adaptation policy discussions.

[20] We note that each set of authors define the adaptive gains from trade slightly differently; we refer the reader to Gouel and Laborde (2018) for a more detailed discussion of the differences between these two papers.

Table 2. Adaptation in quantitative general equilibrium models

Reference	Climate shock	Adaptive margin	Sectoral heterogeneity	Geographical scope	Spatial resolution	Impact of adaptation
Adaptation over time						
Marto et al. (2018)	Cyclones	Public infrastructure investment, public savings in contingency fund	One sector	Vanuatu	ADM-0	Ex ante adaptation reduces public infrastructure damages by 5%, private capital damages by 10%, productivity losses by 4%
Mallucci (2022)	Hurricanes	Disaster clauses	One sector	Seven Caribbean countries	ADM-0	Coupon suspension clauses reduces welfare losses from climate change by 15% Debt reduction clauses reduce welfare losses by 50%
Fried (2022)	Severe storms	Private investment, public disaster aid and adaptation subsidies	One sector	U.S.	ADM-2	Adaptation reduces the welfare cost of climate change by 11%
Cantelmo et al. (2023)	Natural disasters	Ex-ante infrastructure investments, ex-post disaster aid	One sector	average Emerging Market and Developing Economy	ADM-0	Ex ante adaptation reduces welfare loss by 20%
Corugedo et al. (2023)	Natural disasters	Public investment	One sector	Dominica	ADM-0	Ex ante adaptation reduces GDP losses from climate change by 6.5%
Phan and Schwartzman (2023)	Cyclones	Catastrophe bonds, disaster insurance	One sector	Mexico	ADM-0	Adaptation reduces welfare losses from climate change by 25%
Van Der Straten (2023)	Sea level rise / coastal flooding	Private investment	One sector	Netherlands	ADM-0	Adaptation reduces house price increases by 25%, demand for mortgage credit increases by 36%, cost of capital increase by 50%, consumption inequality by 50%
Adaptation over space						
Costinot et al. (2016)	Temperature	Trade, crop specialization	Agriculture, non-agriculture	50 countries, 10 crops	ADM-0	Crop switching restrictions increase welfare losses from climate change by 300% Full trade restrictions increase welfare losses from climate change by 4%
Gouel and Laborde (2021)	Temperature	Trade, crop specialization	Agriculture, non-agriculture	50 countries, 35 crops	ADM-0	Crop switching restrictions increase welfare losses from climate change by 37% Full trade restrictions increase welfare losses from climate change by 23%
Conte (2023)	Temperature	Trade, migration, crop specialization	Agriculture, non-agriculture	Africa	100x100km grid cell (1°)	Bilateral migration restrictions increase welfare losses from climate change by 8%. Removing trade tariffs reduces welfare losses by 0.18%. Allowing crop switching reduces welfare losses by 2.44%
Nath (2023)	Temperature	Trade, sectoral reallocation	Agriculture, manufacturing, services	17 countries	ADM-0	Fully removing trade frictions reduces welfare losses from climate change by 22%; reducing them to current global openness frontier reduces welfare losses by 13%
Castro-Vincenzi (2023)	Floods	Plant location and capacity	Automotive	World	Plant	Removing plant location and capacity decisions reduces firms' profits due to extreme precipitation by 5-6%
Balboni et al. (2023)	Floods	Suppliers' sourcing in production network	Manufacturing	Pakistan	Firm	Removing changes in sourcing behavior after 2012 floods increases damages in a 2015 flood scenario by 1%
Castro-Vincenzi et al. (2024)	Floods	Suppliers' sourcing in production network	Manufacturing	India	Firm	Allowing free trade increases average real wages with current climate risk by 6.5%
Adaptation over space and time						
Desmet and Rossi-Hansberg (2015)	Temperature	Trade, migration, innovation	Agriculture, manufacturing	World	Latitudes (hemisphere)	Migration restrictions increase welfare losses from climate change by 1.7% Migration restrictions and trade barriers of 20% increase welfare losses from climate change by 3%
Shayegh (2017)	Temperature	Skill-heterogeneous migration	Agriculture, manufacturing	Africa, West Europe	Continent	Allowing for skilled and unskilled migration, output per capita increases by 3%
Conte et al. (2021)	Temperature	Trade, migration, sectoral specialization	Agriculture, non-agriculture	World	100x100km grid cell (1°)	50% increase in trade costs raises welfare losses from climate change globally, but decreases them in Canada and Siberia
Desmet et al. (2021)	Sea level rise	Trade, migration, innovation	One sector	World	100x100km grid cell (1°)	25% increase in migration, trade, or innovation costs raises welfare losses from climate change by 21%, 21%, and 5%, respectively
Burzyński et al. (2022)	Temperature, sea level rise, extreme weather events	Skill-heterogeneous migration	Agriculture, non-agriculture	World	5x5 km grid cell	Migration restrictions reduce share of extremely poor inhabitants under climate change by 5%
Bilal and Rossi-Hansberg (2023)	Storms, heat waves	Migration, capital investment, forward-looking anticipation	One sector	U.S.	ADM-2	Restricting ex ante anticipation reduces welfare losses from climate change by 0.9% (for workers) to 2.6% (for capitalists). Restricting migration reduces welfare losses by 2.2% (for workers) to 6% (for capitalists)
Rudik et al. (2024)	Temperature	Trade, migration, sectoral labor reallocation	Agriculture, manufacturing, services	U.S.	ADM-1	Allowing trade reduces welfare losses from climate change by 16%. Allowing migration and industry switching reduce welfare losses by 0.1%. All margins jointly reduce welfare losses by 25%

Notes: The table includes all studies that develop a quantitative general equilibrium model for which it is possible to extract estimates of the economic value of adaptation to climate change. In the "Spatial resolution" column, ADM-0 indicates country, ADM-1 indicates the first administrative unit (e.g., a U.S. state), ADM-2 indicates the second administrative unit (e.g., a U.S. county). Rudik et al. (2024) allow for sectoral heterogeneity of climate damages across three sectors (agriculture, manufacturing, services), but they account for a granular set of 20 industries within these three sectors and allow for industry switching and worker unemployment in their calibration. Other studies (e.g., Bakkensen and Barrage, 2022; Cruz and Rossi-Hansberg, 2023; Cruz, 2021; Bakkensen et al., 2023; Hong et al., 2023) include adaptation within the model, as discussed in the main text, but do not directly quantify the impact of modeled adaptation margins, and are therefore omitted here.

2.1.3 Adaptation within Integrated Assessment Models and process-based models

A final set of approaches to estimate aggregate global climate damages includes designing an Integrated Assessment Model (IAM) in which climate, economic activity, and adaptation are endogenously determined, or developing a process-based model in which climate change and/or adaptation are exogenously prescribed. IAMs have been used extensively to inform mitigation policy (Greenstone et al., 2013), while other forms of process-based models are used to simulate various exogenous climate change and climate change adaptation scenarios. These models include treatments of ex post and ex ante adaptation that either implicitly embed adaptation (as in the reduced form literature) or enumerate individual elements of $\boldsymbol{b}$ and/or $\boldsymbol{k}$ (as in the quantitative general equilibrium literature). Here, we focus our attention on how these two sets of models have accounted for adaptation; we refer the reader to Diaz and Moore (2017) and to Chapter 1 of this Volume by Dietz (2024) for more comprehensive reviews of IAMs, and to Martinich and Crimmins (2019) for a review of process-based models studying climate change damages.

Adaptation in Integrated Assessment Models The first generation of IAMs, pioneered by the Dynamic Integrated Climate-Economy (DICE) model (Nordhaus, 1992, 1993), did not explicitly include adaptation. Instead, adaptation was accounted for implicitly via "damage functions" – calibrated relationships between aggregate monetized damages from climate change and the magnitude of global mean surface temperature change – that sometimes were estimated inclusive of adaptation and its costs (Manne et al., 1995; Tol, 2006; Sokolov et al., 2005). In this implicit treatment of adaptation, both the costs of adaptation and the cost of residual damages were accounted for, although the two components were rarely distinguished from one another.[21] To help separate these effects, De Bruin et al. (2009) develop the Adaptation in DICE model to include adaptation as an explicit decision variable calibrated from empirical estimates. This model quantifies adaptation benefits that range between 9% and 45% of gross damages.

[21] An important exception is the Policy Analysis of the Greenhouse Effect (PAGE) model, which introduces adaptive policies and their associated costs separately from the damage function (Hope et al., 1993).

Other IAM damage functions also implicitly account for adaptation by exogenously imposing a process of adjustment to a changing climate represented through transition costs and transition time (Tol, 1995). This approach heavily relies on modelling assumptions regarding the speed and costs of reducing climate damages through adaptation. In a recent example, Moore and Diaz (2015) model adaptation using an exponential decay curve in which the short-run impacts of temperature on GDP growth declines over time and the long-run effect is zero.

In a third approach, IAMs enumerate adaptation margins explicitly as an endogenous variable that can be set at a specific level or optimized. For example, the World Induced Technical Change Hybrid (WITCH) model endogenously accounts for adaptive effects of learning-by-doing and R&D investments (Bosetti et al., 2006). The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model considers adaptation to sea level rise in the form of coastal protection and/or displacement (Tol, 2007). Diaz (2016) calibrates the Coastal Impact and Adaptation Model (CIAM) to model the economic damages of sea level rise, finding that optimal protection and retreat reduce global damages by a factor of seven. Depsky et al. (2023) expand CIAM and calibrate adaptation to empirical levels (as opposed to optimal levels), finding adaptation impacts of 90-94%. Benveniste et al. (2020, 2022) extend FUND to include international migration and remittances as forms of adaptation, while Dietz and Lanz (2022) develop a new IAM to study adaptation through capital accumulation, demographic change, innovation, land-use change, and sectoral reallocation.

Computable General Equilibrium (CGE) models represent a related but complementary approach to IAMs for climate damage estimation. In contrast with IAMs, CGE models focus on the relations between different economic agents and are more sectorally disaggregated. Early examples study just one sector, such as health impacts (Bosello et al., 2006) or sea level rise (Bosello et al., 2007). These studies allow for ex post adaptation via adjustments to sectoral composition and trade patterns. Multi-regional CGE models link economic activities across sectors and regions through international trade and factor reallocation (Château et al., 2014; Dellink et al., 2019; Takakura et al., 2019). Some studies focus on adaptation in the energy sector, which propagates to the rest of the economy via price adjustments, including the Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model (Roson and van der Mensbrugghe, 2012), the Intertemporal Computable Equilibrium System (ICES) model (Eboli et al., 2010), the Global Responses to Anthropogenic Change in the Environment (GRACE) model (Aaheim et al., 2009, 2012), and the Intertemporal General Equilibrium Model (IGEM) (Jorgenson et al., 2004).

Finally, a set of IAMs has recently emerged with the objective of estimating the social cost of greenhouse gases (US Environmental Protection Agency, 2022). These are often called "SC-IAM"s and they have very heterogeneous treatments of adaptation. Rennert et al. (2022) build and calibrate the Greenhouse Gas Impact Value Estimator (GIVE) model to obtain a measure of the social cost of carbon that accounts for damages to agriculture, energy, mortality, and sea level rise. However, only sea level rise damages obtained from the CIAM account for adaptation. Dietz et al. (2021) develop a meta-analytic IAM (META), which introduces eight climate tipping points but does not explicitly model adaptation. The Data-driven Spatial Climate Impact Model (DSCIM) (Climate Impact Lab, 2023) builds a spatially granular SC-IAM using damage functions across five sectors estimated inclusive of both adaptation costs and benefits (Carleton et al., 2022; Rode et al., 2021; Depsky et al., 2023; Rode et al., 2022; Hultgren et al., 2022).

Exogenous adaptation in process-based models Process-based models combine a structural model with a set of exogenous climate and socioeconomic scenarios to estimate sector-specific climate damages accounting for adaptation costs and benefits. While adaptation is explicitly modeled in such analyses, adaptive adjustments are set exogenously as opposed to being determined endogenously based on optimizing behavior (as in quantitative GE models or some IAMs). Process-based models offer the advantage of accounting for high levels of complexity and nonlinear interactions (e.g., detailed hydrologic modeling) and of simulating the effects of many adaptation margins simultaneously. However, such models rely heavily on extensive parameterization, which often constrains the scope of the analysis; many papers are limited to studying specific sectors within the U.S.

Three sectors have been heavily studied using process-based models. First, public infrastructure, where ex ante infrastructural investments or ex post repairs serve as key margins of adaptation. Analyses specifically investigate: roads (Chinowsky et al., 2013); bridges

(Wright et al., 2012); railroads (Chinowsky et al., 2019); and urban drainage systems (Price et al., 2016). In a multi-climate risk multi-sector effort, Neumann et al. (2015) estimate impacts of temperature, precipitation, sea level rise, and coastal storms in the U.S., modeling and quantifying the benefits of multiple margins of adaptation, including abandonment, structure elevation, and a wide range of road, bridge, drainage, and property protection and repair investments. Similar multi-sector studies have focused on adaptation of roads, buildings, airports, railroads, and pipelines to changes in permafrost, precipitation, and precipitation-induced flooding in Alaska (Larsen et al., 2008; Melvin et al., 2017). Overall, these studies find substantial benefits from ex ante and ex post adaptation. In particular, ex ante adaptation is found to substantially reduce estimated climate damages, often with net benefits exceeding those from mitigating greenhouse gases directly, even when accounting for adaptation costs.

Second, process-based models have been used extensively to study the impacts of sea level rise and storm surge on coastal property, where ex ante adaptation margins include property elevation, armor, and abandonment. Examples include the U.S. National Coastal Property Model (Neumann et al., 2011, 2015; Lorie et al., 2020; Yohe et al., 1996) and the global Dynamic Interactive Vulnerability Assessment (DIVA) model (Hinkel and Klein, 2009; Hinkel et al., 2014), which has also been used to study floods in Indonesia and adaptation through spatial planning of new urban areas and flood protection enhancement (Muis et al., 2015).

Finally, agriculture and natural resources compose a third focus. Agronomic process-based models simulate climate damages accounting for adaptation margins including crop choice, production practices, land allocation, and international food trade (Beach et al., 2015; Mosnier et al., 2014). The impacts of climate change on water supply have been studied in municipal and industrial settings, in which adaptation is modeled as ex post reallocation across sectors (Henderson et al., 2015). Additionally, Wobus et al. (2017) assess the impact of changes in snowpack on recreation visits for skiing and snowboarding, where artificial snow-making is the simulated adaptation response.

2.2 The study of adaptation to inform adaptation policy

A completely distinct motivation for studying adaptation, and perhaps a more intuitive one, is to inform policies and programs that influence adaptation directly. To do so, a second body of literature focuses on directly recovering estimates of the second two adaptation terms on the righthand side of Equation (3). In some contexts, the goal may be only to identify interventions that lower damages due to climate change, regardless of the particular adaptation strategy undertaken by individuals, groups, firm, or governments – that is, to recover estimates of the lefthand side of expressions like Equation (4). In other settings, program evaluations are conducted explicitly to assess the demand for and efficacy of specific actions or technologies $\boldsymbol{b}$ or $\boldsymbol{k}$, to change the available information set to improve decisions, or to address market failures that are believed to constrain adaptation. In contrast to the literature reviewed in Section 2.1, this literature has focused less on the quantification of magnitudes and more on signing the impact of specific interventions. We discuss specific motivations behind adaptation policies, as well as their welfare justifications, below in Section 3. Regardless of the specific intervention setting or motivation, studying adaptation interventions directly requires isolating variation in the adaptation decision environment that will induce agents to reoptimize $\boldsymbol{b}^*$ and $\boldsymbol{k}^*$.

