Fifty Years of U.S. Natural Disaster Insurance Policy*

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Abstract

The high and increasing cost of natural disasters around the world motivates a growing body of literature on the role of natural disaster insurance in adapting to climate change. This chapter reviews current challenges in both public and private natural disaster insurance markets in the United States and how the nature of these challenges has changed over the past fifty years. We discuss how the infrequent, spatially correlated, and extreme events that distinguish these markets complicate both the supply of and demand for natural disaster insurance, with spillovers to related markets such as real estate. We also highlight open questions that would be helpful to answer to inform analysis of currently proposed natural disaster insurance reforms.

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1 Introduction

In 2022, the United States experienced over $140 billion of natural disaster damages. Globally, damages exceeded $270 billion (Straub et al., 2023). This year is not an anomaly, but rather reflects a trend in increasingly severe weather events. Natural disaster insurers are struggling to respond to the rate of increase of costs, with over 200 bills related to natural disaster insurance reform currently discussed at various levels of government in the U.S., while homeowners are experiencing increasing difficulty obtaining affordable insurance coverage (Wagner, 2022b; Wing et al., 2018).

Large natural disasters are not a new phenomenon in the United States, and have caused insurance market upheaval in the past. The Great Mississippi Flood of 1927 is one such example, after which private insurers who previously sold flood coverage walked away from the flood insurance market completely. Their justification for doing so was that the massive losses they had sustained and would inevitably experience in the future required raising insurance premiums to unaffordable levels. These private insurance companies were replaced in 1968 by the National Flood Insurance Program (NFIP), a public program that sells government-backed flood insurance at subsidized rates to homeowners throughout the country (Gaul, 2019). Fast forward fifty years and flood insurance in the U.S. is provided almost exclusively through the NFIP today.

However, the scale and scope of current and predicted future damages have fostered concern about whether markets designed fifty years ago are appropriate for adapting to climate change risks. Over its fifty year history, the NFIP has amassed a $40 billion revenue shortfall, relying on its ability to borrow from the U.S. Treasury and its funding by federal taxpayers to survive where private insurers could not (Gaul, 2019). And the costly events that sank private flood insurance markets decades ago are now arriving in markets for natural disasters other than floods. In recent years, for example, insurers have started to pull out of areas at high-risk of wildfire in the western U.S., leading policymakers to question whether natural disaster insurance risk is insurable by private markets, or at all (Cignarale et al., 2019; Rothschild and Stiglitz, 1976). The general divergence between risk and premiums in natural disaster insurance markets has created uncertainty about the future solvency of insurers in a world affected by climate change and the ability of homeowners to insure themselves against its effects.

The goal of this chapter is to provide an overview of how insurers and homeowners are responding to challenges in natural disaster insurance markets in the U.S., and to highlight areas of fruitful future study. Our intent is to survey both public and private markets, many of which focus on different, specific disasters; while literature on the NFIP has burgeoned in recent years, our analysis places the NFIP both in a historical context and relative to other markets that have received less attention. Though we limit our discussion here to U.S. natural disaster insurance markets on which we have both conducted research, many of the behaviors of insurers and homeowners are common to international markets that are also experiencing the effects of climate change.

Why review natural disaster insurance separately from other insurance markets? A first reason is that these markets have received limited attention in comparison with other insurance markets, such as health, unemployment, and disability insurance. And yet, the rate at which costs are increasing in natural disaster insurance markets suggests an urgency in understanding insurer and homeowner behavior to undertake efficient reforms. A second reason to focus on analysis of natural disaster risk is that it isn't clear that conclusions from other, more commonly studied insurance markets generalize. Natural disaster risk is different from other types of insurable risk because losses are highly spatially correlated, less frequent, and larger than most other types of insurable risk, such as health (Wagner, 2022b). The resulting difficulty in predicting risk and the potential downside of getting the predictions wrong changes both insurer and homeowner behavior, as we will discuss.

We begin our study with discussion of the supply side of natural disaster insurance markets in Section 2. The public NFIP provides a starting point for our analysis of the challenges faced by insurers even in the presence of large geographic diversification and seemingly unlimited borrowing potential. We then discuss how these challenges differ in private markets for other natural disaster insurance types that are also complicated by greater insolvency risk, more stringent rate regulations, and more limited ability to diversify risk across space. In Section 3, we review how homeowner behavior on the demand side of the market complicates these challenges faced by insurers. Section 4 comprises analysis of how changes in natural disaster insurance markets affect other related markets, such as housing. We conclude in Section 5 with a discussion of important areas for future work.

2 Supply of Natural Disaster Insurance

This section reviews the supply side of natural disaster insurance markets in the U.S. We distinguish between public and private markets, which face different challenges. We discuss potential market failures that arise in both of these settings and policy solutions that could address them.

2.1 Public Insurance Markets

We begin with an analysis of public natural disaster insurance markets in the U.S. The largest, and perhaps best known, such market is the NFIP, which services almost all demand for flood insurance in the country. In addition, several other public natural disaster insurance markets exist in individual states, for different disasters. All of these markets share common benefits and challenges that are characteristic of publicly provided natural disaster insurance, which we discuss in detail here.

The motivations for public natural disaster insurance markets have a theoretical basis. Natural disasters are infrequent and catastrophic, and the on-going effects of climate change on the distribution of risk are hard to predict. Weitzman (2009) discusses how this uncertainty surrounding the distribution of climate change risk creates challenges for calculating the probabilities of natural disasters and, by extension, actuarially fair insurance premiums. Rothschild and Stiglitz (1976) claim more strongly that their standard model of insurer behavior doesn't apply to natural disaster risk, and that the potential uninsurability of such risks by private markets justifies public provision. Their insight is that it is difficult to credibly model natural disaster insurers as risk neutral, as is typical in insurance markets, because premiums and claims are rarely in balance: in some years, no natural disaster occurs, while losses in other years can be catastrophic. By contrast, other insurance lines, such as health and automobile insurance, typically break even in any given year (Michel-Kerjan, 2010). Private natural disaster insurers would have to build up a large amounts of liquid assets in case a loss occurs—which is characteristic of risk averse behavior. Institutional features of the tax code and legal framework in the U.S. discourage the accumulation of large quantities of cash for rainy days; the lack of financial reserves was a contributing factor to the exit of private flood insurers in the early twentieth century, for example (Gaul, 2019). While reforming capital markets to encourage the accumulation of such reserves is one possible solution, an

alternative is for the government to supply insurance directly (Jaffee and Russell, 1997).[1]

The greater geographic diversification and solvency potential of governments suggest that public provision of natural disaster insurance may have advantages relative to private markets.[2] A public insurer can smooth risk over a larger geography, therefore reducing the risk that any individual event results in bankrutpcy. They also potentially have access to to greater financing capacity than any individual private insurer does, allowing them to better weather large loss events, such as Hurricane Katrina, by borrowing from taxpayers.

The NFIP exemplifies these advantages of public natural disaster insurance markets. As a federal program administered by the Federal Emergency Management Agency (FEMA), they write over 5 million annual flood insurance contracts for homeowners nationwide, insuring both buildings and their contents. Figure 1 shows that the number of contracts sold by the NFIP has increased substantially over the program's lifetime. Their geographically dispersed market allows them to cross-subsidize claims in one part of the country with contemporaneous premium revenues from unflooded places. A distinguishing feature of natural disaster insurance markets is that claims are highly correlated in space, and so greater geographic diversification increases the amount of premium revenue available to offset claims in disaster areas. Today, the NFIP collects over $4.6 billion of annual premium revenue from customers across every state and insures over $1.3 trillion of assets (Horn, 2022; Michel-Kerjan, 2010).

The NFIP also benefits from seemingly unlimited borrowing potential. Flood insurance premium revenue has remained relatively constant in real terms since 1990, but flood insurance claims, by contrast, are highly variable (Kelly, 2017). Unlike health risks, natural disaster insurance payouts are infrequent but are more likely to be catastrophic if they happen (Jaffee and Russell, 1997). Since seventeen of the most costly flood events in the U.S. have occurred since 2000, claims have eclipsed premiums even with the NFIP's geographic diversification (Gaul, 2019); this increasing annual premium shortfall is shown in Figure 2. The program is currently over $20 billion in debt, but it continues to stay afloat by borrowing from the Department of the Treasury to finance their payouts. Under these circumstances,

[1] Jaffee and Russell (1997) propose several other capital markets solutions, including reforming accounting standards to permit tax-deductible catastrophe reserves, expanding reinsurance markets to improve coverage of cataptrophic risk, and relaxing regulatory constraints that current prohibit large premium increases. We return to the topic of financial market reform in Section 4.2 below.