In this section, we first review the empirical methods used to isolate variation in adaptation in order to study specific adaptive actions and outcomes. We then review the literature studying adaptation interventions directly, categorizing studies by the source of variation in the adaptation decision environment that they employ or induce. We note that while this section focuses on empirical analysis, the structural general equilibrium studies, IAMs, and process-based models reviewed in Section 2.1 contribute substantially to our understanding of the efficacy of specific adaptation margins and interventions. Because these models sit between the climate damages literature and the adaptation interventions literature, we review them only in one place (above).

2.2.1 Methodology

Empirical approaches used to study adaptation directly exploit both quasi-experimental and experimental variation in the decision environment. Here, we overview these methods and highlight a set of key methodological challenges confronting papers in this literature.

Direct empirical estimation of ex post and ex ante adaptation As detailed above in Section 2.1, panel data fixed effects models are widely used to isolate plausibly random variation in the weather that can be leveraged to estimate climate damages. These models are then modified to implicitly account for ex ante adaptation (as previously discussed), but also to generate and study variation in adaptive investments directly. To achieve the latter, studies rely on variation in some factor we denote E which, as described in Section 1.3 above, restricts, enables, or otherwise shapes ex post or ex ante adaptation choices. E may represent a cash transfer (expanding the budget constraint y), a technology subsidy (changing prices of adaptation $\boldsymbol{p}$ or $\boldsymbol{r}$), a vocational training program, or myriad other interventions aimed at modifying adaptation choices and thus outcomes under climate change.

Studies directly investigating adaptive investments fall into one of two broad empirical classes. First, many studies regress a welfare-relevant outcome variable, such as agricultural revenues, household consumption, or health, on a measure of the weather, c, the factor E, and the interaction between these two:

$$u_{it} = \beta E_{it} + \gamma c_{it} + \delta E_{it} \times c_{it} + \alpha_i + \mu_t + \varepsilon_{it}, \tag{5}$$

where E is a source of variation unrelated to climate change and where fixed effects α_i and μ_t can be more elaborately defined if desired. In cases where E is randomized in an experiment, fixed effects may not be necessary and E varies across units i only. We note that Equation (5) is closely related to the "response heterogeneity" econometric approach detailed above in Section 2.1.1 and used to recover implicit estimates of ex ante adaptation. The key distinction between these methods is that E is an intervention exogenous to climate change that modifies adaptation choices, while the response heterogeneity approach interacts a measure of the weather c with a measure of the long-run climate C.[22] This distinction is critical, as E is generally a policy-relevant intervention that can be used to directly address adaptation needs; in contrast, C is determined by the global process of climate change and cannot be perturbed by policymakers seeking to improve adaptive responses to climate change.

The object of interest in Equation (5) is generally δ, which measures how the intervention or factor E influences the direct effect of weather c on a welfare-relevant outcome u. Using the notation from the framework in Section 1, while γ recovers the direct welfare impact of the intervention $\frac{du}{dE}$, δ recovers $\frac{\partial^2 u}{\partial E \partial \boldsymbol{c}}$, a measure of how the intervention changes welfare effects of a weather shock. Notably, these two objects are themselves insufficient for quantifying Equation (4), the effects of an intervention on the damages from long-run climate change – we discuss below how the literature can better bridge this gap. In Equation (5) and its many permutations, variation in E is intended to generate changes in ex post or ex ante adaptive behavior through changes in adaptation prices, income, information, market structure, and other frictions, although specific adaptive margins are not uncovered through estimation of this equation alone.

In panel data fixed effects models with wide spatial and temporal coverage, variation in E is often limited to cross-sectional comparisons only. This leaves many threats to identification of δ. For example, Carleton et al. (2022) estimate a model along the lines of Equation (5) in which E_i is defined as the long-run average income per capita of an administrative unit, the outcome variable u_{it} is the mortality rate, and $\boldsymbol{c}$ is a vector of nonlinear temperature exposure variables in an unbalanced panel from 1968 to 2010 for 11,881 sub-national units in 40 countries. In contrast, RCTs experimentally manipulate E, enabling causal identification of both β and δ, generally with much smaller sample sizes. For example, Macours et al. (2022) estimate a similar specification combining experimental variation in a social protection program in Nicaragua with weather variability to uncover benefits of cash and training in reducing weather damages to consumption and income. They leverage variation from the RCT implemented in 2005 and measure outcomes in two follow-up surveys in 2006 and

[22] In some studies, researchers combine approaches to include interactions with long-run climate C as well as other factors, such as irrigation (Hultgren et al., 2022) or income (Carleton et al., 2022).

2008.[23] Randomization in a sufficiently large sample creates balance on the characteristics of the treatment and control samples, including in their climate history and distribution of weather realizations before and after treatment.[24] This makes inference straightforward: δ in Equation (5) (and (6), below) identifies the causal effect of an adaptation intervention, conditional on a weather draw.

In Equation (5), β represents the marginal effect of the intervention or factor E under average climate conditions (as long as c is defined relative to mean conditions, which is common). Estimation of β and δ jointly therefore enables the researcher to uncover the extent to which aggregate impacts of an intervention manifest through mitigating losses under adverse weather. In contrast, in some panel data regression settings, E may be collinear with fixed effects and therefore its uninteracted effect (first term in Equation (5)) is omitted. This allows the researcher to investigate how the factor or intervention E shapes weather responses, but not its average treatment effect on u. The implications of this difference for adaptation policy are discussed below in Section 4.

While Equation (5) is useful for studying the impact of various interventions on climate damages, it sheds little light on the specific adaptive actions, behaviors, or investments that underlie the impacts (i.e., it says little about individual elements in the $\boldsymbol{b}$ and/or $\boldsymbol{k}$ vectors). That is, these studies recover either $\frac{du}{dE}$ or $\frac{\partial^2 u}{\partial E \partial \boldsymbol{c}}$, but not $\frac{\partial^2 \boldsymbol{b}}{\partial E \partial c}$ – the second term from Equation (4) that determines how an intervention alters a specific adaptive decision. To unpack which ex post or ex ante adaptation decisions are made in response to interventions, a second empirical class of regressions takes the following form:

$$b_{it} = \beta E_i + \gamma c_{it} + \delta E_i \times c_{it} + \mu_t + \varepsilon_{it}, \tag{6}$$

where all variables are defined as above and b_{it} represents one element of either the $\boldsymbol{b}$ or $\boldsymbol{k}$ vector (e.g., irrigation use, seed varietal choices, etc.). The objects of interest are β, γ, and,

[23] Their approach differs in that they do not use quasi-random weather variation in the reduced form estimation of Equation (5), but use block averages of self-reported shocks and instrument them with weather variation. Their RCT was implemented in 44 blocks across six municipalities.

[24] Papers reporting on randomized trials conventionally include statistics testing balance on key covariates between treatment and control. For adaptation papers, particular emphasis should be placed on balance on the full distribution of long term weather and short run weather shocks.

in particular, δ, which represents $\frac{\partial^2 b}{\partial E \partial c}$, the key component in Equation (4) used to assess how an intervention changes the welfare impacts of climate change.

This specification is estimated both in panel data settings as well as in randomized experiments and variation in E can be across time and space (in which case E would have both subscripts i and t) or be limited to cross-sectional variation only. For example, Cattaneo and Peri (2016) use international migration data to estimate a version of Equation (6) in which migration rate is the outcome variable and E is an indicator for the bottom quartile of the GDP per capita distribution, which reduces the migration propensity under hotter temperatures due to liquidity constraints.[25] In the social protection RCT mentioned previously, Macours et al. (2022) augment their estimation of Equation (5) with a version of Equation (6) estimated for multiple left-hand side variables, including non-agricultural wage work, migration and business creation. This allows the authors to uncover the mechanisms, i.e., the elements in $\boldsymbol{b}$ and $\boldsymbol{k}$, through which the intervention facilitates income and consumption smoothing in response to shocks.

In some cases, the adaptation technologies $\boldsymbol{b}$ and $\boldsymbol{k}$ studied in Equation (6) are purposely designed to reduce climate sensitivity under deteriorating weather conditions (as opposed to raising welfare generally). The question of interest is then how to induce take up or use of the technology or behavior. In such settings, researchers will omit the weather variable c from the regression entirely, estimating average treatment effects of E only. For example, Aker and Jack (2023) show that an agricultural training intervention in Niger dramatically increased adoption of a water-saving agricultural technique using a version of Equation (6) in which c is omitted. This is only useful for understanding adaptation to the extent that there is strong prior evidence that the technology of interest lowers the welfare cost of weather conditions that will become more frequent under climate change.

Much of the literature estimates versions of Equation (6) in which b represents an ex post adaptation strategy (e.g., energy use, irrigation practices, daily labor decisions), but interventions E may also alter ex ante adaptive decisions $\boldsymbol{k}$. For example, Lane (2024) estimates the effect of eligibility for guaranteed credit lines (E) in Bangladesh, focusing on

[25] Benonnier et al. (2022) go one step further and show that irrigation access offsets the temperature-migration liquidity constraint effect.

changes to ex ante agricultural investments as outcome variables, including fertilizer and pesticides investments, input costs, and non-agricultural investments. This is motivated by the fact that guaranteed credit, which provides loan access conditional on a flood, can facilitate adaptation by encouraging farmers to make more costly adaptation choices, which they might have been unwilling to adopt in the presence of weather risk.

For Equations (5) and (6), causally identifying the "adaptation effect" of policy interventions δ requires exogenous variation both in the adaptation environment E and in weather c. Below, we discuss two empirical challenges that this literature confronts while aiming to assess and inform adaptation interventions.

Empirical challenge #1: Sources of variation in weather The identification of weather variation in Equations (5) and (6) relies on the assumption that deviations from long run averages within a location are as good as randomly assigned. In these regressions, identification comes from either variation within location over time (time series variation) or across locations within time (cross sectional variation), or some combination of the two. When these equations are estimated in long panel data settings, weather variation is always time series, as discussed in detail above in Section 2.1. However, in studies that exploit the random or quasi-random roll-out of adaptation interventions, sufficient time series variation is not always available. Such studies, common in the literature that focuses on adaptation intervention, are forced to leverage different sources of variation in the weather, which come with important limitations.

Limited variation in weather

A key limitation that emerges with better identification of adaptation interventions E is that the range of variation in weather is often constrained. This is true because exogenous variation in access to adaptation typically comes from policy variation or a randomized trial, which typically limit the scale of implementation to a single country or sub-country region. In many cases, this implies highly correlated climate histories and climate shocks across locations in the sample, limiting the between-location variation in weather realizations c_{it} used to identify γ and δ. When outcome data come from primary data collection, as is the case for many randomized controlled trials, a single follow up survey is typical.[26] Even when researchers rely on administrative data sources or third party surveys, the number of outcome observations is often limited by infrequent data collection (e.g., decadal censuses) or limited time since the intervention. This constrains the within-location time variation in weather realizations c_{it} that can be used to identify γ and δ. In general, studies focusing on isolating random variation in E rarely investigate or report the resulting variation in c, but this variation is critical to credible identification of δ and to its interpretation. For example, a statistically significant δ may be the result of just a few outlier c shocks, or may be relevant only over a very limited range of c. We suggest possible solutions to this challenge in Section 4.

Variation in weather rarely linked to long-run climate change

The historical weather shocks studied in the adaptation interventions literature often do not reflect future weather under climate change, limiting their relevance for long-run climate change. While climate impacts studies reviewed in Section 2.1 combine econometric estimation with future projections of climate change to directly assess how weather responses from the historical record will change outcomes under future climate change, studies focused on adaptation rarely make this link explicitly. In other words, while $\frac{\partial u}{\partial \boldsymbol{b}} \frac{\partial \boldsymbol{b}^*}{\partial \boldsymbol{c}}$ (or its counterpart for ex ante adaptation $\boldsymbol{k}^*$) may be identified in Equation (3), $\frac{d\boldsymbol{c}}{d\boldsymbol{C}}$ is often ignored.

Climate models can be used to guide researchers toward studying the weather variation most relevant to a particular region in the future. However, in some cases the models lack the necessary spatial resolution for localized analyses, or they exhibit wide uncertainty bands or substantial disagreement across models (Lee et al., 2021).[27] In any case, such model forecasts are rarely used to inform the type of shock analyzed. Even more problematically, the relevant variation for climate change may not exist in the study observations. For example, in a region that is growing wetter (like many parts of Africa), the adverse weather shocks of the past

[26] McKenzie (2012) calls for repeated outcome data collection to reduce noise in stochastic measures like agricultural production or firm profits. The inverse argument can be made – with the same recommendation for repeated outcome measurement – when the interest is in characterizing an important component of the volatility in these outcomes.

[27] This is particularly true for precipitation, which is very widely used as the variable of interest c in the studies investigating adaptation directly.

may have come in the form of droughts, while the adverse shocks of the future might come in the form of floods. If floods are particularly infrequent in the past, then it is with low odds that one appears in the short window during which treatment effects are identified.

This disconnect between the weather shocks analyzed and the changes in weather shocks projected under climate change raises questions about the ability of studies in this literature to inform adaptation interventions that will be effective under long-run climate change. We return to this point and provide some recommendations in Section 4.

Functional forms of weather responses

The functional form used to model weather plays a crucial role in the identification and interpretation of analyses in the adaptation interventions literature, just as it does in the climate damages literature in Section 2.1. Specifically, the estimation of different weather functional forms corresponds to implicit underlying assumptions regarding beliefs and expectation formation. There is a stark contrast between the functional forms used in studies with large spatial and temporal extents versus those with more limited weather variation. When weather variation is minimal, for example due to primary data collection in an RCT, the most common approach is to compute weather shocks as anomalies above or below a certain threshold, often defined in standard deviations from a long-run mean. Using a time-invariant baseline assumes stationarity of the weather distribution. Different time intervals used to compute long-run means imply different assumptions on the belief formation process of the agents and the speed of adjustment to the climate distribution.