[2] The benefits of public provision of insurance here are in addition to possible welfare gains from addressing textbook market failures, such as adverse selection, that have been studied extensively in other settings. See Einav et al. (2021) for a review of selection in insurance markets.

any private insurance market would conceivably have been declared insolvent years ago. By contrast, Congress continues to increase the NFIP's borrowing limit, which currently exceeds $30 billion and is 1500% higher in real terms than its initial 1968 level (Horn, 2022).

In addition to the NFIP, several other U.S. public natural disaster insurance markets exist. Many of these other markets were also created in response to a large loss event that triggered the exit of private insurers. For example, the California Earthquake Authority formed in 1996 after the 1994 Northridge earthquake precipitated the exit of private homeowners insurers from the earthquake line; this state-run earthquake insurer sells earthquake policies throughout California at actuarially fair rates (Marshall, 2017). The public Florida Citizens Property Insurance Corporation serves as an insurer of last resort for Florida homeowners who cannot obtain property and casualty coverage in private markets due to high perceived risk from flooding, wind, and other natural perils; the original market was established after high claims in private markets for damage caused by Hurricane Andrew in 1992 (Citizens, 2020). The Louisiana Citizens Property Insurance Corporation and the California Fair Access to Insurance Requirements (FAIR) Plan Association similarly publicly supply homeowners' insurance to residual markets in their respective states; the later has become increasing important in the last five years as private insurers in California struggle to bear rising fire costs, as we will discuss in Section 2.2 (Cignarale et al., 2019). While many of these markets are smaller in scope, they share the characteristics and potential benefits common to public natural disaster insurance markets.

Given these potential benefits of public markets, why is widescale reform of the NFIP currently discussed? Regulatory concerns are centered on the high debt burden that the NFIP has incurred despite their ability to smooth risk across localities throughout the country. Many of today's challenges stem from the original design of the NFIP. Initial flood insurance premiums were set to cover losses incurred in an average loss year, and it was understood that the program would not break even during catastrophes as a result and would borrow from Congress. During the interim period between the exit of private flood insurers in the 1920s and the inception of the NFIP in 1968, the federal government had already been providing public disaster relief to victims of floods; the creation of the NFIP formalized this process. The program's original dual objectives were to increase the availability of flood insurance coverage and to manage development in floodplains. To accomplish the first objective, the program included explicit premium subsidies, below actuarially fair levels, on existing construction in high-risk flood zones to

maintain affordability of flood insurance contracts for homeowners for whom actuarially fair rates would be very high (Michel-Kerjan, 2010). To accomplish the second objective, the NFIP also worked with the U.S. Army Corps of Engineers to produce Flood Insurance Rate Maps (FIRMs) that delineate areas at high- and low-risk of flooding; new contruction in high-risk flood zones is required to meet minimum standards to reduce their flood risk or otherwise pay very high actuarially fair premiums. These minimum construction standards mandate that the elevation of houses' foundations exceed the height of the flood that has a 1% probability of occuring (Hovekamp and Wagner, 2023).[3] The gradual mapping of the U.S. expanded the NFIP's scope to include almost all of the country today.

Since 1968, it has proven difficult to make changes to this original set-up. Together, political opposition to increasing premiums to reflect changes in flood risk and modelling contraints on determining what those risks actually are help explain why flood insurance premiums have remained largely constant in real terms for over half of the NFIP's history (Kelly, 2017). In response to rising costs for the older structures grandfathered into the program at lower rates, Congress attempted to phase out statutory subsidies in 2012 through the Biggert-Waters Flood Insurance Reform Act. Specifically, this bill proposed to remove the subsidies for houses that were built before flood maps came into effect at a rate of 25% per year if the house was sold, grandfathered into a riskier flood zone, or classified as "severe repetive loss" by the NFIP.[4] However, the spatial nature of these premium increases lead to widespread concern from homeowners that coastal properties would experience substantial devaluation and from local governments that property tax revenues would fall. These premium changes were ultimately so unpopular that they were rescinded after only one year and replaced with more modest increases in a second bill, the Homeowners Flood Insurance Affordability Act, in 2013. This alternative legislation implemented more modest premium increases of between 5% and 18% for all properties receiving explicit subsidies, until premiums reached levels that the government's flood risk models suggested were actuarially fair. The new bill excluded severe repetitive loss properties, which were still subject to the original rate increases of 25% (NRC, 2015).

Updating flood maps is challenging for the same political reasons, but also for scientific ones. Political opposition to updating flood maps arises because real estate markets and natural disaster insurance

[3]These construction standards apply in areas that have a "1-in-100 year" or higher chance of flooding, which the NFIP refers to as "Special Flood Hazard Areas" (Horn and Brown, 2018).

[4]Severe repetive loss properties are those that have made at least 4 claims in excess of $5,000 or at least 2 claims that, in total, exceed the property's value (Horn and Brown, 2018). Grandfathered properties are structures that were remapped from a low-risk flood zone to a high-risk one and kept their low-risk rates (NRC, 2015).

markets are inextricably linked, and so rezoning houses into high-risk flood zones reduces their value (Hino and Burke, 2021). However, a more binding constraint on using NFIP flood maps to price flood insurance is that many of the maps do not in fact reflect current risk levels. Approximately two-thirds of official flood maps are out-of-date and do not incorporate the latest flood risk information available to the government; approximately 20% of maps were last updated more than 15 years ago (GAO, 2021a). The scale at which these maps are produced also means that many of the historical government flood risk models use coarse-resolution terrain data and simplifying assumptions about the physics of local hydrology, including the effects of extreme precipitation events that are becoming more common.[5] Recent research using independent flood risk models shows that there are more than three times as many houses in high-risk flood zones as the NFIP's maps suggest (Wing et al., 2018). One change that the NFIP did make was the implementation of a mandatory flood insurance purchase requirement for homeowners with federally-backed mortgages (Michel-Kerjan, 2010). However, even this take-up mandate has been difficult to enforce in practice (Petrolia et al., 2013); we return to demand-side challenges in Section 3.

How might these supply-side rate setting and information challenges be addressed? There is increasing acknowledgement that continually increasing the NFIP's borrowing from the Treasury will be untenable if flood insurance costs continue to increase. The federal government has committed over four billion dollars to update NFIP flood maps to provide accurate information about current risk levels through the 2009 FEMA Risk Mapping, Assessment and Planning Program. Since issuing a new flood map can take five to seven years, modernizing all flood maps is a long-term objective (GAO, 2021a; Weill, 2022). Using the information from these new maps and from independent catastrophe models, the NFIP is currently implementing a new series of premium changes, called Risk Rating 2.0, with the goal of bringing premiums into greater alignment with actuarially fair levels. This new rate setting methodology is the first major change to NFIP rate schedules since the 1970s. The new methodology will incorporate structured-specific characteristics and risk from heavy rainfall, which historically have been excluded from the calculation of premiums. Using more granular flood risk models will result in the removal of implicit subsidies to risky homes, while explicit subsidies to older contruction will continue to be phased out following the guidlines of the Homeowners Flood Insurance Affordability Act; about 75% of policy holders are expected to pay

[5]The NFIP's coarse rate schedule reflects their lack of granular data on flood risk. Premiums are set based on a handful of structural characteristics, including construction year, flood zone, foundation elevation, and basement depth.

higher premiums as a result (Horn, 2022; Kousky and Mulder, 2023).