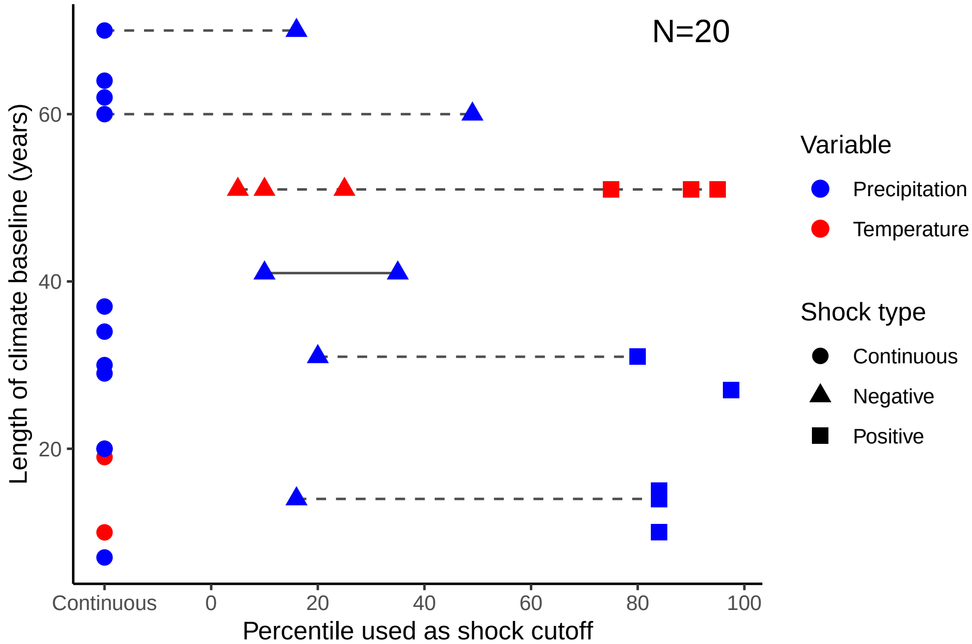
Such assumptions regarding belief formation and stationarity are rarely discussed, made explicit, or empirically justified in this literature, and they differ starkly across studies. To demonstrate this heterogeneity, Figure 1 plots the length of time used to define the long-run climate baseline (y-axis) against the threshold used to define a weather "shock" (x-axis) for all adaptation papers we reviewed that estimate effects of weather anomalies on outcomes of interest (N=20). The time frame over which the long-run mean is computed varies from a decade in Adhvaryu et al. (2024), who study conditional cash transfers in Mexico, to more than sixty years in (Rocha and Soares, 2015), who study water and sanitation infrastructure in Brazil. Notably, no paper we reviewed includes a robustness analysis in which multiple baseline periods are used to define the long-run mean.[28] Anomalies are constructed in terms of standard deviations or percentile deviations from the long-run mean and similarly vary substantially across papers. "Negative" shocks range from those falling the 5^{th} percentile of the long-run distribution to the 50^{th} percentile, while "positive" shocks range from the 75^{th} to the 97.5^{th} percentile. Only Premand and Stoeffler (2022) show robustness to altering the cut-offs used to compute anomalies. Instead of using discrete shock variables, some studies employ a continuous measure of weather deviations from baseline, such as the degrees of temperature difference from the long-run mean; such studies are indicated as "continuous" on the far left of the figure. The baseline period used to define the long-run mean differs substantially across these studies as well.[29]

The implications of highly heterogeneous weather functional form decisions are illustrated in Figure 2. Specifically, this figure uses monthly maximum temperature data obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) for Punjab, India to plot the total number of positive temperature heat shocks that would be observed in a given sample (y-axis) against the percentile of the long-run distribution used to determine the definition of a shock (x-axis). Each line shows a different possible study window, and each subplot indicates a different time period used to define the climate baseline. These plots show that both the baseline time period and the percentile cutoff chosen dramatically influence the number of shocks observed in a given sample. With shorter baseline periods, a study sample is less likely to contain an extreme shock, particularly if it happens to fall in cooler years. The discrete jumps shown in each panel indicate that the choice of the threshold can considerably influence whether a given location-month falls into "treatment" or "control" weather conditions. This one case study demonstrates the

[28] While these studies do not investigate adaptation explicitly, Moore et al. (2019) show that climate-related social media posting behavior reacts differently to temperature anomalies depending on how the baseline period is defined. Additionally, Kahn et al. (2021) alter the definition (20-, 30-, or 40-year moving averages) in a cross-country GDP-temperature regression to study adaptation implicitly.

[29] Note that the period used to define the long run mean around which anomalies are measured is generally far longer than the length of the panel used to estimate impacts. Of the 20 studies shown in Figure 1, all but three include time fixed effects, which further de-mean the dataset. This affects interpretation of the γ and δ terms in e.g., Equation (5), which – in the presence of time fixed effects – represent deviations from i's average anomaly over the panel period.

Figure 1. Weather functional form assumptions in studies of adaptation interventions

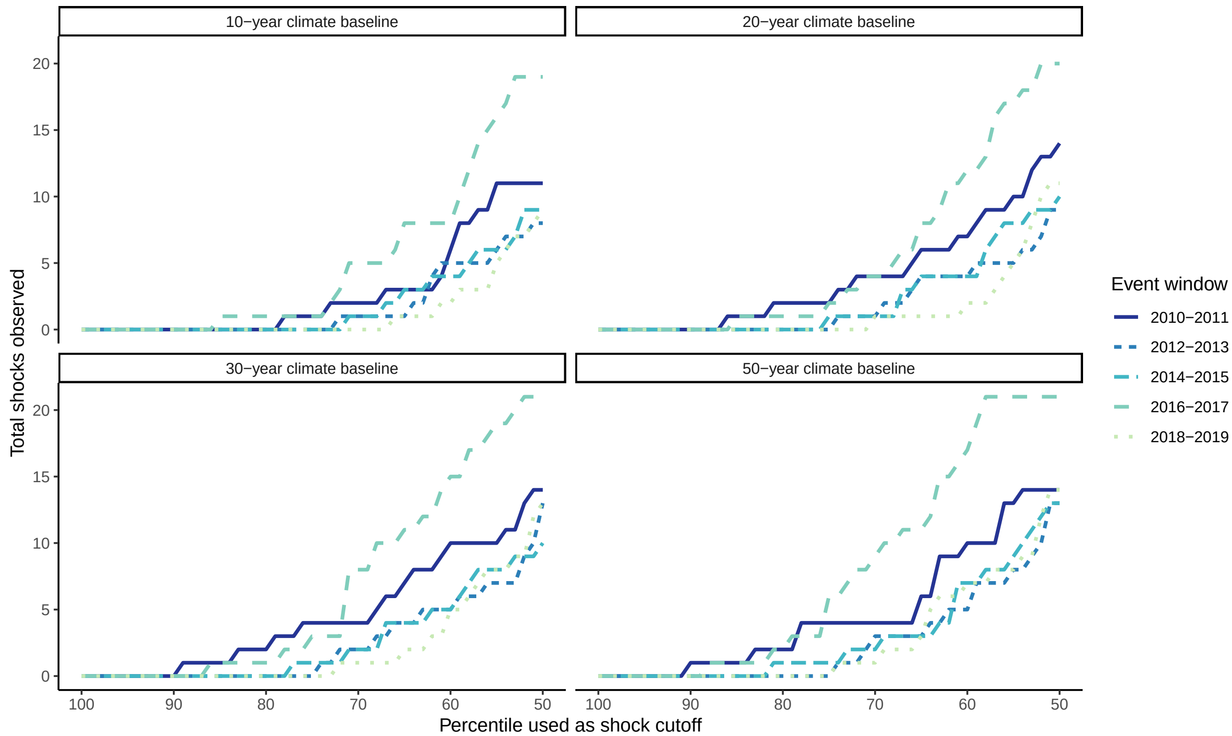


Notes: Each point represents one definition of a weather anomaly or shock used in the 20 studies that normalize weather variation with respect to a long-run climate norm (underlying data are reported in Appendix Table A1). Point color denotes the weather variable used (temperature or precipitation). Point shape denotes whether the anomaly captures positive shocks, negative shocks, or is continuous. Dashed lines connect multiple definitions used within the same study. A solid line is used for Premand and Stoeffler (2022), who show robustness across negative shock thresholds at every integer from the 10^{th} to the 35^{th} percentile. Positive and negative shock definitions measured in standard deviations have been assigned percentile values using properties of the normal distribution, such that a positive shock threshold at 1 standard deviation above the mean is assumed to fall at the 84^{th} percentile.

importance of conducting robustness when key functional form choices must be made without empirical justification.

Empirical challenge # 2: External validity Looking to the past to learn about the future presents a natural problem of external validity. This challenge exists in the climate damages literature discussed in Section 2.1, but can be even more pronounced in the literature that focuses explicitly on identifying changes in the adaptation decision environment. As noted earlier, none of the papers that we have identified project forward the adaptation benefits of studied interventions using identified interaction term(s) and climate model projections. While these projections are important for understanding the intervention's value

Figure 2. Sensitivity of weather variation to functional form assumptions



Notes: Each line plots the total number of anomalous months observed within a 2-year event window against the threshold used to define the anomaly relative to the historical temperature distribution (in units of percentiles). Percentiles on the x-axis are defined by calendar month and use a dynamic baseline climate period covering the 10, 20, 30, or 50 years preceding the start of a given event window (each subplot uses a different baseline climate time period). Temperature data are daily maximum temperatures obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) for the city of Kapurthala in Punjab, India, and are aggregated to the monthly level.

under future climate change, conducting such a counterfactual confronts several potential pitfalls that need to be overcome.

First, the weather shocks identified in historical data and used to assess adaptation interventions may not represent the types of shocks relevant under future climate change. Second, and related, the relevant adaptation margin may be sensitive to the distribution of shocks. For example, while health care access may reduce the effect of currently extreme temperatures on health (Cohen and Dechezleprêtre, 2022; Mullins and White, 2020; Nyqvist et al., 2023), whether such public services will similarly soften the impacts of the weather shocks that will become more common in the future is unclear. Repeated exposure to adverse conditions like heat and drought may result in a level of malnutrition or disease exposure that renders public health services far less effective than they are today. More extreme temperatures and longer heatwaves may undermine refrigeration for drug supply or the benefits of hospitalization, or conversely, infrastructure and facilities may innovate and adapt themselves to future climate change. In small-scale case studies, the trade-off between in-sample variation for identification and observing the relevant extremes to make informed projections is particularly stark (as illustrated in Figure 2). While never fully solved, the challenge of using historical weather shocks to inform future projections has been a focus of methodological innovation in the climate damages literature reviewed in Section 2.1 – we discuss approaches to apply these insights to the adaptation interventions literature in Section 4.

2.2.2 Literature evaluating adaptation interventions

Here we review the findings of the empirical analyses estimating versions of Equations (5) and (6). We categorize these studies into three groups based on the three key sources of variation in the decision environment that they use: *(i)* variation in the costs of adopting specific $\boldsymbol{b}$ or $\boldsymbol{k}$ actions, i.e., lowering prices $\boldsymbol{p}$ or $\boldsymbol{r}$ in Equations (1) and (2); *(ii)* variation in the level or volatility of the income constraint y_t and $\overline{y}$ in Equations (1) and (2); and *(iii)* variation in other determinants of adaptation decisions, such belief updating or forecast information. In all of these cases, variation in the decision environment induced by an intervention E causes variation in adaptation decisions, allowing researchers both to study the impacts of adaptation and the effect of interventions to relax constraints to adaptation. We discuss each in turn here.

Changes to adaptation technology access or its price $\boldsymbol{p}$, $\boldsymbol{r}$ A set of papers using the estimation strategies laid out in Equations (5) and (6) rely on spatial and/or temporal variation in access to or prices of specific adaptation behaviors or technologies to identify the extent and efficacy of adaptation. For example, using long panel datasets, multiple studies have shown that the temperature-agricultural yields relationship is moderated by access to irrigation (Butler and Huybers, 2013; Hultgren et al., 2022). Similarly, the temperature-mortality temperature is moderated by doctors per capita, share of the population with residential electricity, share with residential AC in the U.S. (Barreca et al., 2016), and by access to health care and quality of the service in Colombia (Helo Sarmiento, 2023). While these papers are informative of how access to particular technologies or resources moderate climate damages, they are prone to endogeneity in the E, the variation used to induce changes in $\boldsymbol{b}$ or $\boldsymbol{k}$, complicating interpretation and policy implications. For example, adoption of irrigation may be driven by unobserved heterogeneity in agricultural profitability, access to credit or farmer characteristics, which may also influence climate sensitivity for other reasons.

To mitigate such endogeneity concerns, a related set of papers uses a similar empirical framework but with *exogenous* variation in an intervention E that improves access to an adaptation technology. Applications in agriculture include randomized access to trial seed packets and training sessions on drought tolerant seeds (Boucher et al., 2021) and a flood-tolerant rice variety (Emerick et al., 2016), which were shown to provide protection against adverse weather events, mitigate long-term drops in farm productivity, and/or encourage ex ante adoption of improved farm practices. In health, exogenous variation in access to technologies that boost baseline health, such as the free provision of vitamin A supplementation, have been shown to reduce damages from negative climate shocks, like tornadoes (Gunnsteinsson et al., 2022). Other examples in health include: the introduction of a community health care worker program in India that moderates the temperature-infant mortality relationship (Banerjee and Maharaj, 2020); the deployment of community health care workers in an RCT in Uganda that reduces the risk of infant mortality following rainfall deficit seasons (Björkman Nyqvist et al., 2023); the roll-out of primary care services provided by Community Health Centers in the U.S. in the 1960s and 1970s that moderate the heat-mortality and cold-mortality relationship (Mullins and White, 2020); and policies randomly increasing access to health care for low-income households in Mexico in early 2000s also moderate the heat-mortality and cold-mortality relationship (Cohen and Dechezleprêtre, 2022). Using gun control policies in the U.S., Colmer and Doleac (2023) show that more prohibitive concealed-carry laws attenuate the temperature–homicide relationship.

As discussed above in Section 2.2.1, for some technologies that are explicitly designed for adaptation, particularly in already marginalized climates, the empirical strategy may not incorporate the weather variation explicitly, and thus focus on estimating versions of Equation

(5) and/or (6) without weather controls or interactions. Examples include studies on the adoption and efficacy of: a submergence-tolerant rice variety that reduces yield variability and delivers higher expected yield (Dar et al., 2013); salinity-tolerant seeds (Patel, 2023); and rainwater harvesting technologies (Aker and Jack, 2023). These papers randomly vary access to adaptation technologies and study the welfare consequences in an experimental setting. By heavily subsidizing the access to these technologies, these studies do not inform what the averted climate damages would be in a counterfactual world where technologies were accessible only at the market price, nor do they directly project adaptation benefits under climate change (as previously discussed).

Changes to income y or access to social insurance programs that reduce income variability Instead of lowering the cost of a specific adaptation technology, other papers relax the opportunity cost of adaptation through changes to the budget constraint. With higher incomes, agents solving Equations (1) and (2) re-optimize and make new adaptive decisions $\boldsymbol{b}^*$ or $\boldsymbol{k}^*$. Agents may similarly re-optimize when provided access to social programs, such as subsidized insurance or conditional cash transfers, which smooth y_t over time and/or states of the world.

Variation in income in randomized control trials

In some cases, variation in the budget constraint comes from a randomized controlled trial. For example, random assignment to treatment generates variation in income constraints through cash transfers in several studies, which mitigate the effect of rainfall anomalies on consumption and food security in Zambia (Asfaw et al., 2017); mitigate welfare effects of rainfall shocks in rural Niger through savings, asset accumulation, and income smoothing in agriculture and off-farm activities (Premand and Stoeffler, 2022); and provide protection against weather shocks in Nicaragua, by facilitating income smoothing and diversification of economic activities when bundled with productive investments or vocational training (Macours et al., 2022). Ultra-poor graduation programs, which provide a bundle of support including assets (usually livestock) and training, have a similar effect in moderating the negative impacts of droughts (Hirvonen et al., 2023). Specifically, in contrast to control households, treated households use enhanced household savings to mitigate the adverse effect of drought on diet, nutrition and intimate partner violence. Anticipatory cash transfers provided to households forecasted to experience extreme floods in Bangladesh reduce the likelihood of spending a day without eating during the flood and increase child and adult food consumption and wellbeing after the flood (Pople et al., 2021). In contrast, however, anticipatory cash transfers in Mongolia do not have any effect on assets, income, adaptive investments, or consumption (Mogge et al., 2024).

Quasi-random variation in income

Other papers have leveraged quasi-random variation in budget constraints, sometimes borrowing identification strategies from prior published papers. These include studies using the world's largest workfare program, the National Rural Employment Guarantee Scheme in India, to quantify how it modulates the effect of temperature on: test scores (Garg et al., 2020); the relationship between temperature and infant mortality (Banerjee and Maharaj, 2020); and the relationship between adverse monsoon rainfall and conflicts (Fetzer, 2020). Other papers have used at-scale cash transfer programs as a source of quasi-experimental variation in income, and find that the roll-out of the PROGRESA/*Oportunidades* conditional cash transfer program in Mexico only modestly decreased the sensitivity of intergroup killings by drug-trafficking organizations to temperature (Baysan et al., 2019), but significantly attenuated the effects of higher same-day temperature on homicides (Garg et al., 2020) and of children's exposure to adverse rainfall shocks on educational and labor market outcomes (Adhvaryu et al., 2024), while also also mitigating the impact of drought on households' caloric intake of vegetables, fruits, and animal products (Hou, 2010). Similarly, the roll-out of a large-scale cash transfer in Indonesia, the Program *Keluarga Harapan*, and a randomized experiment of the same program, have been found to reduce the impact of rainfall shocks on suicides (Christian et al., 2019). Knippenberg and Hoddinott (2019) use the Ethiopia's Productive Safety Net Program to document a substantial reduction in the impact of drought shocks on food security thanks to the program, which fully eliminates the adverse impact on food security within two years. Christian et al. (2019) combine exposure to a cyclone in the Bay of Bengal region of India with the staggered rollout of the

Odisha Rural Livelihoods Program, and find that program participation mitigated some of the reductions in household nonfood expenditure and women's consumption, but not on food expenditure, induced by the cyclone. Overall, the majority of studies using random or quasi-random variation in the budget constraint find that higher incomes lead to meaningful reductions in the damages caused by adverse weather.