In addition, there is early evidence that the government may be increasing enforcement of the mandatory flood insurance purchase requirement for homeowners, which will increase the salience of the social costs of living in a high-risk flood zone (GAO, 2021b). As these costs rise, homeowners may find lower risk properties increasingly attractive. "Managed retreat" policies explicitly compensate homeowners in exchange for relocating further out of harm's way. FEMA also runs a voluntary residential buyouts program that purchases flood-prone properties, allowing their residents to move to areas with lower flood risk and the property to be converted to open space. This federal buyouts initiative is the largest managed retreat-type program in the country, and yet has purchased fewer than 50,000 properties since its creation (Shi et al., 2022). Overall, the implementation of such policies to encourage migration away from risk areas in the U.S. has been limited.

Addressing these problems is worthwhile because publicly-provided natural disaster insurance may also distort signals about risk in other markets. The government's historical subsidization of flood insurance, below expected payouts, and coarse flood maps signal to homeowners that their risk is lower than reality. Homeowners may then underestimate their risk levels and, by extension, overvalue property located in risky areas (McGuire, 2018). We discuss how natural disaster insurance markets interact with complementary markets, such as real estate, in greater detail in Section 4.

Despite these challenges, there is some discussion now of whether the benefits of the public model outweigh the costs, and whether private natural disaster insurance markets should in fact become public as a result. We turn now to discuss private natural disaster insurance markets.

2.2 Private Insurance Markets

While the public provision of flood insurance through the NFIP is the primary channel through which homeowners can insure themselves against flood risk, insurance markets for other types of natural disasters remain predominantly private. Insurance contracts that provide coverage against other natural disaster types are sold by many of the same private insurers who sell standard homeowners' multiperil policies. These private markets are characterized by additional challenges to adapting to changing distributions of natural disaster risk. We discuss the differences between public and private markets, and the challenges

that these differences create, in this section.

The structure of private natural disaster insurance markets differs along several dimensions from that of public markets. First, the contract structure itself is different: unlike the contracts sold by the NFIP, coverage for other natural disasters isn't typically provided through a separate policy. Instead, coverage is either included in standard homeowners' policies, as is the case for wildfire coverage in California or windstorm coverage in Florida, or is sold as a supplementary policy to extend basic coverage limits, for extreme events such as earthquakes.[6] Second, many private natural disaster insurance markets service homeowners in individual states, and so their markets are less geographically diverse than the NFIP (USGAO, 2007). Third, while public markets may borrow from taxpayers to elastically supply insurance contracts, private insurers do not necessarily have the same borrowing potential. Indeed, private insurers have historically had the option to refuse to renew contracts or to pull out of certain geographies altogether, in contrast with the national market of the public NFIP (Cignarale et al., 2018). Finally, the private natural disaster insurance market structure typically comprises several competitive insurers regulated by the state, rather than a single public provider (Oh et al., 2021). While public insurers have historically offered statutory subsidies to encourage take-up, private insurers have a profit-maximizing objective that aims to set premiums high enough to finance payouts while remaining competitive with other insurers and complying with state regulations. As a result, premiums may be closer to actuarially fair levels in these markets.

The market for wildfire insurance in California is one salient example of a private natural disaster insurance market in the U.S. with these characteristics. Damages resulting from fire have traditionally been covered by standard home insurance policies across the country, and the same is true for wildfire-related property damage in the California. Unlike the federal market for flood insurance, there are over 220 distinct insurers selling wildfire coverage in California. The premiums charged by these insurers are regulated by the state, with increases in excess of 7% per year subject to extensive regulatory review (APCIA, 2020; Chan, 2022). Historically, private insurers had no problem aggregating wildfire damages with damages from other insured perils, but the rate of wildfire occurrence and severity has been steadily

[6]These supplementary policies also exist in markets that are dominated by a public insurer. For example, high-value homes that require coverage exceeding the NFIP maximums, which are currently set at $250,000 for building property and $100,000 for personal property, can supplement this coverage with additional insurance from a private provider (Horn and Webel, 2018). Such supplementary policies are the norm for earthquake coverage in most states as well, though California exceptionally has a public earthquake insurance market (Marshall, 2017).

increasing since 1980. Average annual wildfire losses in California were $30 million between 1979 to 1988, and forty years later, this number has increased to almost $1 billion annually (Buechi et al., 2021). In September 2015 alone, the Valley and Butte wildfires caused over $1 billion in insured damages and destroyed over 1,700 homes, and then again in October 2017, wildfires damaged or destroyed over 14,700 insured homes (Cignarale et al., 2018). These extreme claims levels precipitated the withdrawal of a number of private insurers from high-risk areas and the increase of some premiums to unaffordable levels. Difficulty in finding insurance plans forced many homeowners in high-risk areas to purchase more expensive policies through the California FAIR plan (Liao et al., 2022).

Wildfires are not the only natural disaster that continues to be covered by standard homeowners' insurance contracts. Damage caused by wind is also covered by most multiperil policies, for example. In coastal areas that are prone to hurricanes, the distinction between flood and wind damage can be important. Public flood insurance only covers damages that are the direct result of rising water levels, which excludes damages caused by rain or roof leaks (FEMA, 2023). Hurricanes typically cause both wind and water damage, so NFIP coverage tends to falls short of the full cost of home repairs in these instances, with the balance borne by private home insurers. In states such as Florida, where a large share of the market is exposed to hurricanes, damages from wind can be very costly, placing strain on private insurers and even creating difficulty for homeowners to find affordable policies. As a result, Florida and other coastal states have developed insurance markets of last resort that have similar objectives to California's FAIR market and that sell wind insurance policies to homeowners who cannot find coverage in private markets (Zhang et al., 2022).

The differences between public and private natural disaster insurance markets make it even more challenging for these private insurers to adapt to increasing climate change risk, as compared with public insurers. Private insurers have had similar difficulties raising premiums at the same rate as natural disaster costs, but it is unclear whether private markets will be able to continue to offer affordable premiums in the future. The additional difficulties stem primarily from the more limited geographic diversification, greater insolvency potential, and more stringent regulation of premiums that characterize the California wildfire insurance market, for example, and distinguish it from the public NFIP (Wagner, 2022b).

First, private insurance markets are more often characterized by low levels of both market concentration and geographic diversification. These two factors together imply that each individual firm may lack

sufficient information on claims history to accurately assess risk for new homes, which in turn results in difficulty setting actuarially fair premiums (Cignarale et al., 2018; Horn and Webel, 2018). Competition disincentivizes insurers from sharing historical claims data, which when combined with the changing distribution of natural disaster risk leads to high levels of uncertainty about how to determine fair premiums. Furthermore, low levels of market concentration and spatial coverage also reduce the ability of individual insurers to cross-subsidize payouts in high-risk areas with premiums in other geographies, as is more feasible for the federal NFIP. As a result, the catastrophic and spatially correlated nature of natural disaster risk makes it more difficult for private insurers operating in limited geographies to break even when a natural disaster occurs, so that geographic concentration and exit probability are positively correlated (Jaffee and Russell, 1997).

Second, private insurers typically face much larger solvency concerns following natural disasters than public insurers. This greater risk of insolvency arises because, unlike public insurers, private insurers are not backed by state or federal funding, and so cannot rely on borrowing from taxpayers to finance payouts. While the NFIP can reliably borrow from the Treasury if claims exceed premium revenue following a costly flood, private insurers must either independently finance their payouts through premium and investment revenue or mitigate their payout risk through reinsurance. The capital demands required for private markets to self-finance all payouts are likely prohibitive; while realized natural disaster damages are highly variable, the risk of a natural disaster is theoretically constant, and so private insurers must keep enough capital on hand each year to cover the payouts of an extreme event.[7] More concretely, for a natural disaster that has a 1% chance of occuring, private insurers would need enough capital to cover 100 times the annual expected loss (Jaffee and Russell, 1997). Faced with such high capital requirements, insurers may exhibit "safety-first" behavior by acting to minimize insolvency potential, rather than maximizing profits (Kousky and Kunreuther, 2018; Roy, 1952; Stone, 1973). Such a model of behavior would support recent insurer decisions to pull out of areas at high risk of wildfire in California, rather than raise premiums above affordable levels (Liao et al., 2022). The increasing development of financial markets, which we discuss in more detail below, helps to mitigate some of these solvency concerns.

Third, there is greater tension in private markets between setting premiums that allow insurers to remain solvent and charging rates that homeowners can afford. Unlike the federally-backed NFIP, private

[7]This capital requirement would increase in the more realistic scenario of currently increasing, rather than constant, risk.

insurers cannot operate at the loss they would incur if they subsidized premiums; indeed, historically low flood insurance premiums kept private flood insurers out of this market for much of the NFIP's history (Gaul, 2019). However, homeowners' insurance is a requirement to obtain federally-back mortgages in the U.S., and so insurance regulators are increasingly intervening in private markets to keep premiums affordable and homeowners insured (Kousky and Kunreuther, 2018). These policies can take several forms. For example, regulators in some states impose effective limits on annual premium increases. Such a constraint exists in California, where wildfire insurance premium increases in excess of 7% per year trigger administrative hearings that can delay the implementation of new premiums by months or years. In response, there is significant bunching of rate increase requests at 6.9% per year (APCIA, 2020). Other types of regulation include limits on the variables or models that insurers can use to price risk, and therefore the extent to which premiums can reach actuarially fair levels. For example, some states prohibit insurers from pricing risk that is correlated with race, religion, income, or other demographic characteristics that could result in regressive premium schedules (Powell, 2020). California also limits which wildfire risk models insurers are permitted to use to set premiums; regulators' concerns here are that select projections of future risk could result in unaffordable rates (APCIA, 2020).

The effects of these additional complexities are already evident in private natural disaster insurance markets in the U.S. In California's wildfire insurance market, limited geographic diversification, insolvency issues, and government regulation are all making wildfire risk increasingly difficult for for-profit companies to insure. California's strict regulatory environment and constraints on premium increases limit insurers' ability to cross-subsidize wildfire risk with premiums from other states where some insurers might operate. Within California, insurers with significiant market share in high-risk areas are increasingly reluctant to continue to sell these policies; between 2016 and 2019, when California insurers experienced unprecedented wildfire claims, the number of high-risk policies dropped by insurers rose by more than 100% (Liao et al., 2022; Oh et al., 2021). At the start of this time period, complaints about premium increases and non-renewals were already 200% higher than the previous decade. This market upheaval prompted the state government to introduce a moratorium on insurer non-renewals in 2020 (Cignarale et al., 2018). The difficulty finding insurance in the private market is evident from the rising market share of insurers of last resort. The FAIR plan in California, for example, almost doubled its market share in high-risk zip codes between 2018 and 2020, while Florida Citizens Property Insurance Corporation, the analogous

insurer of last resort in Florida, experienced a similarly sized increase in market share over the same time period (Liao et al., 2022).

There a number of potential solutions to the series of challenges outlined above, many of which would also benefit public natural disaster insurance markets. Indeed, the extreme nature of natural disaster risk suggests that some type of public-private partnership may be helpful for natural disaster insurance markets to function well. The public sector may have advantages over the private sector for implementing adaptation policies that reduce costs to insurers, transfering risk away from insurers, and communicating risk to homeowners. For example, expanded state funding for adaptation, such as sea walls or rubber coating for power lines in forested areas, could reduce overall natural disaster risk and mitigate property damage in areas covered by both public and private markets (Kousky and Kunreuther, 2018). Encouraging the development and adoption of reinsurance policies and other financial products would also allow private insurers with geographically concentrated markets to better diversify their natural risk. Utilizing these financial markets to reduce local exposure to natural disasters would reduce the need to explicitly cross-subsidize risky areas with lower risk policies in other, less stringently regulated states (Oh et al., 2021). In addition, the public sector may have advantages communicating information about risk to homeowners. Public markets such as the NFIP and the CEA make flood and earthquake risk maps publicly available to homeowners, and publicizing analogous risk information for natural disasters more commonly covered by private markets would provide informative signals to help homeowners and developers make informed decisions about mitigation and adaptation to natural disasters (Kousky and Kunreuther, 2018). Information also plays an important role in stimulating demand for natural disaster insurance, which is the focus of the following section.

3 Demand for Natural Disaster Insurance

This section reviews the demand side of natural disaster insurance markets. We begin with a discussion of take-up in public and private natural disaster insurance markets and then turn to determinants of these take-up rates and possible policy solutions to increase them.

3.1 Demand Stylized Facts in Public and Private Markets

A key diference between demand for natural disaster insurance in public and private markets is the extent to which natural disaster risk is bundled with other types of insurable risk. Private natural disaster insurance markets typically bundle some natural disaster risks with other perils, with separate policies available for coverage amounts in excess of the basic limits included in standard homeowners policies. This structure is characteristic of the Californian wildfire insurance market, for example: while most wildfire damages are insured by standard homeowners' policies, extended coverage policies can be purchased separately to provide full insurance in the case of complete destruction of the house by fire (Klein, 2018). Other natural disasters are explicitly excluded from homeowners' multiperil policies, including the risks of earthquakes and floods discussed above. Insurance contracts for these natural disasters must be purchased separately from the CEA or NFIP respectively, for example, and these contracts will include coverage only for the natural disaster insured by that particular market (Kousky and Kunreuther, 2018).

Demand for natural disaster insurance seems to reflect these differences in contract structures. When natural disaster risk is bundled with other perils, homeowners are more likely to be insured against those risks. Over 95% of homeowners in the U.S. carry a general insurance policy against standard perils such as theft, vandalism, and other common risks to property (Klein, 2018). By contrast, take-up of policies for specific natural disasters that are excluded from standard home insurance policies is much lower. For example, only approximately 10% of homeowners in California purchase earthquake insurance (Marshall, 2017). Take-up of flood insurance is also so low that the literature routinely refers to the "insurance gap" in this market, even though Figure 1 suggests that flood insurance demand is much higher than at most times in the fifty-year history of the NFIP (Kousky and Kunreuther, 2018). Overall, only approximately 4% of homeowners in the U.S. purchase a flood insurance contract, with much of this take-up driven by demand in high-risk flood zones (Bradt et al., 2021). However, even in these high-risk flood zones, over 40% of homeowners are uninsured (Wagner, 2022a). The supplementary coverage policies available for bundled natural disaster risks, such as wildfires, are also less likely to be purchased than the basic multi-peril policies (Klein, 2018). This puzzlingly low uptake for natural disaster-specific policies suggests that homeowners' behavior in these markets differs from other perils, which underscores the importance

of research on these markets.

These low extensive-margin take-up rates for natural disaster insurance are especially remarkable given the large expected benefits of insurance for homeowners. Standard theory predicts that risk-averse homeowners should be willing to pay their expected insurance benefit plus a risk premium that reflects their benefits from the reduction in the variance of consumption provided by insurance (Hendren, 2020). Though there are few estimates of risk aversion in natural disaster insurance markets, homeowners are generally thought to be risk-averse, as in most other domains (Snydor, 2010).[8] Willingness to pay for insurance rises as the variance of realized risk rises, and the infrequent, catastrophic nature of natural disasters creates a large difference between the financial consequences of a natural disaster if a homeowner is insured relative to when they are uninsured. It is therefore surprising that many homeowners are uninsured against natural disaster risk when contracts are actuarially fair, as in the case of the CEA, or even better than actuarially fair, as for subsidized policies sold through the NFIP; risk-averse homeowners should be willing to pay more than an actuarially fair premium, and yet we find that a majority of homeowners throughout the country are unwilling to do so in markets for natural disaster insurance specifically. The gradual phase-out of flood insurance subsidies after 2012, for example, led to reductions in the share of insured homeowners well before premiums reached actuarially fair levels, and the extent to which current premium changes under Risk Rating 2.0 will affect coverage levels remains to be seen. Overall, extensive margin price elasticities of demand for flood insurance are estimated to be around -0.30 (i.e., relatively inelastic) (Bradt et al., 2021; Wagner, 2022a).[9]

In addition to the decision of whether to purchase a natural disaster insurance contract, unbundled contracts for natural disaster risk also typically allow an intensive margin purchase choice: conditional on purchase, homeowners can choose different levels of coverage for buildings and their contents. Though there has been more limited analysis of the decision of how much natural disaster coverage to purchase, existing work suggests that homeowners are not price elastic on this margin; intensive-margin demand elasticities for flood insurance coverage are in the range of -0.01, with the small demand response arising through adjustments in contents coverage purchased rather than coverage for the structure itself (Wagner,

[8] In fact, the limited work estimating risk aversion parameters for homeowners' insurance suggests that risk aversion is higher than in more commonly studied insurance settings such as health or unemployment, and almost implausibly so, with coefficients of absolute risk aversion in the range of 1.7×10^{-3} instead of around 5×10^{-4} (Hendren, 2020; Snydor, 2010).