Cross-sectional variation in income

In many panel data settings with large spatial and/or temporal scope, quasi-random variation in the budget constraint is not feasible. Thus, many studies simply use cross-sectional variation in income to identify δ, similar to the use of cross-sectional variation in the long-run climate used in many of the econometric methods implicitly identifying adaptation discussed in Section 2.1.1. In one of its first applications, Dell et al. (2012) find heterogeneous effects of temperature on GDP growth between poor and rich countries. Subsequent studies with a similar application find contrasting results: Burke et al. (2015b) and Kahn et al. (2021) cannot reject the hypothesis of no differential temperature effects on poor versus rich countries.[30] Carleton et al. (2022) find that GDP per capita moderates the effect of heat on mortality across 40 countries. Auffhammer (2022) finds that household income increases electricity use on hot days, Rode et al. (2021) document a similar pattern at the global scale, and Bakkensen and Mendelsohn (2016) find a large income elasticity of damages from cyclones in most of the world, with the exception of the U.S., where damages are high regardless of income. In a meta-analysis, Carleton et al. (2016) show that the conflict-climate relationship is moderated in studies conducted in wealthier regions of the globe. However, income may not always be beneficial for mitigating climate damages – Hultgren et al. (2022) shows that staple crop yields are *more* sensitive to heat in wealthier regions of the globe, possible due to seed varietal differences and/or access to subsidized insurance (Annan and Schlenker, 2015), a topic we return to in Section 3.

Identifying specific margins of adaptation

[30] One possible reason for this discrepancy in findings is functional form; Burke et al. (2015a) estimate a nonlinear relationship between growth and temperature and argue that poor countries are estimated to be more sensitive in Dell et al. (2012) only because they are on average hotter than wealthier nations.

Evaluation of these variations in financial resources through the estimation of Equation (5) informs the "reduced-form" effect of the policy and its potential climate sensitivity benefits. With additional measurement of the specific changes $\boldsymbol{b}$ and $\boldsymbol{k}$ induced by a relaxation of the budget constraint, these studies have the potential to offer additional policy-relevant insights by estimating Equation (6) (and thus enabling the calculation of the righthand side of Equation (4)). For example, measurement of the income elasticity and welfare benefits of specific adaptation strategies is informative of agents' preferences across different alternatives. Of course, if strategies are very heterogeneous or otherwise hard to measure, this can be difficult in practice. Additionally, to inform the cost effectiveness of adaptation policies that target a single b or k, studies need to both estimate the effect of an intervention on adaptation (e.g., $\frac{\partial^2 \boldsymbol{b}^*}{\partial E \partial \boldsymbol{c}}$), as well as how that adaptive decision changes a welfare relevant outcome (e.g., $\frac{\partial u}{\partial \boldsymbol{b}}$). For example, Premand and Stoeffler (2022) show that cash transfers in Niger strengthen poor households' ability to mitigate the welfare effects of drought shocks. To understand which adaptive margins are re-optimized after exogenous changes in the decision environment induced by the cash transfer program, they show that the intervention increases household capacity to smooth income when shocks occur, with an intensification of agricultural activities and operation of off-farm household activities. This suggests that interventions targeting these adjustment margins may provide adaptation benefits consistent with household preferences.

Insights from the consumption smoothing literature

This collection of studies has some parallels to a long literature in development economics that uses weather shocks as a source of variation to understand both formal and informal ex ante and ex post consumption smoothing strategies. A primary objective of this literature has been to test a null hypothesis of full insurance in the absence of functioning insurance markets, but some papers also analyze heterogeneity in the degree of smoothing. We note two insights from this literature that are particularly relevant for studying climate adaptation.

First, idiosyncratic shocks are more easily insured than are aggregate shocks (Townsend, 1994, 1995). That said, aggregate shocks may also be partially insured, though more often through private actions than through informal risk sharing strategies within villages or among kin (Morduch, 1995; Kazianga and Udry, 2006; Corno and Voena, 2023). For example, even in the absence of formal financial institutions, precautionary savings or buffer stocks can smooth the consumption response to "normal" income fluctuations (e.g., Paxson, 1992; Rosenzweig and Binswanger, 1993), though a changing climate may undermine the effectiveness of these strategies. Ex ante, in addition to precautionary savings, households diversify their income, migrate, marry into families with low-correlated shocks, enter into labor contracts that share risk between employers and employees, and a variety of other strategies. Ex post, they adjust labor supply and income sources, migrate, and receive remittances (Kochar, 1999; Yang and Choi, 2007; Jack and Suri, 2014). While these strategies do not always result in full smoothing – i.e., consumption still varies with weather realizations – they do speak to the potential for private actions and investments to make considerable progress toward reducing vulnerability to weather shocks.

Second, this literature has documented the importance of general equilibrium effects of weather shocks and of behavioral responses to those shocks. For example, Jayachandran (2006) shows that weather-induced productivity shocks lead to lower wages, which are further lowered by inelastic labor supply. This acts as a transfer to landowners from laborers, who tend to be poorer, reducing the income volatility of the former and increasing that of the latter. In settings with better-developed infrastructure to support adaptation – more banks and lower migration costs – the wage response to productivity shocks is dampened. Accounting for these general equilibrium and distributional consequences of adaptation can be difficult in smaller-scale partial equilibrium studies.

Changes to the broader adaptation decision environment A third way of studying adaptation choices and their impacts is through policies or other interventions designed to relax frictions in the broader adaptation decision environment. We group such constraints into the following categories: behavioral and informational, associated markets such as credit or insurance, and market structure. In Section 3, we return to the question of whether such frictions or constraints justify policy intervention in adaptation from a welfare or efficiency standpoint.

Information, beliefs and behavioral biases

As articulated in Equation (2), ex ante climate adaptation depends directly on beliefs about future weather realizations, which in turn depends on the information environment and on individuals' belief formation process. As discussed in Section 2.1.1, a growing number of papers show behavioral and market responses to weather forecasts. While these papers help implicitly identify ex ante adaptation when assessing climate change damages, as previously considered, they are also relevant to the study of adaptation interventions, as changes in forecast information provide a source of exogenous variation in the decision environment (Shrader et al., 2023; Molina and Rudik, 2023; Rosenzweig and Udry, 2014; Burlig et al., 2024; Du Puy and Shrader, 2024). Some rely on variation in forecast quality. For example, Shrader et al. (2023) use plausibly random variation in the difference between the forecasted and realized temperature to show that improving the accuracy of temperature forecasts reduces mortality in the U.S. Molina and Rudik (2023) find similar results with hurricanes: when forecasted windspeeds are closer to realized windspeeds, total spending (including protective spending and post-hurricane repairs) is lower. In agricultural settings, information about the upcoming growing season is important for ex ante decision-making. Rosenzweig and Udry (2013) find that farmers in India learn about forecast quality: in places where forecasts tend to be inaccurate, farmers respond to them less than in places where they tend to be accurate. In a similar setting, also in India, Burlig et al. (2024) combine variation in weather forecasts with careful measurement of farmer beliefs. In their field experiment, farmers are given information much further in advance than in the typical forecast study – recent innovations in monsoon forecasts allow for rainfall onset forecasts up to six weeks in advance. They find that changing the farmer's decision environment through more accurate information changes farmer investments and – consistent with a Bayesian updating model – the direction of change depends on farmer priors.

Forecasts have also been used as a source of variation in the financial sector, where markets and firm valuations respond to hurricane forecasts (Kruttli et al., 2023) and weather news (Letta et al., 2022), and future weather derivative prices respond both to short-term weather forecasts (Dorfleitner and Wimmer, 2010) and longer-term warming trends (Schlenker and Taylor, 2021), although sometimes risk information is not always fully reflected in valuations

(Hong et al., 2019). Lemoine and Kapnick (2024) shows that firms react to improvements in ENSO and hurricane seasonal forecast quality, which help them reduce - but not fully eliminate - exposure to the forecastable component of climate risk, but investors still hedge the forecast news with firms reducing their exposure but only at the cost of reducing their stock market value. Forecasts are likely to affect numerous other domains of economic activity, including recreation and labor markets. Downey et al. (2023) show that employment falls in response to forecasted rainfall and Song (2024) documents that labor supply adjusts to temperature forecasts.

A related literature studies the effect of changes in long-run climate risk information, focusing disproportionately on flood risk in the U.S., and has generally found that improving information lowers home values and decreases exposure in high-risk regions. Most papers exploit policies and events that work as flood risk signals, which change the decision environment through information and beliefs, such as new floodplain maps (Gibson and Mullins, 2020), individual events like Hurricane Sandy (Addoum et al., 2024; Gibson and Mullins, 2020), and the Home Seller Disclosure Requirement (Lee, 2023). Households learn about their risk through flood maps, experience with extreme events, and information campaigns and make investments in adaptation accordingly (Mulder, 2022). The market also responds, with flood risk and sea level rise at least partially capitalized into home values (Severen et al., 2018; Bernstein et al., 2019; Shr and Zipp, 2019; Hino and Burke, 2021), though others have shown concerning distributional consequences and persistent overvaluation of risky properties (Baldauf et al., 2020; Murfin and Spiegel, 2020; Weill, 2023; Gourevitch et al., 2023).

The effect of information on adaptation decisions depends on prior beliefs and the learning process. Studying the climate learning process poses significant challenges due to its inherent complexity and the fact that it is not directly observable. While individuals can observe weather events $\boldsymbol{c}$, they cannot directly observe the underlying probability distributions from which these weather events are drawn, i.e., the climate $\boldsymbol{C}$ (Moore, 2017). Early models assume a Bayesian updating model to describe how individuals learn about climate change, given observations of weather (Kelly et al., 2005). Since then, a number of studies have shown that Bayesian models of belief formation are inconsistent with the empirical evidence (Deryugina, 2013; Gallagher, 2014; Kala, 2017; Ji and Cobourn, 2021; Moore et al., 2019; Zappalà, 2023). A more recent line of research combines surveys of climate beliefs with adaptive actions and welfare measures to study how beliefs and information provision shape adaptation decision-making. For example, Barrage and Furst (2019) document that climate skepticism delays adaptation, and Bakkensen and Barrage (2022) show that flood risk misperceptions give rise to market inefficiency. In an agricultural context, Gine et al. (2015) show that farmers' subjective beliefs about the timing of the onset of the monsoon in India determine agricultural decisions. Zappalà (2024), Patel (2023) and Burlig et al. (2024) go one step further to show that correcting inaccurate beliefs or expectations can change investment decisions and agricultural returns.

Imperfections in associated markets

In many settings, insurance, credit, land, and labor markets may operate with frictions due to poor contract enforcement, limited liability, or asymmetric information (Bardhan and Udry, 1999). These affect adaptation decisions, and researchers use naturally occurring or induced variation in these markets as a source of variation in adaptation. For example, Burgess et al. (2017) exploit variation in the proximity to bank branches in India to show that bank access is correlated with a lower impact of heat on mortality in India, due plausibly to a combination of better saving and better borrowing opportunities. Rajan and Ramcharan (2023) show benefits of bank access for drought recovery in the 1950s U.S. Similarly, newer financial technologies may lower risk or otherwise facilitate adaptation. Examples include mobile money services, which decrease the variability of remittances and attenuate consumption losses induced by rainfall shocks in Tanzania (Riley, 2018) and Kenya (Jack and Suri, 2014) and satellite-based index insurance, which increases investment and mitigates both the immediate and longer term consequences of weather shocks (Boucher et al., 2021; Janzen and Carter, 2019; Stoeffler et al., 2022; Hill et al., 2019).[31] Existing financial products may also be tailored to reduce damages from weather risk, such as the contingent loans studied by Lane (2024) and Collier et al. (2024). Access to a line of credit conditional

[31] Even when insurance markets are not distorted, a large literature documents low levels of take up at actuarially fair prices that may be partly explained by time inconsistency or credit constraints (Cole et al., 2013; Casaburi and Willis, 2018).

on flooding affects both ex ante investment decisions and ex post consumption smoothing, which echoes other findings on risk-reducing technologies (Emerick et al., 2016). Variation in the functioning of land, labor or other input markets may also be a source of variation in adaptation outcomes, particularly where there are complementarities across markets as in the decision to adopt irrigation (Jones et al., 2022). We discuss the role for government intervention in these and other markets in Section 3.

Market structure

The very structure of markets – the degree of market integration and competition, fixed costs, and externalities – may also shape private adaptation decisions. A series of papers uses variation in aspects of market structure to understand adaptation, with findings that suggest ample room for improving private adaptation choices, most often through policy intervention.

Trade openness and infrastructure are important spatial determinants of adaptation, with insights coming largely from the spatial general equilibrium literature discussed above in Section 2.1.2. For example, trade barriers together with subsistence preferences have been shown to prevent low-income countries from reallocating sectoral activities that alleviate the productivity effects of rising temperatures (Nath, 2023). Infrastructure affects trade costs, and improvements to transportation infrastructure have been shown to attenuate the rainfall-famine relationship in India (Burgess and Donaldson, 2010) and reduce volatility in market prices and trade in Rwanda (Brooks and Donovan, 2020) and India (Allen and Atkin, 2022). Transportation infrastructure also determines the cost of ex ante and ex post adaptation. For example, in China, rapid expansion of both air and rail transportation has led to a decline in the share of the population exposed to extreme temperatures (Barwick et al., 2022). Balboni et al. (2024) provide evidence that firms in Pakistan update their beliefs about flood risk in response to flood events and permanently change their composition of upstream suppliers to less risky transportation routes and less risky locations. Infrastructure and policy may also influence the degree of competition in markets, which can shape private adaptation decisions in, for example, the agricultural sector in India (Kochhar and Song, 2023).