[9] A more extended set of papers based on panel regressions without quasi-experimental price variation or on simulation models estimate demand elasticities in the range of -0.49 to -0.06 (Browne and Hoyt, 2000; NRC, 2015; Kriesel and Landry, 2004).

2022a). Conditional on purchasing a flood insurance contract, for example, homeowners appear to fully insure their homes, rather than making a piecemeal decision to insure a fraction of the house's value. Indeed, total purchased coverage exceeds damages for almost all claims submitted to the NFIP, and in some instances also exceeds the value of the house (Collier and Ragin, 2020). This stylized fact justifies the treatment of natural disaster insurance contracts as full insurance contracts in empirical work even the homeowner could in theory decide sequentially whether to purchase insurance and then how much to buy. The relatively few purchasors of natural disaster insurance therefore seem to fully insure themselves against these risks. Next, we discuss candidate explanations for why demand for natural disaster insurance is so puzzlingly low.

3.2 Challenges and Policy Solutions

Homeowners' low levels of demand for natural disaster insurance are surprising because premiums underestimate the expected benefits of insurance in many of these markets. Natural disaster insurance premiums have increased much more slowly than natural disaster risk in the last fifty years, so that many policies are implicitly subsidized relatively to current actuarially fair levels; the current flood insurance subsidy is about 30% of payouts on average, for example (Wagner, 2022a). Many of these uninsured homeowners are in fact at risk of natural disasters. After Hurricane Harvey in 2017, for example, only approximately 20% of homeowners who experienced flooding were insured (Healy, 2018). This same pattern is evident in other markets after natural disasters: two-third of homeowners affected by the Tubb Fire in California in that same year did not have the supplementary wildfire coverage needed to rebuild their homes (Frazee, 2017).

There are many candidate explanations for low take-up of natural disaster insurance, some of which are economic and some of which are behavioral. Economic explanations for low observed demand allow that homeowners are rational, but that unobserved additional costs or benefits influence homeowners' decisions, leading to lower uptake than we might expect based on average payouts alone. Some examples in this setting that could decrease willingness to pay include private information about natural disaster risk (i.e., adverse selection), implicit insurance through government bailouts, limited liability due to low home equity, and credit constraints. Adverse selection is the textbook economic explanation for

inefficiently low demand for insurance; it arises when the lowest cost homeowners also have the lowest willingness to pay, so that average insurance costs increase when prices rise above the willingness to pay of the lowest cost individuals. The distinction between marginal and average costs in selection markets means that some homeowners choose not to purchase insurance because their private, marginal insurance costs are lower than the premiums set at average cost that they are charged. Prior work shows that adverse selection is an important driver of insurance purchase decisions in other markets, such as health, unemployment, and life insurance; Einav et al. (2021) reviews the implications of selection in these other markets in detail. Finkelstein et al. (2019) also provides evidence that public bailouts—a second economic explanation—contribute to low health insurance demand in some markets, where uninsured individuals do not in fact pay for their uninsured healthcare expenditures. In addition, there are several economic costs that could be excluded from measured average payouts, including search costs of acquiring information about true risk, hassle costs of obtaining risk assessments necessary to calculate natural disaster premiums, and information processing costs of understanding contract characteristics. Many of these costs exist in other insurance markets. For example, high search costs needed to learn about health insurance plan characteristics seem to discourage individuals from optimally choosing a contract (Abaluck and Gruber, 2011; Handel, 2013; Handel and Kolstad, 2015).

Behavioral explanations for low take-up include misperception of natural disaster risk, mistaken expectations about the likelihood of public bailouts, mistaken beliefs about included perils in homeowners insurance, cognitive dissonance in relation to the probability of climate change occuring, and inertia in purchase decisions, among others. Existing work shows that many of these frictions distort demand in other insurance markets. For example, consumers of health insurance are in some instances misinformed about both the benefits of health insurance and the treatments that it covers. Pauly and Blavin (2008) propose that some individuals may not understand the value provided by different plan characteristics, and make suboptimal insurance purchase decisions as a result of these mistakes, while Zhou-Richter et al. (2010) shows a similar pattern for long-term care insurance purchases. Bhargava et al. (2017) show that individuals often choose health insurance plans that are financially dominated, plausibly because they lack the competence required to translate premiums into relevant out-of-pocket costs. Papers that estimate search costs in health insurance markets also point to similar behavioral explanations, such as inertia and mistaken beliefs about the ways in which health insurance plans differ, as contributing factors

to the very high switching costs that these models find (e.g., Abaluck and Gruber, 2011; Handel, 2013; Handel and Kolstad, 2015). Handel and Schwartzstein (2018) review additional examples of behavioral mistakes in health insurance and other markets.

The distinction between these competing explanations is important because the existence of additional unmeasured economic costs that are excluded from average insurance payouts would mean that homeowners are making rational decisions when forgoing the purchase of natural disaster insurance; accounting for these additional costs borne by homeowners would explain why demand is puzzlingly low in these markets. By constrast, if individuals are making behavioral mistakes, then there is a role for policy to remove these frictions to allow homeowners to make more informed choices (Handel and Schwartzstein, 2018).

Existing work supports that both economic costs and behavioral frictions may contribute to low take-up for natural disaster insurance, though in ways that differ from other insurance types such as health and unemployment. Economic explanations for low take-up in other insurance settings appear to play a smaller role in natural disaster insurance markets, and alone seem unable to explain the extent of uninsurance in these markets. For example, while adverse selection is evident in many other insurance markets, private information in natural disaster insurance markets appears to be limited (Wagner, 2022a). Homeowners don't seem to have more information about their private natural disaster risk than insurers do, plausibly because most determinants of natural disaster risk are based on features of local geography and therefore in theory could be perfectly observed by both sides of the market.[10] In addition, the public bailouts that depress demand in some health insurance markets are much less important in natural disaster insurance markets. As mentioned above, Finkelstein et al. (2019) find that public payment of uninsured low-income individuals' medical bills can fully explain low uptake of insurance in low-income health insurance exchanges, but the analogous federal grants post-disaster are only about 0.03% of average flood insurance payouts during hurricanes; state grants are larger, but homeowners may obtain these funds regardless of whether or not they have purchased insurance, so we wouldn't expect these grants to distort willingness to pay for insurance (Horn, 2018). Search costs or hassle costs also seem unable to fully rationalize low willingness to pay because many homeowners purchase insurance for only one year (i.e.,

[10]Indeed, the development of more sophisticated risk models suggests if anything that we might expect insurers to have an information advantage relative to consumers.

in their first year of owning their home), and then fail to renew it. It then seems implausible that such unmeasured costs would explain low demand because these costs are highest in that first year of policy tenure, when regulators undertake an assessment of the structure to determine the premium that applies (NRC, 2015).

Credit constraints and limited liability may both play larger roles in natural disaster insurance markets than in other insurance markets, though both seem unlikely to be able to explain the extent of uninsurance. Low-income homeowners may indeed forgo flood insurance if they can't afford it; however, the average flood insurance premium is about 1% of median income in high-risk, high-amenity flood zones, which suggests the cost of flood insurance is not prohibitive for most homeowners (CBO, 2017). Limited liability may be comparatively more important in this setting because the insurable risk is to houses rather than people, though bankruptcy occasionally acts as implicit insurance for uninsured individuals in health insurance markets (Liao and Mulder, 2021; Mahoney, 2015). The intuition here is that homeowners with mortgages may in fact have relatively little capital at risk, and uninsured homeowners with little home equity could choose to default on their mortgages and avoid paying reconstruction costs in the event of a natural disaster. However, given that most homeowners have equity in their home at least equal to the average flood insurance payout due to their down payment, it seems somewhat unlikely that limited liability is the primary explanation for low takeup (Li and Goodman, 2016).

Behavioral explanations, such as misperception of risk and incomplete understanding of policy structure, also appear to play some role in natural disaster insurance markets. For example, a growing body of literature points to underestimation of natural disaster risk as a plausibly important explanation for low willingness to pay. This evidence is based both on direct surveys of homeowners' beliefs and on indirect hedonics analysis of house price responses to new information about natural disaster risk. Surveys of flood risk beliefs typically elicit risk probabilities that are lower than both the NFIP's conservative inundation model and the more sophisticated models of private companies (Bakkensen and Barrage, 2021; Royal and Walls, 2019). Hedonic regressions of house prices on natural disaster risk measures also suggest that realized floods or fires, or updated map information about areas at high-risk of these disasters provide novel information that homeowners use to update their priors on their risk (Gibson and Mullins, 2020; Hino and Burke, 2021; McCoy and Walsh, 2018). Gallagher (2014) also shows that homeowners respond to the direct experience of a flood by purchasing insurance the day after one occurs. Similar to the spike

in insurance demand after natural disasters, there is also typically a spike in litigation by homeowners who feel duped by flood or fire insurers about the terms of their contract and its benefits (Klein, 2018). This response suggests that homeowners' incomplete understanding of natural disaster coverage and exclusions from standard homeowners' insurance policies may bias demand downward. In addition, many of the other behavioral explanations for low take-up that exist in other insurance markets (e.g., inertia) have yet to be tested in these markets, and we view this line of inquiry as a fruitful direction for future work.

The nature of risk in natural disaster insurance markets suggests that behavioral frictions may potentially be more important in these markets than in more commonly studied insurance markets, such as health insurance. The large, infrequent, and spatially correlated natural disasters that complicate the calculation of actuarially fair premiums on the supply side also create difficulties for homeowners to assess their risk. The high costs and low probabilities involved may be more difficult for individuals to conceptualize than the comparatively larger probabilities of making a health insurance or automobile insurance claim, especially if a homeowner has never experienced a natural disaster directly. There is some evidence that individuals may round very small probabilities to zero, even if the highly unlikely event would result in a large negative income shock (Sunstein, 2002). Hence, if the probability of experiencing a natural disaster is perceived to be below some critical threshold, homeowners' willingness to pay could be quite low. The difficulty of collecting information on the probability of a natural disaster that is infrequently observed may also make it easier for homeowners to underestimate the probability of it ever occurring. Consistent with this interpretation, Gallagher (2014) shows that a Bayesian learning model, in which experiencing a flood provides new information about true flood risk and encourages homeowners to update their priors on flood risk probabilities, can explain observed insurance demand increases immediately after an event occurs.

The presence of behavioral mistakes is problematic because it means that homeowners' full benefit from insurance isn't reflected in their willingness to pay. Many of these frictions seem likely to bias willingness to pay downward: homeowners will undervalue natural disaster insurance if they underestimate their probability of experiencing a flood, a fire, or an earthquake, for example. Hence, at any given level of premiums, many homeowners may be uninsured who would actually benefit from insurance in expectation, and raising premiums can exacerbate the extent of inefficient underinsurance. Using this revealed

preference willingness to pay to evaluate the effects of proposed policies may lead to biased estimates of changes in social welfare. If these frictions are important in natural disaster insurance markets, then the ongoing phase-out of NFIP subsidies and wildfire insurers' regulatory filings requesting increases in premiums for wildfire coverage seems likely to lead to even lower levels of demand for insurance—even if premiums remain actuarially fair or better.

To encourage homeowners to purchase insurance, regulators could employ either allocative or mechanism policies (Handel and Schwartzstein, 2018). An allocation policy assigns consumers to specific options; mandating the purchase of natural disaster insurance would be one example. By constrast, mechanism policies typically target specific distortions, by encouraging uptake through the provision of accurate information to correctly align homeowners' beliefs with reality, for instance. The objective of both types of policies is to attain the efficient level of insurance coverage, where all homeowners who would benefit from insurance are covered. Mechanism-type policies typically require more information about the source of any distortion since these policies would target the removal of one or another specifically; allocation policies more bluntly require (or strongly suggest) that homeowners purchase a certain level of coverage, and so identifying the underlying source of the distortion is less important.[11]

Both allocation and mechanism policies are beginning to be more broadly employed to address the "coverage gap" in natural disaster insurance markets. The existing mandate for homeowners with federally-backed mortgages to purchase flood insurance is one example of an allocation policy. Mortgage lenders appear to be beginning to enforce this mandate more stringently than at any time since its inception in 1973 (Michel-Kerjan, 2010). New information-based mechanism policies are also being rolled out in many states. For example, the NFIP flood map updates that more accurately represent homeowners' risk and housing disclosure laws mandating the publishing of flood zone status for new transactions are two current policies that emphasize providing accurate information about flood risk to homeowners. The implementation of these policies changes house prices, suggesting that homeowners do in fact update their beliefs about their flood risk based on this new information (Hino and Burke, 2021; Lee, 2022). Another solution that is currently discussed is the auto-renewal of flood insurance policies, to avoid the decline in demand after the year that a house is purchased (Kousky et al., 2019). In wildfire insurance markets, basic coverage is already mandatory under the current market structure

[11] Handel and Schwartzstein (2018) review a wide range of policies employed in health insurance and other markets.

because most homeowners are required to carry standard multiperil policies to obtain a mortgage. In addition, ongoing improvements in climate risk models will also allow insurers to obtain more accurate information about homeowners' risk of natural disasters, and efforts to digitize many of these maps could improve homeowners' access to the information they need to make informed insurance purchase decisions (Weill, 2022).

4 Complementary Markets

Reforms to natural disaster insurance markets also have spillover effects in other complementary markets. In this section, we discuss how natural disaster insurance markets interact with housing markets, financial markets, construction decisions, and other public programs.

4.1 Real Estate Markets

The geographic nature of natural disaster risk creates a tight link between housing markets and natural disaster insurance markets. Natural disaster insurance contracts are house-specific, rather than individual-specific in the manner of health insurance, life insurance, automobile insurance, or most other insurance contract types. The nature of this risk means that natural disaster insurance premiums are one feature of houses that homeowners could conceivably consider when choosing between houses to purchase. If these insurance premiums rise, potential homeowners could find risky homes less appealing, and so increases in location-specific premiums could drive decreases in property values. As a result, local governments have an unusually high level of interest in natural disaster insurance market regulation because of the potential implications for their property tax base. Current estimates of homes exposed to serious flooding suggest that the number of Americans living in high-risk flood zones is almost 41 million—approximately 3 times as high as estimates based on NFIP flood maps—and so the potential house price effects of making flood insurance actuarially fair is a significant concern for many local governments throughout the country (Wing et al., 2018).

There is an extended literature showing that risk signals provided either through insurance premiums or through information policies do in fact affect house prices. The gradual phase-out of flood insurance

premium subsidies, for example, seems to have contributed to house price declines in risky areas that began to face higher, more accurate risk-based premiums; on-going premium increases seem likely to contribute to additional devaluation (Gibson and Mullins, 2020). Updating natural disaster risk maps also reduces prices for houses newly mapped into high-risk zones, for floods (Hino and Burke, 2021), fires (Garnache, 2020), and earthquakes (Singh, 2019); these effects also seems likely to persist as maps reflecting new climate change risk distributions are disseminated. Providing risk information through other means, such as a separate (dis)amenity listing on house sales profiles, has a similar effect as map updates (Lee, 2022). Other work finds that natural disaster events themselves reduce house prices for undamaged properties by up to 20% (Hallstrom and Smith, 2005; Kousky, 2010).