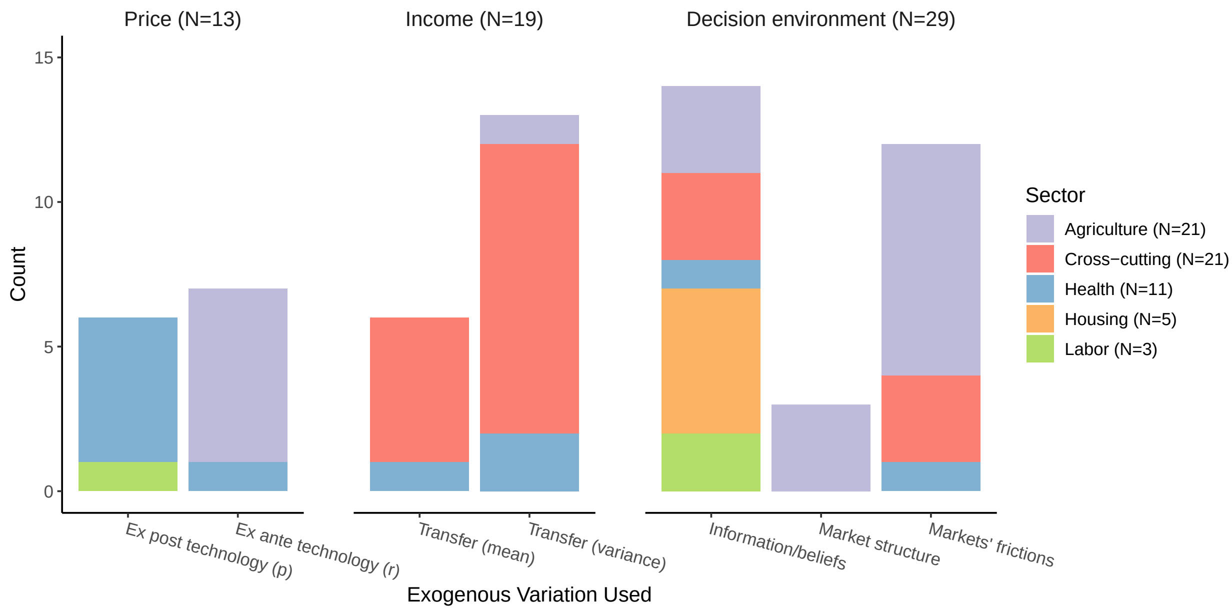
Fixed costs, economies of scale, public goods, and externalities are all important determinants of private adaptation decisions. In many cases, public intervention will be necessary to overcome coordination failures and incentive problems. For example, negative externalities from energy use or groundwater extraction will tend to lead to too much reliance on these adaptation technologies, from a social perspective (Auffhammer, 2022; Colelli et al., 2022; Abajian et al., 2023; Bruno et al., 2023). Policy-induced variation may offer insights into private adaptation incentives. For example, Baylis and Boomhower (2021) find that mandating wildfire-resilient building materials lowers home destruction during fire and potentially reduces wildfire spread – a positive externality. This finding is suggestive of some distortion but leaves open the question of whether regulation is efficient. We discuss this, other policy responses to market failures, and unintended consequences of government intervention in adaptation in Section 3.

2.2.3 Summary of studies quantifying impacts of specific adaptation interventions and/or constraints

Figure 3 summarizes the key characteristics of the adaptation interventions literature by plotting the distribution of studies across the three categories discussed above. That is, studies that exploit variation in: *(i)* the price of adaptation; *(ii)* the budget for adaptation; or *(iii)* frictions in the adaptation decision environment. Figure 3 additionally shows how studies are distributed across different outcome sectors, such as agriculture, health, and housing.

This figure shows that most studies have focused on relieving various frictions in the decision environment, particularly credit markets and information provision. Only a handful of studies have investigated how access to insurance or market power shapes adaptation outcomes. Agriculture has been the sector of focus for the majority of studies across all three sources of variation, while cross-cutting metrics such as income or consumption have been more dominant in studies manipulating budget constraints, credit access, and/or information. Interestingly, while ex post adaptation is generally more straightforward to study than ex ante adaptation, given the complexities of expectation formation and dynamics, price interventions are roughly evenly split between those lowering the costs of accessing ex post adaptation strategies versus those that make ex ante adaptation more affordable.

Figure 3. Summary of variation exploited and sectors studied in the adaptation interventions literature



Notes: Bar chart plots the count of studies (in total 55) that utilize exogenous variation in: the price of ex post or ex ante adaptation technologies (left panel); transfers designed to change the mean or the variance of income (middle panel); or frictions in the decision environment (right panel). In the middle panel, income interventions that benefit all households in a region (e.g., unconditional transfers or workfare programs made available to all) are classified as "transfer (mean)", while those that target only the most vulnerable households (e.g., the poorest or the most shock-exposed) are classified as "transfer (variance)". Color is assigned according to the primary sector represented by the outcome of interest in the study. "Cross-cutting" includes studies that examine changes in income, consumption, expenditures, and/or education. Six papers that consider multiple outcomes or include multiple sources of variation are included in all relevant categories and sectors. Specifically: Banerjee and Maharaj (2020) is included in the price and income categories; Boucher et al. (2021) is included in the price and decision environment categories; Burlig et al. (2024) is included in the information/beliefs and markets' frictions subcategories; Hirvonen et al. (2023) and Knippenberg and Hoddinott (2019) are each included in the transfer (mean) and transfer (variance) subcategories; Patel (2023) is included in the price and decision environment categories. All other studies appear only once. Underlying data are reported in Appendix Table A2.

3 The role of public policy in shaping adaptation outcomes

Under standard economic assumptions of perfect markets, in which individuals are fully informed and markets are efficient, there is little justification for policy interventions in adaptation to climate change. Under such conditions, individual agents will adapt endogenously to a gradually changing climate, choosing adaptive behaviors and investments that reflect their preferences and budget constraints. The role of the public sector is then to design climate change *mitigation* policies that properly weigh the costs of lowering emissions against the benefits of avoiding climate damages, inclusive of both the costs and benefits of endogenous adaptation.

As the literature reviewed in Section 2.2 makes clear, private adaptation decisions are shaped by budget constraints and prices, and are influenced by a number of associated markets and market frictions. This raises a critical set of questions regarding how, when, and for whom the public sector should intervene in order to guide adaptation outcomes at scales ranging from the individual to the community to the entire economy. Here, we first describe two approaches to adaptation policy choice: *(i)* a standard welfare evaluation that seeks to maximize social welfare incorporating all costs and benefits of a policy under climate change; and *(ii)* a narrow evaluation that considers only the effects of intervention on damages from weather and/or climate change. The second of these is motivated by emerging policy discussions. We then describe how in the first, theoretically-founded approach to policy choice, adaptation interventions can be justified on two grounds: market failures and equity-based social welfare functions. While the literature on adaptation policy and its theoretical foundations is limited, we highlight studies that have contributed to our understanding of each policy justification. Finally, we discuss inefficiencies and unintended consequences of public provision of climate adaptation.

3.1 Two approaches to adaptation policy evaluation

We consider two approaches to adaptation policy – one that corresponds to theoretically-justified welfare maximization, and another guided by pragmatic funding and policy prioritization.

In the first approach, adaptation to climate change fits into standard cost benefit analysis that aims to maximize welfare by accounting for the full costs and benefits of an intervention. This raises two measurement challenges. First, when a potential policy intervention explicitly designed for climate change adaptation is assessed, its ancillary costs and benefits on other aspects of the economy, including any externalities due to market failures, must be accounted for. For example, cooling centers use energy that produce global and local pollutants (Abajian et al., 2023; Deschenes, 2022), sea walls change property values with potential distributional implications (Hsiao, 2024), ex post disaster relief may crowd in other public spending (Deryugina, 2017), and adaptation infrastructure may damage the natural environment (Gittman et al., 2016; Rodríguez et al., 2017; Tognin et al., 2021). When planners aim to maximize welfare, cost benefit analysis of adaptation policies should account for these ancillary impacts, which extend beyond adaptation itself.

Second, many policies that do not explicitly target climate change adaptation may still have adaptation consequences that ought to be accounted for in policy cost benefit analyses. For example: land use regulations may encourage building in high climate risk areas (Ospital, 2023), raising future climate damages; expanding public health facilities may increase medical service provision following extreme heat events (Mullins and White, 2020), lowering morbidity and mortality effects of heat; and relaxing trade barriers may facilitate adaptive sectoral reallocation (Nath, 2023), mitigating economic damages from climate change. These adaptation-driven impacts may be positive or negative, but if they are ignored in the analysis of long-run policy costs and benefits, such evaluations will be inaccurate. Given uncertainty around future climate, climate adaptation inclusive assessments will result in a range of plausible costs and benefits for any given intervention. Importantly, accounting for the adaption consequences of long-run policies may highlight opportunities for policies themselves to adapt. For example, adjusting existing cash transfer programs to make payouts contingent on weather forecasts or realizations may increase the net benefits of the policy under climate change – by helping increase the resilience of vulnerable populations – without increasing costs.

In the second approach to adaptation policy, climate adaptation is a narrowly defined priority, in which interventions are evaluated based only on their net benefits for reducing the impacts of weather variability and/or long-run climate change. This approach has gained recent traction in policy and funding circles. For example, the Green Climate Fund, the largest climate financing organization dedicated to supporting developing countries, awards adaptation funding based a project's adaptation "impact potential", as opposed to a general cost benefit analysis that seeks to maximize overall welfare. Similarly, the Adaptation

Fund supported by the United Nations Framework Convention on Climate Change is a \$1.1 billion fund dedicated to adaptation projects in developing countries, where project evaluation is conducted based on a project's potential to reduce climate vulnerability and/or increase adaptive capacity. These and other adaptation financing regimes compare alternative projects based on their ability to cost-effectively flatten the climate damage curve. Measurement challenges aside – and they are myriad – this narrow frame for policy evaluation may prioritize projects with negative consequences in other domains or miss policies that provide large welfare gains but small adaptation benefits. At the same time, this narrow approach to policy evaluation need not focus exclusively on adaptation policies; inexpensive policies with large adaptation co-benefits (e.g., improving access to credit) may rank relatively well.

In spite of the potential pitfalls of this narrow approach to policy evaluation, it also presents some pragmatic advantages: a transparent way to compare policies based on their adaptation benefits can guide spending toward the most cost effective adaptation investments. This is closely analogous to wide-ranging efforts to compare the cost per ton of avoided carbon emissions when evaluating the cost-effectiveness of mitigation policy (Hahn et al., 2024; Gillingham and Stock, 2018) (note that it is also similar to how much sector-specific public spending is allocated, in domains such as education, health, and international aid). However, ranking the cost effectiveness of adaptation interventions analogously to mitigation interventions is complicated by the fact that adaptation is not a global public good, so the ranking is context dependent, and that the ideal outcome for comparison is utility or welfare, which is proxied in a diversity of ways so that direct comparison is difficult.[32]

This narrow evaluation of impacts also permeates the academic literature. For example, authors often focus on measuring how an intervention E mitigates the damages from a weather shock ($\frac{\partial^2 u}{\partial E \partial \boldsymbol{c}}$), but do not measure or report average treatment effects of the intervention (i.e., impacts of the intervention in a "typical" year or season, $\frac{du}{dE}$). And yet, such mean effects may be economically significant: for example, agricultural technologies often present a mean-variance trade-off, as varietals that have higher average yields are often

[32] An example of practical guidance on how to do this is offered by Adaptation & Resilience Investors Collaborative (2024).

more sensitive to input use or weather (Gatti et al., 2023). To the extent that adaptation interventions present a similar trade-off, measuring the mean effect is crucial to a holistic welfare accounting. In other cases, interventions more targeted to climate adaptation may receive more credit for their adaptation impacts than broader interventions in which the climate adaptation benefits are harder to isolate. For example, an information intervention that provides households with long range forecasts and changes housing stock decisions gets evaluated as generating large adaptation benefits, while a credit market intervention that has a similar impact on housing stock decisions (and on many other decisions) typically does not.

3.2 Justifications for policy intervention in adaptation

While there is substantial discussion surrounding the need for adaptation funding and policy (UNFCC, 2024), the conceptual justifications for policy intervention in private adaptation decisions are rarely clear. When adaptation interventions are being considered in isolation from other public policies, as they are in the growing number of adaptation financing organizations, no economic justification is provided; it is simply taken for granted that intervention is merited. However, when the decision of whether and how to intervene is faced by a welfare-maximizing social planner, adaptation policies require clear justification on welfare grounds.

Here we articulate two broad classes of justifications for policy intervention on climate adaptation. In the first, we include both policy action that alters the privately optimal amount of adaptation and that substitutes public for private adaptation. By focusing on market inefficiencies, we highlight policy interventions that are justified even under a utilitarian social welfare function. The second set of justifications lends itself to a broader range of policies by describing how alternative welfare functions that are often invoked implicitly in discussions of climate adaptation may also justify policy action.

3.2.1 Policy intervention can be justified when market imperfections distort private adaptation decisions

In the presence of market imperfections or missing markets, private provision of adaptation will be inefficient. Thus, policy can improve welfare by either addressing the market failure directly (e.g., regulating insurance markets to reduce "cream skimming") or by providing or subsidizing a particular adaptive behavior or technology (i.e., an element of $\boldsymbol{b}$ and/or $\boldsymbol{k}$) that is under-adopted due to the market failure.[33] Here we consider a number of market imperfections that potentially distort private adaptation decisions. Research on how these distortions shape adaptation decisions is reviewed above in Section 2.2; below, we focus on studies that uncover the efficacy of policy interventions aimed at mitigating adaptation-distorting market failures. Later, we describe the possible distortions introduced by public policy itself (either because the intervention was not justified by a particular market friction or because its implementation introduces additional market imperfections).

Information and beliefs Information is a public good, and is therefore often underprovided.[34] Individuals may also hold persistent incorrect beliefs in situations where learning is slow or otherwise difficult. Climate change is just such a situation, as discussed in Section 2.2. This suggests a role for the public sector, both in providing accurate climate projections to inform adaptation decision-making and – potentially – in supporting decision-making directly.

Short-run weather forecasts and long-run climate risk assessments are prime examples of the public provision of information to aid decision-making. As detailed in Section 2.2.2, a growing body of work empirically demonstrates the ex ante adaptive benefits of forecasts and climate risk information. However, these studies also highlight that the quality of such information is critical (Rosenzweig and Udry, 2013; Molina and Rudik, 2023; Shrader et al., 2023), suggesting a role for regulation of the quality of information. Moreover, information alone may be insufficient to generate welfare-improving adaptation decisions. As discussed

[33] Of course, over-adoption of adaptation behaviors or technologies is also possible; in this case, taxation or rationing may be justified. Based on the review of available literature, over-adoption appears far less common than under-adoption.

[34] We discuss other public goods separately below. Because of the prominent role of information in shaping adaptation decisions, we consider it separately here.

in Section 2.2, learning about climate is challenging, and responses to weather or risk information may be prone to behavioral biases (e.g., Deryugina, 2013; Gallagher, 2014). To date, little work has focused on the potential for other decision support – for example, to help people interpret and respond to climate information – to improve the adaptation benefits from the public provision of information.

Together, the papers in this literature highlight the value of public investment in the availability and accuracy of weather and climate information to facilitate private ex ante adaptation. However, translating these findings into policy prescriptions requires some caution. First, as noted above, forecasts update beliefs about weather, not climate, though work on responses to climate risk or longer-run climate model predictions also show some promise (e.g., Schlenker and Taylor, 2021). To the extent that weather becomes more volatile and less predictable with climate change, public investment in better weather or disaster forecasts may support climate adaptation; however, this may not be true if forecast quality deteriorates with climate change, i.e., forecasts become less accurate as $\frac{dc}{dC}$ becomes large. Second, simpler information – for example, a monsoon onset date – may be easier to forecast accurately, and to communicate to the public, than more complex multi-dimensional forecasts or predictions about multi-faceted risk. This is particularly important in making the leap from relatively short run forecasts that inform labor supply or planting decisions to long run forecasts of climate change that inform migration decisions or educational investments. Finally, information about upcoming weather may be insufficient for successful adaptation if people also lack information on how to best respond to the information – that is, they may also need information about the availability, costs and benefits of adaptation strategies.

Public goods and natural monopolies Where efficient adaptation requires coordination or investment in public goods, or imposes fixed costs, private markets will tend to result in coordination failures, free riding, and under-provision. These classic justifications for public intervention in markets apply to numerous types of climate risks. An obvious case is infrastructure investments: seawalls, elevated highways, and desalinization plants will not be constructed by individual agents. They require raising revenue to finance construction. In some cases, infrastructure is, itself, an adaptation investment, as in the case of seawalls or levees (Benetton et al., 2022; Bradt and Aldy, 2022; Kelly and Molina, 2023). In other cases, such as transportation infrastructure, it changes the decision environment and lowers the cost of adaptation, for example by facilitating migration (Barwick et al., 2022), improving supply chain resilience (Balboni et al., 2024), and reducing uncertainty in market access (Brooks and Donovan, 2020). Other types of publicly provided services, such as water, electricity, or health care, play an important role in household or firm level exposure and vulnerability to climate shocks (Rocha and Soares, 2015; Lin et al., 2021; Ponnusamy, 2022; Cohen and Dechezleprêtre, 2022; Mullins and White, 2020; Nyqvist et al., 2023). Yet, as the climate changes, demand for, supply of, and revenue from these services will change (Flores et al., 2024). As a result, changes to their regulation and/or to forward-looking investments may be necessary to avoid collapse (Abajian et al., 2024).