The price response to new information about risk provides further evidence that homeowners have an incomplete understanding of the extent to which they are exposed to natural disasters. If homeowners' priors accurately reflected their risk, then natural disaster map updates conceivably would not contain any new information and we would not expect a house price response. By contrast, Baldauf et al. (2020) show that increases in future inundation risk are differentially capitalized into house prices depending on whether homeowners report that they believe climate change is occuring. In addition, Bakkensen and Barrage (2021) provide direct survey evidence that homeowners who live in risky flood zones are more optimistic about flood risk than homeowners who live in low-risk flood zones—a pattern that is opposite to their true risk. One implication of these biased beliefs in their model is that natural disaster risks, such as coastal sea level rise, are incompletely capitalized into property markets, so that prices of at-risk houses are higher than they would be with accurate beliefs. Their estimates of the wedge created by unpriced climate risk suggest that houses in high-risk flood zones are over-valued by at least 13%. Mispricing of natural disaster risk in property markets isn't a new phenomenon; these markets have historically undercapitalized natural disaster risk since informative signals from changes in natural disaster insurance premiums and updates to maps were limited throughout much of the history of these markets; recent estimates suggest that homes in high-risk flood zones are over-valued by approximately $200 billion in aggregate (Gourevitch et al., 2023). However, the wedge between true value and market value of at-risk homes could plausibly increase as exposure to climate change risk increases.

Providing accurate signals about risk through natural disaster insurance premiums is one way to help correct the over-valuation of at-risk property. Charging homeowners actuarially fair insurance premiums

forces them to internalize true costs of living in risky areas; if these costs are high, then it may be efficient to incentivize homeowners to move out of harm's way. Panjwani (2022) estimates that both excluding flood risk premiums from mortgages and providing homeowners with funds to rebuild lead to inefficiently high levels of construction and density in high-risk flood zones; this paper estimates that a tax on homeowners equal to the median flood insurance premium would have reduced the number of New Jersey homeowners exposed to Hurricane Sandy in 2012 by 17%. Baylis and Boomhower (2023) show a similar phenomenon for public funding intended to prevent wildfires from destroying homes (i.e., before insurance claims are made); such funding provides an implicit subsidy exceeding 20% of the value of the homes in the areas at highest risk of wildfires in the Western U.S. However, despite the efficiency gains in property markets by providing accurate insurance price signals about true risk, increasing natural disaster insurance prices to be actuarially fair continues to be strongly opposed by both homeowners and local governments. In addition, in the presence of behavioral mistakes, implementing actuarially fair insurance prices can have unintended welfare costs, such as encouraging homeowners who underestimate their risk from purchasing insurance at higher prices (Wagner, 2022a). Correcting distortions in both insurance and real estate markets will require separate policies designed to address the distinct challenges in each of these related markets.

4.2 Financial Markets

The link between natural disaster insurance markets and financial markets complicates the functioning of these other markets, but also creates possible solutions for some of the supply-side challenges we identify in Section 2. While residential mortage lenders and residential real estate markets are both exposed to natural disaster risk through their location-specific products, lenders typically engage more frequently with property transactions than the typical homeowner, and thus may respond to changes in risk in different ways (Nguyen et al., 2022).

The challenges in financial markets arise because of the substantial uncertainty surrounding the costs of financing homeowners who might be exposed to natural disaster risk. The difficulties accurately pricing climate risk that complicate setting actuarially fair insurance premiums and allowing homeowners to learn about their risk also create pricing challenges for mortgages, for example. It is difficult to predict the

effects of climate change over the lifespan of a conventional thirty-year mortgage in the U.S., and this uncertainty is evident in banks' pricing decisions. Residential mortgage lenders do not price sea level rise exposure in a systematic way: they charge higher interest rates for thirty-year mortgages in areas that recently experienced a hurricane, but this premium declines over time and is attenuated in areas where fewer residents believe that climate change is occuring (Hurst et al., 2016; Nguyen et al., 2022). Consistent with other markets, financial institutions also have relatively limited ability to accurately predict how climate change will affect their products.

The uncertainty surrounding financing costs is greater for homeowners who are uninsured. Increasing risk of default or delinquency for uninsured homeowners experiencing large negative income shocks after natural disasters has led mortgage lenders to transfer climate risk to other agents in financial markets. Risk is transferred both back to uninsured homeowners and to securitizers of mortgages. Sastry (2022) shows that homeowners without flood insurance are required to make higher down payments than their insured counterparts; this higher equity at risk (i.e., lower loan-to-value ratio) reduces exposure of banks at the expense of homeowners with more natural disaster exposure. Ouazad and Kahn (2022) find a similar pattern of risk transfer upstream: lenders offload mortgage debt written in high-risk flood zones to government-sponsored enterprises (e.g., Fannie Mae and Freddie Mac) who do not price flood risk in their guarantee fees. Similar to the distribution of mortgage down payments, this risk transfer is smaller in areas where flood insurance is required. Higher flood insurance penetration rates would therefore alleviate some of the risk to homeowners and financial institutions by sharing risk with insurers.

Despite this pricing uncertainty, financial markets offer potential remedies to challenges in natural disaster insurance markets. Markets for reinsurance products and catastrophe bonds have both developed as possible solutions to insurers' insolvency risk resulting from highly spatially correlated, costly natural disasters. Reinsurance markets allow natural disaster insurance markets to make payments to designated reinsurance companies, such as Munich Re or Swiss Re, in exchange for idemnifying specific natural disaster losses; global reinsurers can therefore pool risk for many disasters across larger geographies than any federal or state-level natural disaster insurer (Kousky and Kunreuther, 2018). Similarly, catastrophe bonds pay investors (e.g., financial institutions) interest up to the point where a pre-specified disaster occurs, at which point at least some of the principle is transferred to the victims of that disaster. Such alternative financial instruments for transferring risk first became prevalent in the 1990s when traditional

reinsurance markets faced challenges in smoothing risk the same way some private natural disaster insurance markets did; the first catastrophe bonds were issued after Hurricane Andrew in Florida in 1992 bankrupted a dozen insurers due to insufficient supply of reinsurance. Both reinsurance markets and catastrophe bond markets have steadily increased in importance and market capitalization since then, with market for catastrophe bonds and other insurance-linked securities exceeding $100 billion today. These types of investments are increasingly popular with investors due to their relatively stable, high-single-digits returns and low correlation with shocks to other types of assets (Braun and Kousky, 2021; Ruoff, 2023). These markets seem likely to become even more important as climate change is predicted to drive demand for creative ways to reduce exposure to rising natural disaster risk (Michel-Kerjan, 2010).

4.3 Construction

Markets for in-place adaptation, such as resilient construction materials, interact with natural disaster insurance markets in two main ways. First, adaptation reduces natural disaster damages, and therefore lowers actuarially fair insurance premiums for houses that are better protected. Second, natural disaster insurance coverage discourages investment in adaptation capital.

Adaptation reduces pressure on natural disaster insurance markets by lowering expected payouts for more resilient houses. Compliance with stringent construction codes in high-risk flood or wildfire zones reduces insurance payouts and increases the probability of house survival. For example, elevating houses at high risk of flooding reduces insurance payouts by 30%, relative to those that are not elevated, with the highest benefits in the most catastrophic floods (Hovekamp and Wagner, 2023). Similarly, mandated minimum construction standards in wilderness areas in California increase the probability that houses will survive wildfires by 40%, and also have positive spillovers on neighboring houses by improving the likelihood that these houses also survive by 6% (Baylis and Boomhower, 2021). In both of these markets, this expected construction benefit is partially priced into insurance rates, so that homeowners who undertake defensive investments obtain a discount on insurance. Flood insurance sold by the NFIP is cheaper for houses that have elevated foundations, for example, though this discount does not fully offset the expected benefits of adaptation (Wagner, 2022a).

Despite this insurance discount, adaptation can also substitute for natural disaster insurance. Wagner

(2022a) finds that houses that are required to be elevated are 25% less likely to be insured against flooding than houses that are not required to be elevated. More generally, Fried (2022) finds that the provision of post-disaster payouts reduces adaptation capital by 5% in a model that includes multiple types of natural disasters. High natural disaster insurance subsidies may be at least partially responsible for this substitution: at-risk homeowners have limited incentive to incur private costs to reduce damages that are borne by insurers. For example, several surveys of homeowners in high-risk flood zones find that only 5 to 17% of respondants reported that they had taken any measures to fortify their homes (Michel-Kerjan, 2010). Risk-reducing investments are usually cost-effective when implemented during the course of construction, and so mandating more stringent adaptation at the onset may be an effective way to reduce the cost burden on insurers (Baylis and Boomhower, 2021).[12] However, the benefits of more resilient construction are not capitalized into house prices, and so adaptation is likely to be underprovided by private homeowners (Hovekamp and Wagner, 2023; Ostriker and Russo, 2022). Many of the reasons for low insurance take-up discussed above also help explain why homeowners may underinvest in defensive investments against natural disasters, including misperceptions of risk, cognitive dissonance, and myopia. In addition to encouraging insurance uptake, reducing this undercapitaliztion of the costs of natural disasters and the benefits of private risk-reducing investments into house prices is another reason to improve access to accurate natural disaster risk information.