The costs and benefits of ex ante infrastructure investments for adaptation should be compared with ex post approaches to achieving similar adaptation outcomes (Davlasheridze et al., 2017; Hovekamp and Wagner, 2023), and to regulation-based alternatives such as restrictions on development (Ostriker and Russo, 2024). In spite of the importance of infrastructure for climate adaptation, less research focuses on its cost effectiveness or optimal investment under uncertainty, with the notable exception of the macroeconomic studies outlined in Section 2.1.2. Choices about how to locate transportation and other types of infrastructure require that policy makers consider evolving climate risks rather than the static or historically optimal placement (Balboni, 2023).

Innovation creates public goods, and is likely to play an important role in adaptation to climate change, as structural model simulations highlight (e.g., Desmet et al., 2021; Dietz and Lanz, 2022). However, innovation for adaptation, such as crop breeding research and development, will tend to be under-supplied in the absence of policy intervention (Zilberman et al., 2012). For example, new agricultural technologies have helped reduce agricultural losses in counties that cultivate crops with large national markets, but lag behind in settings where market signals and government support are weaker (Moscona and Sastry, 2023). At the same time, innovation may respond to catastrophic disasters rather than anticipate them (Miao and Popp, 2014; Hu et al., 2018; Auci et al., 2021; Moscona, 2021; Noy and Strobl, 2023). Innovations may also fail to diffuse without interventions to support their spread

(BenYishay and Mobarak, 2019). This suggests an important role for policy to support both the supply and diffusion of innovations for adaptation, particularly in contexts where markets provide insufficient incentives on their own.

Adaptation externalities Many adaptation decisions create externalities. When left unregulated, this leads to classic market failures that distort private adaptation markets: goods or services that generate negative externalities (such as air conditioning) will be over-adopted and those that generate positive externalities (such as wildfire fuel management) will be under-adopted. Policy intervention can correct these distortions, either through corrective pricing or regulation, and restore adaptation investments to the socially efficient level. We note that effective internalization of these externalities may, in the case of adaptation technologies with negative externalities, *decrease* adaptation in practice – optimal government intervention will weigh the forgone adaptation benefits against their social costs in determining optimal pricing. Of course, negative externalities can arise from public adaptation investments themselves – here we discuss the literature on private adaptation externalities, but return to the unintended consequences of public adaptation investments in Section 3.3.

The negative externalities imposed by adaptive use of energy and water are perhaps the most studied. Both inputs have been shown to mitigate the harms from a wide range of weather risks, including heat-related mortality (Deschênes and Greenstone, 2011), heat-driven reductions in student learning (Park et al., 2020), and drought and heat-induced crop loss (Hultgren et al., 2022). However, prices of both energy and water fall below their socially efficient levels in many settings, implying adaptive use of these inputs is likely too high. For example, adaptation through changes in final energy use affects greenhouse gas emissions and air pollution (Auffhammer and Aroonruengsawat, 2011; Abajian et al., 2023; Colelli et al., 2022; Deschenes, 2022); when prices are unregulated, these negative externalities impose unpriced external costs. The standard policy prescription applies: correct the market failure to ensure optimal use of each input. Where, for example, water markets function well, changing water use patterns will be reflected in market signals (Ayres et al., 2021; Rafey, 2023). Without such regulation, extraction and use are likely to be unsustainable, particularly as climate change raises demand (Ayres et al., 2021; Carleton et al., 2024).

The examples of energy and water use highlight that while some adaptation externalities are local (within a single aquifer, for example), others are larger scale (air conditioning emits globally harmful greenhouse gases), raising very distinct political economy challenges regarding efficient regulation of the market failure.

Energy and water use are not the only channels through which adaptation generates environmental externalities. Changes to agricultural production or other forms of land use may affect water quality, energy use, or biodiversity (Renard et al., 2023; Chakravorty et al., 2023). Transportation infrastructure may enable supply chains to adjust more fluidly to natural disasters (Balboni et al., 2024), but such investments have well-documented environmental externalities (Balboni et al., 2023). Other externalities likely exist but are yet unstudied – climate-induced migration may reshape disease transmission and changes to trade networks under climate change may influence the spread of invasive species. In such cases, correcting the market failure may be more challenging and complementary public policy may be needed.

Incomplete markets As discussed in Section 2.2, insurance, credit, land, and labor markets shape private adaptation choices. However, these markets may operate with frictions due to poor contract enforcement, limited liability, or asymmetric information (Bardhan and Udry, 1999). In some cases, intervening in these markets to improve their efficiency will be the best approach to improving adaptation decisions – while also improving welfare in other domains. In other cases, the underlying causes of market inefficiencies are intractable and the adaptation decision should be targeted directly. Which of these is preferred will depend both on the setting and the policy evaluation framework, as discussed above in Section 3.1.

Mitigating risk leads to clear private adaptation gains, as seen in studies of index insurance (Hill et al., 2019), conditional credit or cash transfers (Lane, 2024), and technology transfer (Dar et al., 2013). In most contexts, then, private incentives to invest in risk mitigation are undistorted, and private markets will supply risk-reducing financial instruments. However, in two important cases, public intervention in risk management is warranted. First, many climate related shocks come in the form of natural disasters that create highly correlated risk. In this case, domestic markets may not be able to insure against aggregate shocks without international reinsurance. Access to these international markets is often costly (perhaps justifiably so), driving up domestic insurance prices, and is sometimes prohibited by regulation (Boomhower et al., 2024). A common solution in these situations is public supply of disaster relief. However, this is imperfect, prone to public liquidity constraints and political distortions (Tarquinio, 2022; Del Valle et al., 2020); it also creates moral hazard (see Section 3.3). While not a solution to the latter concern, sovereign insurance products have begun to offer a solution to the former two (Del Valle et al., 2020), though their use remains limited and additional research on optimal design, efficiency, and impacts of these products is needed. Second, insurance markets are often incomplete, unreliable, or subject to high levels of basis risk. Behavioral biases or credit and liquidity constraints may also undermine take up. In these cases, individuals may not insure against weather shocks without public intervention, even when the social benefits from insurance clearly outweigh the (undistorted) cost of provision (Casaburi and Willis, 2018; Cole et al., 2013). Policy may directly intervene by fixing insurance pricing or subsidizing premiums, or it may provide shock-contingent relief such as weather indexed cash transfers.[35] We discuss the potential moral hazard concerns associated with public provision of insurance or post-disaster transfers in Section 3.3, but note that these may be outweighed in many contexts by the welfare benefits of buffering vulnerable populations from negative weather shocks.

Credit and other financial market frictions will also distort private adaptation decisions. In the case of ex ante adaptation investments with high fixed costs, the higher the interest rate or transaction cost of credit access, the lower adoption will be. Of course, high interest rates may simply reflect high costs to lenders. However, better contract enforcement, credit tracking, and risk screening can all bring down these costs, resulting in better credit availability. The innovations that facilitate these improvements in credit markets often require government intervention. Rather than repairing the entire credit market (or the courts), subsidizing some forms of credit that provide particularly large adaptation benefits may be justified. For example, Lane (2024) and Collier et al. (2024) find that emergency credit improves ex post coping with weather shocks and increases ex ante investment in Bangladesh

[35] A large literature evaluating cash transfer programs finds little evidence of wasteful spending (Banerjee et al., 2024).

and in the U.S., respectively. In both cases, the emergency credit line is offered as a public intervention, implying that high costs of administering loans, a lack of collateral, or some other friction prevents the private market from supplying emergency credit at a sufficient scale.[36] Of course, it is not enough to show that subsidies deliver benefits when markets are incomplete; clear articulation of the market failure and accounting of costs and benefits is important for justifying policy intervention. Land and labor market may operate imperfectly as well, particularly in developing country contexts, with implications for adaptation investment and justifying some forms of policy intervention, such as land titling.

3.2.2 Policy intervention can be justified on equity grounds

Private adaptation typically requires diverting resources away from other needs. Low-income households, with a high marginal value of consumption, will thus spend less on adaptation, all else equal, than will high income households. Depending on the market, this unequal investment in adaptation can have further impacts on the poor through pecuniary or fiscal externalities (Abajian et al., 2024; Hsiao, 2024). A growing body of empirical work shows that higher income households and/or populations are better insulated against a wide range of climate risks, including heat-related mortality (Burgess et al., 2017; Carleton et al., 2022), heat impacts on student learning (Park et al., 2021), heat effects on crime and conflict (Carleton et al., 2016), and heat impacts on the workforce (Behrer et al., 2021; Rode et al., 2022). Further exacerbating these inequities, the countries or regions that have the highest income or wealth today have contributed disproportionately to the stock of greenhouse gases that drive climate change (Callahan and Mankin, 2022).

These concerns about equity and moral responsibility underlie a second, welfare-based motivation for policy intervention *even in the absence of market failures*. Specifically, we consider two potential social welfare functions that justify policy action on climate adaptation: *(i)* distributional preferences or inequality aversion and *(ii)* moral responsibility or "polluter pays" preferences. The first is more familiar to economists, though the second has long stymied climate negotiations and serves to motivate much international adaptation spending, such as the Loss and Damage Fund. Either provides justification for policy inter-

[36] Lane (2024) calculates positive profits to the implementer from the intervention.

vention in a wider range of situations than those justified by market inefficiencies defined under neoclassical welfare assumptions (Section 3.2.1).

Equity weights To the extent that local, national, and/or international planners have a distaste for inequality, intervention on adaptation can be justified on the grounds of reducing inequality (Saez and Stantcheva, 2016). While the equity implications of mitigation have been well studied (e.g., Diffenbaugh and Burke (2019); Prest et al. (2024)), the equity implications of adaptation and equity-motivated adaptation policy have received far less attention.

Even in the absence of inefficient markets, public spending to support adaptation may reduce inequality if it lowers the cost of adaptation, flattening the income gradient in adoption, or if the benefits are disproportionately targeted to the poor. To the extent that adaptation is a normal good and marginal benefits of adaptation are decreasing, even untargeted policy support for adaptation will tend to disproportionately help the poor. Targeting might arise because benefits of take up are larger for lower income households, leading them to adopt more, or because of explicit or implicit policy design. For example, cooling centers might be more heavily utilized by low-income households if they have few available substitutes (e.g., in-home air conditioning), or if centers are strategically located in space.

While mounting evidence shows that relaxing budget constraints can flatten the damage curve for low-income households (see Section 2.2), one often voiced concern with scaling such insights is that economic growth itself is carbon intensive (Rozenberg et al., 2015). While the current carbon intensity of GDP does not support such an argument from a cost-effectiveness standpoint, it has also been argued that growth can increase inequality rather than lessen it (Aghion et al., 1999; Rubin and Segal, 2015). Thus, more targeted interventions, to increase the income of the poorest, may provide similar access to adaptation while being simultaneously fiscally feasible and less carbon intensive than economy-wide growth. For example, Chancel et al. (2023) calculate that bringing the entire global population living below \$ 5.50/day (nearly half of the global population) up to that level would increase global emissions by one-third of the amount that the top 10% of global emitters produce annually.

Of course, not all adaptation policy will reduce inequality. Infrastructure investments can create winners and losers, disaster relief or insurance payouts may miss households that do not fill in necessary paperwork, and public spending on adaptation may crowd out resources devoted to other forms of social protection. Private adaptation choices may also have distributional implications. For example, Hsiao (2024) studies how migration decisions in response to sea level rise in Jakarta affect land values. Wealthier households move, while poorer households stay behind; reduced demand lowers land prices, resulting in a decrease in low-income households' assets and thus imposing a pecuniary externality. For factors with inelastic supply, these pecuniary externalities are likely to be strongest, and while these price signals are not necessarily distorted, they do have distributional implications. Similarly, in the Cape Town water case discussed in Abajian et al. (2024), a revenue requirement by the municipal water utility meant that as richer households adopted groundwater as a substitute for surface water during drought, more of the fiscal burden of maintaining the water supply was shifted onto the middle and lower class.

Moral responsibility Policy motivated by economic efficiency considerations alone may fail to gain policy traction. Arguably, one of the main reasons that international climate agreements have repeatedly failed to get necessary global buy-in is a tension between high income countries that argue for an efficiency-based approach and low and middle income countries that demand attention to past and current contributions to atmospheric carbon concentrations. This tension is exacerbated by the inequities in damages and adaptation capacity discussed above. Thus, moral responsibility serves as an alternative justification for policy intervention in private adaptation decisions – that is, nations whose historical emissions have contributed the most to current and future climate change are argued to be obliged to expand budget constraints for adaptation in the world's poorest and most climate vulnerable nations (Okereke and Coventry, 2016).

Justifications for public spending on adaptation based on historical emissions contributions to climate damages have featured prominently in international discussions of a "Loss and Damage" fund. Burke et al. (2023) propose one approach to calculating contributions to damages that incorporate both past and future emissions and that aligns with the methodologies employed by social cost of carbon calculations. While transfers under such a fund need not be spent on adaptation per se, adaptation benefits of such transfers are generally an important part of the motivation (Okereke and Coventry, 2016). Transfers between countries will only address a portion of the inequality in both contributions and damages. Within-country inequality in emissions has overtaken between-country differences (Chancel et al., 2023), requiring transfers both domestically and internationally. One proposed approach would, for example, tax the world's richest corporations or individuals and transfer the revenue to the poorest using direct cash transfers.[37] As discussed in Section 2.2, there is growing evidence that cash transfers reduce sensitivity to weather shocks, implying potential adaptation benefits from such proposals.

3.3 Potential inefficiencies from public provision of climate adaptation

While there is substantial scope for public policy to correct market failures and address inequities in climate adaptation, much of the adaptation literature has focused on the potential pitfalls of public intervention in private adaptation markets. We highlight three important considerations: crowd out, moral hazard, and political economy. In forming optimal policy, these costs must be weighed against the many benefits of intervention: if the underlying distortion to socially optimal adaptation is large relative to any potential inefficiencies an intervention creates, then welfare will still be improved and careful policy design can minimize the inefficiencies. While many studies quantify the costs or the benefits of adaptation interventions, few (including Fried (2022)) holistically weigh the market-correcting benefits of intervention against its possible distortionary effects.

Even in the best case, where public and private adaptation investments are substitutes and neither is distorted relative to the first best, the cost of raising public funds to pay for adaptation may justify leaving adaptation up to private markets. If public spending crowds out private adaptation with a sufficiently high substitution elasticity, and the marginal cost of public funds is also high, then adaptation may be best left up to private markets. Of

[37] For example, the poorer half of the Chinese population only generates 17% of total carbon emissions in China while the top emitters are responsible for almost half of them (Chancel et al., 2023).

course, equity concerns or distortions in private markets will offset the marginal cost of public funds, meaning that the justification for policy intervention will depend on the specific case. Numerous instances of crowd out have been documented in the literature (Peltzman, 1975; Kousky et al., 2006; Boustan et al., 2012; Annan and Schlenker, 2015; Kousky et al., 2018; Baylis and Boomhower, 2021; Fried, 2022), but presence of such a distortion does not constitute a full welfare accounting.

One important channel that erodes the effectiveness of public adaptation spending is moral hazard. A number of papers have documented increases in costs or damages when the public sector takes on environmental risks. For example, in the U.S., federal fire protection increased development in high hazard areas (Baylis and Boomhower, 2023) and subsidized crop insurance and farm aid reduce reduce private investments in insurance and agricultural inputs, lowering crop revenue and increasing vulnerability to extreme temperatures (Annan and Schlenker, 2015; Deryugina and Kirwan, 2018). Similarly, the National Flood Insurance Program has been shown to increase the population living in high risk areas (Peralta and Scott, 2024) and to exhibit adverse selection (Wagner, 2022). Past reforms aimed at phasing out subsidies on flood insurance premiums in the National Flood Insurance Program increase the flood insurance price but decrease both property prices and insurance demand, showing potential trade-offs (Hennighausen et al., 2023). Coastal erosion mitigation programs increase building and eventual storm damages (Li et al., 2024). Similar moral hazard issues arise in disaster relief; if the government provides disaster aid after an adverse event, it will slow private investment in adaptation, such as inland migration (Hsiao, 2023; Kydland and Prescott, 1977).

Policy, of course, is subject to capture, and adaptation interventions are no exception. For example, Tarquinio (2022) and Schneider and Kunze (2023) show that drought relief in India is mistargeted, with allocations that are influenced by reelection concerns. Similarly, Mahadevan and Shenoy (2023) find that water scarcity creates an opening for political capture of voters. While policy has the potential to correct market distortions, it can also exacerbate them if, for example, they concentrate market power among preferred market actors, as shown in agricultural markets in India (Kochhar and Song, 2023). Policymakers may also distort information about climate change to justify preferred policies or favor certain groups (Weill, 2023), or may respond to shocks in ways that create jurisdictional externalities (Hsiao et al., 2024). The literature on the political economy of climate adaptation is still nascent, and represents an important area for research as investments in adaptation increase (Bobonis et al., 2022; Fitch-Fleischmann and Kresch, 2021; Cole et al., 2012).

Some unintended consequences of public adaptation may be positive. For example, the Great Plains Shelterbelt increased tree cover across the American Midwest following the Dust Bowl, and led to increased precipitation and decreased temperatures due to local evapotranspiration effects. This, in turn, increased agricultural activity in nearby areas (Grosset et al., 2023; Li, 2021). This suggests that private adoption of nature-based adaptation may be too low given that benefits accrue at a scale beyond that of the individual decision-maker (Das and Vincent, 2009; Edmondson et al., 2016; Menéndez et al., 2020). At the same time, evidence suggests that adaptation infrastructure can undermine these positive spillovers by, for example, damaging wetlands and estuaries (Gittman et al., 2016; Rodríguez et al., 2017; Tognin et al., 2021).

4 Priorities for future research on adaptation

As this chapter has demonstrated, the literature on adaptation to climate change is diverse and rapidly growing, though major holes remain. Here, we provide guidance for this emerging body of research in two areas. First, we make methodological recommendations that may help improve the quality and depth of current lines of questioning, whether the intent is better estimation of climate damages as reviewed in Section 2.1 or understanding the efficacy of adaptation interventions as reviewed in Section 2.2. Second, we lay out a set of priority areas for new research that we believe will help this literature better guide adaptation policy. To date, most adaptation research has focused on assessing whether and how adaptation is taking place. Prioritizing research on practical policy considerations will allow rapidly developing adaptation policy to draw more directly on research findings and evidence.

4.1 Methodological recommendations

Throughout Sections 2.1 and 2.2, we have noted methodological challenges facing the climate adaptation literature. Here, we provide recommendations aimed at helping surmount some of these challenges in future research. We discuss the two literatures together, both because many empirical challenges cut across them and because some areas for improvement lie at their intersection.

Improving econometric identification of ex ante adaptation at scale The largest contribution of the climate damages literature to our understanding of adaptation is its ability to assess, at scale, the extent of ex ante adaptation to long-run climate change without needing to enumerate individual adaptive margins (of which there are likely too many to identify). Yet, many of the econometric contributions in this area leverage cross-sectional or long-run variation in the climate, which is rarely exogenous to other determinants of adaptation. Identification of ex ante climate adaptation can be improved by following the few studies seeking to identify plausibly random spatial discontinuities in long-run climate (e.g., Hagerty (2022); Hornbeck and Keskin (2014); Blakeslee et al. (2020); Druckenmiller and Hsiang (2018)) or by evaluating natural experiments that introduce plausibly random shocks to long-run climate risk information, such as climate change reporting or the release of new scientific consensus reports. In the literature on adaptation interventions, exploiting these sources of variation can also better inform what specific ex ante adaptation strategies are used and their efficacy.

Theoretical and/or empirical justification for the functional form of climate and weather Many reduced form econometric studies make ad hoc choices about the functional form of long-run variation in the climate or of short-run weather shocks. As noted in Section 2, these modeling choices impose implicit assumptions on the expectations that underlie ex ante adaptation. For example, do populations update beliefs based on the long-run average daily temperature (e.g., Carleton et al., 2022) or long-run average cooling degree days (e.g., Rode et al., 2021)? Are expectations formed based on mean conditions or historical weather variability (e.g., Roth Tran, 2023)? How many years constitute the "long-run," and how should that historical record be weighted when constructing these variables? Similar questions arise around the functional form on shocks, particularly where data are too limited to allow fully non-parametric approaches. These critical modeling decisions should be informed by the growing body of evidence on expectation formation and belief updating (e.g., Zappalà, 2024; Patel, 2023; Kala, 2017), as well as considerations of relevant decision horizons affecting, e.g., capital stock turnover. When such evidence is lacking, discussion of how climate variation relates to assumptions about belief formation and decision horizons can aid interpretation, and exploration of the sensitivity of results to alternative characterizations of the long-run climate can inform robustness of the results to alternative assumptions.

Robustness tests when short-run weather variation is limited A related challenge is limited available variation in weather conditions. This affects long panel studies, but is particularly problematic in small-N studies where the variation in weather is constrained by the number of time periods or cross-sectional units. The proliferation of studies that interact existing interventions with weather variation and claim insights about climate adaptation are particularly prone to this problem. To combat this challenge, we first recommend that studies investigate and report the residual weather variation used to identify coefficients of interest. In particular, if the variation used for identification is far less than the variation relevant to long-run climate change, this should be communicated transparently. Beyond transparency, a set of robustness checks, many of which have been applied in the climate damages literature, can be conducted to assess reliability of results recovered with limited weather variation. These include: robustness to exclusion of weather outliers; placebo checks in which weather time series are randomly reshuffled; and placebo checks in which current outcomes are regressed on future weather shocks. When researchers have control over the roll out of an intervention – through, for example, an RCT – the variation in the intervention should aim to maximize variation in weather over space and/or time. For example, randomization can be stratified by climate zone or historical climate variation, across regions with documented differences in the distribution or nature of shocks (e.g., on either side of a rain shadow or at different elevations of a mountain range), or across periods forecasted to be on opposite ends of the El Niño Southern Oscillation cycle.

Studying adaptation to moderate weather conditions in addition to extremes In small-N studies with limited weather variation, researchers generally focus on empirically identifying the impacts of, and adaptation to, extreme weather shocks (e.g., annual rainfall less than two standard deviations below the long run mean; see Figure 1). This emphasis on extremes emerges because the (presumably) larger treatment effects of more extreme conditions are easier to statistically recover in small samples. However, moderate weather conditions are critical to understanding the welfare impacts of climate change and of adaptation interventions, since most weather will, by construction, be moderate. For example, 66% of global population-weighted daily average temperatures fall between the moderate temperatures of 12.5°C and 27.5°C; this share is projected to fall to 42% by end-of-century under high emissions climate change (Abajian et al., 2023). Thus, understanding how people and firms respond to these changes in moderate temperature exposure is critical to assessing adaptation today and under future climate change. This need is underscored by the many climate damage studies that have uncovered response functions in which even moderate temperatures or rainfall variations have economically meaningful impacts, for example on mortality (Carleton et al., 2022), energy consumption (Wenz et al., 2017), and crop yields (Schlenker and Roberts, 2009). As discussed above, when researchers control data collection, sampling design can be used to maximize variation in the weather so that such moderate effects can be statistically recovered even when sample sizes are small. In some cases, estimating average effects of an intervention without exploiting weather variation may also be informative (e.g., Aker and Jack, 2023), but closer attention to mechanisms and evidence of maladaptation in the absence of the intervention is necessary.

Improving relevance to future climate change Like other case studies, many papers documenting the adoption and/or efficacy of specific adaptation margins lack external validity. When applied to climate adaptation, relevance of empirical results to future time periods is particularly important (in particular, future years in which climate change has already unfolded). To improve such external validity, the definition of weather shocks investigated in historical data should be chosen based on forecasted weather under anthropogenic climate change. As discussed above, while this is relevant for large panel data settings, it is particularly challenging in small-N analyses, where the number of relevant weather realizations is limited, and in the study of rainfall, as projected rainfall patterns differ substantially across the globe (Lee et al., 2021). To make insights regarding resilience to short-run shocks relevant to potential adaptation benefits under long-run climate change, shocks that are projected to increase in frequency and/or intensity should be prioritized in observational data.

Relatedly, this literature would benefit from careful consideration of how responses to short-run shocks will change under long-run climate change due to ex ante adaptation. The climate damages literature reviewed in Section 2.1 has emphasized that ex ante adaptation decisions shaped by slow-moving climate change fundamentally change the effect of short run weather variation. The adaptation interventions literature, on the other hand, has largely ignored the fact that gradual climate change is likely to alter results based on current weather variation. Actionable steps to be taken in this regard include: quantitative assessment of how responses to short-run shocks differ across heterogeneous climates observed within a single sample (similar to Rosenzweig and Udry, 2020); comparison of results across studies with different climates; and investigation of whether results change when repeated shocks are experienced, relative to isolated events.

Leveraging long-run forecast information The adaptation literature increasingly leverages weather forecasts to estimate climate damages inclusive of ex ante adaptation decisions that are informed not only by past experience but also by forecast information (e.g., Shrader et al., 2023). While these studies are valuable in their ability to demonstrate the returns to ex ante adaptation over daily to seasonal time scales, the literature has placed relatively less emphasis on the impact of longer-run climate risk information on adaptation decision-making.[38] To the extent that key adaptation decisions require multi-year planning, such as home remodels, public infrastructure investments, and migration, projections of long-run climate change (and its associated uncertainty) are the relevant source of information to guide ex ante adaptive choices. Forecasts are also increasingly used to understand ex ante belief formation and its impact on specific adaptation strategies (e.g., Burlig et al., 2024).

[38]Long-run climate risk information has been studied most extensively in the context of flood risk in the U.S. (e.g., Gibson and Mullins, 2020; Addoum et al., 2024).

Methods developed for short-run forecasts should be adapted to deliver insights regarding the extent and nature of ex ante adaptation to long-run climate projections.

Integration of empirical evidence into integrated modeling The reduced form econometrics of adaptation has developed largely in isolation from the evolution of adaptation within quantitative general equilibrium models, IAMs, and process-based models. There is substantial scope for better integration of econometric results – either those that implicitly account for ex ante adaptation as reviewed in Section 2.1 or those that explicitly assess specific adaptation margins at scale as reviewed in Section 2.2 – into the parameterization of structural models of climate change damages.

4.2 Improving the literature's ability to inform adaptation policy

Although the literature reviewed in Section 2.2 is generally motivated by the need to inform adaptation interventions and policy, both it and the climate damages literature reviewed in Section 2.1 are not always well-suited to emerging adaptation policy needs. Here we list six lines of questioning that may help better align adaptation research with policy demand.

How to evaluate and adapt adaptation policy? The net benefits and cost effectiveness of existing policies will change under climate change. While standard cost benefit analysis accounts for future uncertainty about states of the world, the uncertainty posed by climate change is unusual insofar as it is highly correlated across sectors, i.e., it has a high "project beta" (Gollier, 2021). As a result, forward looking policy evaluation (in any sector) should account for climate risks and for the risk reduction associated with effective adaptation policy. Theoretical work on how to appropriately evaluate climate policy remains an active area of work (e.g., Millner and Heal, 2023); however, most work has emphasized mitigation policy over adaptation policy, though parallels are presumably considerable. Practical guidance on applications to adaptation policy will increase the likelihood that these insights influence policy.

As discussed in Section 3, policy must adapt to facilitate climate adaptation. However, evidence on the costs and benefits of relevant policy interventions remains very scarce. For example, anticipatory cash transfers receive a lot of policy attention as a tool to facilitate adaptation, yet numerous design alternatives and targeting approaches remain unstudied. The US Occupational Safety and Health Administration recently released guidelines on worker protections during heatwaves built from scant evidence on impacts such regulations may have on worker health and productivity or on costs to employers. Information about cooling centers are a ubiquitous part of emergency messaging during heatwaves, but evidence on take up, targeting, and effectiveness is missing. Without evidence on these and other increasingly common adaptation policies, policy makers are left to improvise, potentially at a high public cost.

What is the scope for adaptation benefits in a given sector and/or region? By quantifying climate change damages both with and without ex ante adaptation, the climate damages literature reviewed in Section 2.1 can indicate the potential for adaptation to lower the damages from climate change. Because these studies generally leverage large-scale datasets cutting across many regions, time periods, and even sectors of the economy, their findings can be used to prioritize where and for whom possible adaptation interventions may be most valuable. This is particularly true when policy is being guided by the more narrow framing discussed in Section 3.1, in which policy choice is informed only by avoided climate damages, as opposed to other dimensions of welfare.

However, because this literature has been focused on climate damages and not directly on isolating adaptation, econometric and/or structural estimates of climate damages can be better leveraged to elucidate potential adaptation returns. Specifically, while Tables 1 and 2 list some studies that quantify returns to adaptation directly, many more studies do not report such results. Using existing methodologies, whether they are reduced form or structural, researchers can report differences in welfare-relevant impacts of climate change when ex ante adaptations are included versus when they are are shut down. While this exercise is generally not feasible for ex post adaptations, as they are difficult to empirically isolate from direct climate damages (see Section 2.1 for details), providing such information for ex ante adaptation will help prioritize both research agendas and policy discussions regarding where and for whom specific interventions may have highest impact.

How constrained is ex ante adaptation? While large-N studies of climate damages can help assess the scope for adaptation, such analyses rely heavily on unrealistic assumptions regarding perfect markets and information. As the literature discussed in Sections 2.2 and 3.2.1 makes clear, in reality, many market imperfections and frictions constrain ex post and ex ante adaptation decisions, possibly explaining observed "adaptation gaps" between regions and/or time periods (Carleton and Hsiang, 2016). The literature providing large-scale assessments of climate damages inclusive of adaptation costs and benefits must confront such constraints to generate results that are relevant for adaptation policy.

There are multiple routes for doing so, particularly within the reduced form econometric literature. First, climate damage studies that aim to account for ex ante adaptation can investigate whether indicators of market frictions or constraints – such as infrastructure quality, credit market function, and market power – explain heterogeneity in weather dose-response functions. While this has been done to some extent – e.g., credit access lowers the mortality effects of heat (Burgess et al., 2017) and the cyclone impacts on economic growth (Noy, 2009; McDermott et al., 2014), while market power in agricultural markets restricts farmer adaptation (Kochhar and Song, 2023) – such constraints are rarely explicitly modeled in estimates of long-run climate damages. Integrating best available data on key market frictions into large-scale climate damage studies can help ensure that insights regarding the scope of potential adaptation (discussed above) include relevant real-world constraints.

Second, climate damage estimates that assume perfect ex ante adaptation decisions generate residual variation that can be exploited to better understand adaptation constraints. Specifically, studies that use long-run variation in climate to explain sensitivity to short-run weather shocks undoubtedly fail to perfectly fit the data. Researchers can use residual variation from such regressions to unpack where and for whom weather sensitivity falls below (or even above) that predicted by a model that assumes perfect ex ante adaptation based on long run climate. Such investigations set the stage for more context-specific analysis of specific adaptation interventions that may help explain or alter constraints to adaptation.

Through which mechanisms do adaptation interventions operate? Many evaluations of adaptation interventions do not unpack the mechanisms through which treatment effects operate. This omission limits the literature's ability to either inform targeted adaptation interventions, or to asses the holistic costs and benefits of interventions that influence adaptation as well as other socially relevant outcomes.

This opportunity to improve the literature's policy relevance comes in at least three forms. First, some studies fail to assess how much of an intervention's overall treatment effect operates through reduced damages from adverse weather events. For example, if cash transfers are found to improve agricultural profits, it is likely some share of that recovered treatment effect is due to improved resilience to adverse weather events. If authors decompose treatment effects into components driven by weather resilience versus those driven by actions or outcomes unrelated to climate change, these studies can directly inform the ranking of potential interventions based on their adaptation potential alone. Without such a decomposition, it is difficult to use such analyses to inform adaptation policy choice. However, we also note several methodological considerations for the growing list of papers that interact development interventions with weather shocks, in the name of climate adaptation (see Section 4.1).

Second, many studies show that an adaptation intervention successfully lowers the damages caused by an adverse weather event (i.e., that $\delta \neq 0$ in Equation (5)), but fail to uncover which actions $\boldsymbol{b}$ or $\boldsymbol{k}$ are being taken by which agents in order to realize those resilience benefits (i.e., do not estimate Equation (6)). If survey data collection can be designed and exploited to enable researchers to estimate *both* Equations (5) and (6) (that is, identify effects on welfare but also the key actions or investments changed by the intervention), policymakers can learn not just that an intervention lowers damages, but which constraints to adaptation were alleviated by the treatment. Elucidating such mechanisms is critical to identifying targeted policies that effectively alleviate binding constraints to adaptation. Moreover, uncovering the actions or investments taken in response to an intervention will allow researchers to assess the full costs and benefits of an intervention, as each mechanism (e.g., increased air conditioning use) may entail different social or economic spillover effects beyond the measured effects on adaptation (e.g., increased greenhouse gas emissions from associated energy use).

Third, constraints to adaptation may exist in combination, such that addressing one does not change outcomes because another constraint continues to bind. An example is information and credit constraints. Informing households about future climate change may be insufficient to spur ex ante adaptation investments if households cannot access credit. Conversely, simply addressing frictions in the credit market may fail to unlock adaptation if individuals have overly optimistic beliefs about future climate. Addressing both constraints in tandem may have multiplicative benefits for adaptation. Similarly, correcting misinformation or biased beliefs in one domain (e.g., upcoming heat waves) may be ineffective if individuals are uninformed in related domains (e.g., the health damages from heat, the location of cooling centers, or the cost of accessing the centers). To date, the literature has tended to focus on single interventions in isolation, rather than understanding the adaptation decision process and potentially interacting constraints to optimal adaptation.

Should the government intervene, and how? As articulated in Section 3, justifying adaptation interventions on social welfare grounds either requires a careful assessment of market failures *or* explicit delineation of a social welfare function that merits redistribution. While a growing number of studies econometrically assess or structurally model impacts of public policies on adaptation and associated welfare outcomes, these studies rarely ground their assessment of a public policy in a clear justification for intervention. For example, while Baylis and Boomhower (2021) estimate the disaster risk benefits of mandated regulations on wildfire-resilient building materials in California, it is unclear which market failures justify such a blunt command-and-control intervention. Whether or not such a costly adaptation policy ought to be rolled out more broadly hinges critically on whether it was correcting an existing market failure or simply requiring homeowners to invest in more adaptation than was privately (and socially) optimal. Analogously, Pople et al. (2021) show that anticipatory cash transfers in Bangladesh reduced food insecurity impacts of flooding. The justification for this intervention appears to be an implicit equity motive on the part of the planner, but the policy justification is not made explicit. In this regard, Hovekamp and Wagner (2023) show that minimum elevation requirements for housing built in high-risk flood areas in the U.S. is efficient because adaptation benefits are not fully capitalized into house prices. Going forward, research aiming to inform policy ought to ground studied interventions with clear theoretical justifications, elucidating the relevant market failure or explicitly characterizing a social welfare function if no market failure motivates the intervention.

Of course, it is not necessary to elucidate the justifications for intervention if a study aims only to inform the more narrow policy agenda of ranking adaptation interventions based on their cost effectiveness (Section 3.1). In this case, researchers should be clear about the link between their work and policy, noting that a comprehensive welfare assessment is not feasible, nor is it the goal.

Do the inefficiencies of public adaptation outweigh its benefits? Throughout this review, we have highlighted the critical role of the public sector in facilitating adaptation, particularly when market frictions or imperfections impede optimal adaptation decisions. However, we have also noted cases where public adaptation interventions are inefficient and distortionary (see Section 3.3). To date, literatures speaking to each side of this coin have largely been independent from one another. This means that in most contexts, it remains unclear whether the benefits of public adaptation interventions outweigh their possible inefficiencies or unintended consequences.

To inform welfare-enhancing adaptation policy, research is needed to carefully assess when the benefits of intervention exceed their costs. Undoubtedly, the answer to this question will vary across contexts. For example, as private insurance markets function relatively well in the United States, the inefficiencies of subsidized crop insurance quantified by Annan and Schlenker (2015) likely outweigh any benefits realized by correcting market failures. But in low and middle income country contexts where accessing actuarially fair insurance policies is nearly impossible, and where an equity motive for lowering damages to smallholder farmers exists, subsidized crop insurance may be welfare-improving. Research that can elucidate when intervention is justified, accounting both for benefits and possible costs of public action, is urgently needed.

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Appendix

Table A1. Studies of adaptation interventions and their definitions of weather anomaly used in Figure 1

Reference	**Variable**	**Climate baseline period**	**Length of climate baseline (years)**	**Shock type**	**Percentile used as shock cutoff**	**Uses fixed effects**
Adhvaryu et al. (2024)	Precipitation	Varies by birth year	10	Positive	84 (1σ)	Yes
Asfaw et al. (2017)	Precipitation	1983-2010	27	Positive	97.5 (2σ)	No
Björkman Nyqvist et al. (2023)	Precipitation	1983-2013	20	Continuous		No
Christian et al. (2019)	Precipitation	1979-2016	37	Continuous		Yes
Christian et al. (2019)	Precipitation	1951-2013	62	Continuous		Yes
Corno and Voena (2023)	Precipitation	1981-2010	29	Continuous		Yes
Deryugina (2013)	Temperature	1949-2000	51	Negative	5, 10, 25	Yes
				Positive	75, 90, 95	
Hirvonen et al. (2023)	Precipitation	1990-2020	30	Continuous		Yes
Jayachandran (2006)	Precipitation	1956-1987	31	Negative	20	Yes
				Positive	80	
Kazianga and Udry (2006)	Precipitation	1965-1985	20	Continuous		Yes
Lin et al. (2021)	Precipitation	1950-2014	64	Continuous		Yes
Mobarak and Rosenzweig (2014)	Precipitation	1999-2006	7	Continuous		Yes
Moore et al. (2019)	Temperature	1981-1990	10	Continuous		Yes
Paxson (1992)	Precipitation	1951-1985	34	Continuous		Yes
Ponnusamy (2022)	Precipitation	2000-2014	14	Negative	16 (-1σ)	Yes
				Positive	84 (1σ)	
Premand and Stoeffler (2022)	Precipitation	1970-2011	41	Negative	10, 11, ..., 35	No
Riley (2018)	Precipitation	Not stated	15	Positive	84 (1σ)	Yes
Rocha and Soares (2015)	Precipitation	1938-2008	70	Continuous		Yes
				Negative	16 (-1σ)	
Rosenzweig and Udry (2014)	Precipitation	1950-2010	60	Continuous		Yes
				Negative	49 (Realization-norm ratio is < 1)	
Schlenker and Taylor (2021)	Temperature	2001-2020	19	Continuous		Yes[1]

Notes: Table lists all studies represented in Figure 1 in the main text. Included studies are those that normalize weather variation with respect to a long-run climate norm when investigating the adoption or efficacy of specific adaptation technologies or strategies. Positive and negative shock definitions measured in standard deviations have been assigned percentile values using properties of the normal distribution, such that a positive shock threshold at 1 standard deviation (σ) above the mean is assumed to fall at the 84^{th} percentile. Note that Moore et al. (2019) include an analysis that compares the number of temperature anomalies identified using a shifting versus a fixed 30-year baseline, but we do not report it in Figure 1 or in this table as it is auxiliary from the authors' main analysis.

[1] In Schlenker and Taylor (2021), fixed effects are included in separate specification from that which uses weather anomalies.

Table A2. Studies of adaptation interventions used in Figure 3, their source of exogenous variation, and sector of focus

Reference	**Variation type**	**Exogenous variation**	**Adaptation intervention**	**Sector**
Adhvaryu et al. (2024)	Income	Transfer*	Conditional cash transfer program (PROGRESA/Oportunidades)	Cross-cutting
Adhvaryu et al. (2020)	Price	Ex post technology (p)	Roll-out of LED lighting in factories	Labor
Aker and Jack (2023)	Price	Ex ante technology (r)	Rainwater harvesting technique training (demi-lune)	Agriculture
Asfaw et al. (2017)	Income	Transfer+	Unconditional cash transfer	Cross-cutting
Balana et al. (2023)	Income	Transfer*	Anticipatory cash transfer	Cross-cutting
Banerjee and Maharaj (2020)	Price	Ex post technology (p)	Community health care worker program;	Health
	Income	Transfer+	Workfare program (NREGA)	
Baysan et al. (2019)	Income	Transfer*	Conditional cash transfer program (PROGRESA/Oportunidades)	Health
Beaman et al. (2021)	Price	Ex ante technology (r)	Agricultural technology training (pit planting)	Agriculture
Bhandari et al. (2022)	Decision environment	Market structure	Technology subsidies for groundwater extraction	Agriculture
Björkman Nyqvist et al. (2023)	Price	Ex ante technology (r)	Deployment of community health care workers	Health
Boucher et al. (2021)	Decision environment	Markets' frictions	Index insurance;	Agriculture
	Price	Ex ante technology (r)	Drought-tolerant seeds	
Brooks and Donovan (2020)	Decision environment	Market structure	New bridge construction	Agriculture
Burgess and Donaldson (2010)	Decision environment	Markets' frictions	Rural bank expansion program	Health
Burlig et al. (2024)	Decision environment	Information/beliefs	Provision of monsoon forecast;	Agriculture
	Decision environment	Markets' frictions	Index insurance	
Christian et al. (2019)	Income	Transfer*	Conditional cash transfer (Program Keluarga Harapan)	Health
Christian et al. (2019)	Income	Transfer*	Staggered roll-out of Odisha Rural Livelihoods Program	Cross-cutting
Cohen and Dechezleprêtre (2022)	Price	Ex post technology (p)	Health care expansion policy	Health
Cole et al. (2017)	Decision environment	Markets' frictions	Rainfall insurance provision	Agriculture
Collier et al. (2024)	Decision environment	Markets' frictions	Contingent loan offerings	Cross-cutting
Colmer and Doleac (2023)	Price	Ex post technology (p)	Gun control policies	Health
Dar et al. (2013)	Price	Ex ante technology (r)	Flood-tolerant rice variety	Agriculture
Downey et al. (2023)	Decision environment	Information/beliefs	Change in forecast quality	Labor
Emerick et al. (2016)	Price	Ex ante technology (r)	Flood-tolerant rice variety	Agriculture
Fetzer (2020)	Income	Transfer+	Workfare program (NREGA)	Cross-cutting
Garg et al. (2020)	Income	Transfer+	Workfare program (NREGA)	Cross-cutting
Garg et al. (2020)	Income	Transfer*	Conditional cash transfer program (PROGRESA/Oportunidades)	Cross-cutting
Gibson and Mullins (2020)	Decision environment	Information/beliefs	Biggert-Waters Flood Insurance Reform Act; Hurricane Sandy; Floodplain maps	Housing
Gunnsteinsson et al. (2022)	Price	Ex post technology (p)	Vitamin A supplement provision	Health
Hill et al. (2019)	Decision environment	Markets' frictions	Index insurance	Agriculture
Hino and Burke (2021)	Decision environment	Information/beliefs	Updated floodplain maps	Housing
Hirvonen et al. (2023)	Income	Transfer*+	Ultra-poor graduation program (Productive Safety Net Program)	Cross-cutting
Hou (2010)	Income	Transfer*	Conditional cash transfer program (PROGRESA/Oportunidades)	Cross-cutting
Janzen and Carter (2019)	Decision environment	Markets' frictions	Index-based livelihood insurance pilot project	Cross-cutting
Jones et al. (2022)	Decision environment	Markets' frictions	Hillside irrigation canal construction	Agriculture
Knippenberg and Hoddinott (2019)	Income	Transfer*+	Social protection program (Productive Safety Net Program)	Cross-cutting
Kochhar and Song (2023)	Decision environment	Market structure	Variation in state-level laws governing agricultural transactions	Agriculture
Lane (2024)	Decision environment	Markets' frictions	Contingent loan offerings	Agriculture
Lee (2023)	Decision environment	Information/beliefs	Homeseller Disclosure Requirement	Housing
Lemoine and Kapnick (2024)	Decision environment	Information/beliefs	Change in forecast quality	Cross-cutting
Macours et al. (2022)	Income	Transfer*	Conditional cash transfer with vocational training or a productive investment grant	Agriculture
Mobarak and Rosenzweig (2014)	Decision environment	Markets' frictions	Index insurance offering	Agriculture
Mogge et al. (2024)	Income	Transfer*	Anticipatory cash transfer	Cross-cutting
Molina and Rudik (2023)	Decision environment	Information/beliefs	Change in hurricane forecast quality	Cross-cutting
Mulder (2022)	Decision environment	Information/beliefs	Improved flood risk classification	Cross-cutting
Mullins and White (2020)	Price	Ex post technology (p)	Health care expansion through Community Health Centers	Health
Patel (2023)	Price	Ex ante technology (r)	Salinity-tolerant seeds	Agriculture
	Decision environment	Information/beliefs	Information on salinity levels	
Pople et al. (2021)	Income	Transfer*	Anticipatory cash transfer	Cross-cutting
Premand and Stoeffler (2022)	Income	Transfer*	Unconditional cash transfer	Cross-cutting
Riley (2018)	Decision environment	Markets' frictions	Roll-out of mobile money providers	Cross-cutting
Rosenzweig and Udry (2013)	Decision environment	Information/beliefs	Change in forecast quality	Agriculture
Shr and Zipp (2019)	Decision environment	Information/beliefs	Updated floodzone mapping	Housing
Shrader et al. (2023)	Decision environment	Information/beliefs	Change in forecast quality	Health
Song (2024)	Decision environment	Information/beliefs	Change in forecast quality	Labor
Stoeffler et al. (2022)	Decision environment	Markets' frictions	Index insurance	Agriculture
Weill (2023)	Decision environment	Information/beliefs	Updated flood maps after Hurricane Katrina	Housing

Notes: Table lists all studies represented in Figure 3 in the main text. In the "Exogenous variation" column, p indicates a price intervention targeting an ex post adaptation technology, while r indicates a price intervention targeting an ex ante adaptation technology, following the notation from Section 1 in the main text. Additionally, superscripts + denote income interventions designed to affect the *mean* of income, while superscripts $*$ denote those designed to affect the *variance*. For example, income interventions designed to affect the mean include unconditional cash transfers and workfare programs made available to all households in a given region, while those that target only the most vulnerable households (e.g., the poorest or the most shock-exposed) are designed to reduce variance.