4.4 Other Public Programs

Natural disaster insurance markets are one of a suite of programs that support homeowners after natural disasters. Insured homeowners receive insurance payouts after natural disasters occur, but other federal, state, and local programs also provide post-disaster bailouts, and these other public payouts may be tied to the purchase of natural disaster insurance. Collier and Kousky (2023) provide a detailed description of financing available to homeowners in the aftermath of natural disasters. The two main grants available to homeowners from the federal government are the Individuals and Households Program and the Small Business Administration Disaster Loan Program, both of which require flood insurance to be purchased as a condition of accepting public assistance after a flood. Receipts from these programs are typically

[12] Ostriker and Russo (2022) and Baylis and Boomhower (2021) show respectively that lower natural disaster insurance premiums and higher natural disaster insurance bailouts encourage construction in risky areas. Accurate signals about risk may therefore also help reduce the density of property in harm's way and, by extension, insurance payouts.

in the range of a few thousand dollars. Other post-disaster grants are administered by state and local governments, and would typically provide higher payouts to insured homeowners than their uninsured counterparts to encourage up-take (Horn, 2018). Deryugina (2018) shows that payments from social programs that are not directly related to natural disasters, such as unemployment insurance and public medical payouts, also increase in their aftermath. While this literature doesn't distinguish between insured and uninsured homeowners, it seems plausible that uninsured homeowners may rely on some form of government transfer from these other programs to recover from a natural disaster.

These other social programs may substitute for formal natural disaster insurance to some extent. As discussed in Section 3, the receipt of public bailouts from these other programs after natural disasters may depress natural disaster insurance demand. There is some evidence that receipts of individual assistance grants and small business administration loans lowers the intensive margin of flood insurance coverage after hurricanes, with no effect on the extensive margin of take-up (Kousky et al., 2018). While the magnitudes of the transfers from these programs seem too small individually to explain the extent of uninsurance, the cumulative role of these public payouts in explaining puzzlingly low take-up is an open empirical question.

5 Conclusion

This chapter surveys evidence of current challenges in natural disaster insurance markets, why these challenges arise, and what can be done to address them. We discuss how the infrequent, spatially correlated, and extreme events that characterizes natural disaster insurance markets complicate both the supply of and demand for natural disaster insurance, with spillovers to interrelated markets such as real estate. These distinguishing market features motivate a growing body of literature studying natural disaster insurance separately from other insurance types, such as health. A key theme throughout this chapter is that the behavior of insurers and homeowners in these markets may necessitate different policy solutions than other insurance markets.

Many of these current challenges discussed in this chapter stem from the historical design of natural disaster insurance markets and the policy choices made over the course of their half-century history. Natural disaster insurance markets, such as the NFIP, were not typically designed to weather the char-

acteristically rare and costly disasters that distinguish these markets, and were certainly not designed to account for the non-stationarity of the distribution of climate change risk. Initially subsidized and heavily regulated insurance premiums were introduced to accomplish take-up objectives under very different distributions of climate risk than those prevailing today, but difficulty changing the initial market structure coupled with rising costs of natural disasters have made it more challenging for insurers to operate in today's changing climate (Gaul, 2019). While this institutional lock-in has largely prevented previous attempts at natural disaster insurance reform, such as the Biggert-Waters Flood Insurance Reform Act of 2012, from accomplishing their objectives, the current rate of increase of costs in these markets suggests that on-going reforms will likely continue to ensure that public or private insurers can carry on offering natural disaster insurance in the U.S. We highlight here a few areas where we believe important work to advance this agenda remains to be done.

The current frontier in the insurance literature is incorporating behavioral mistakes into insurance markets. Theoretical models of insurance markets are beginning to emphasize the potential role of frictions such as biased beliefs, myopia, and inertia on demand, and to highlight the additional empirical quantities needed to estimate welfare in insurance markets in the presence of such frictions (Handel and Schwartzstein, 2018; Handel et al., 2019).Willingness to pay for natural disaster insurance may be more biased by these types of mistakes than in other insurance markets due to the additional challenges of learning about risk in a market with infrequently observed and extreme events. The resulting distortions in demand have important implications for the supply side of natural disaster insurance markets as well: private insurers cannot break even if homeowners are unwilling to pay even their own expected damage costs for insurance. These distortions also support implementing information-based policies that provide accurate signals to homeowners about their risk (e.g., modern risk maps), in addition to the current actuarially fair pricing reforms (Wagner, 2022a). Future research quantifying the contributions of different frictions to remarkably low willingness to pay for natural disaster insurance would help inform the implementation of policies designed to address them.

An additional open question is the extent to which these proposed policies may have inequitable effects across different populations in the U.S. The high and increasing costs of natural disasters mean that many of the solutions that are debated focus on the first-order problem of insuring continued access to insurance, and the incidence of premium changes on consumers and insurers. However, these effects

of these policies, and indeed the effects of climate change themselves, are distributed heterogeneously across the country. Low-income and minority homeowners tend to sort into higher risk neighborhoods because these houses are often cheaper even if their prices do not fully reflect underlying risk. Insurance premiums are also highest in these high-risk areas, and so low-income households are more exposed to higher natural disaster risk and higher insurance costs. The NFIP, for example, is typically considered a regressive program (Bin et al., 2012). Further, some evidence supports that although currently proposed premium reforms would increase overall welfare, these reforms would disproportionately burden low-income homeowners; by constrast, actuarially fair premiums in combination with federal transfers to low-income households could improve both equity and economic efficiency (Bakkensen and Ma, 2020; Kousky and Kunreuther, 2018). The effects of climate change seem likely to continue to increase annual natural disaster costs for the foreseeable future, and so the design of policies to minimize the burden on both homeowners and insurers will be an important area for future research.

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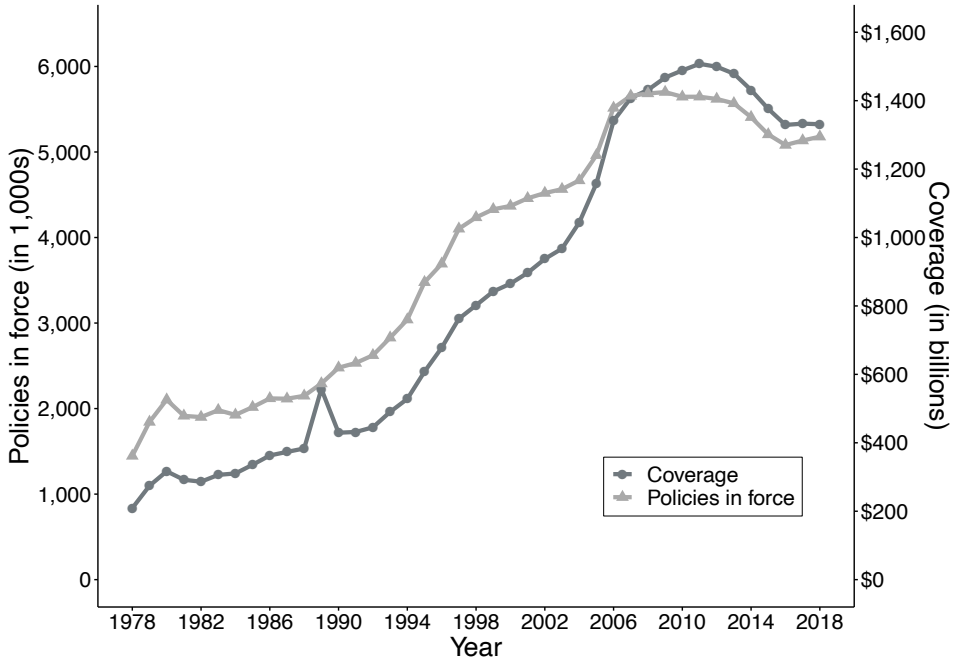
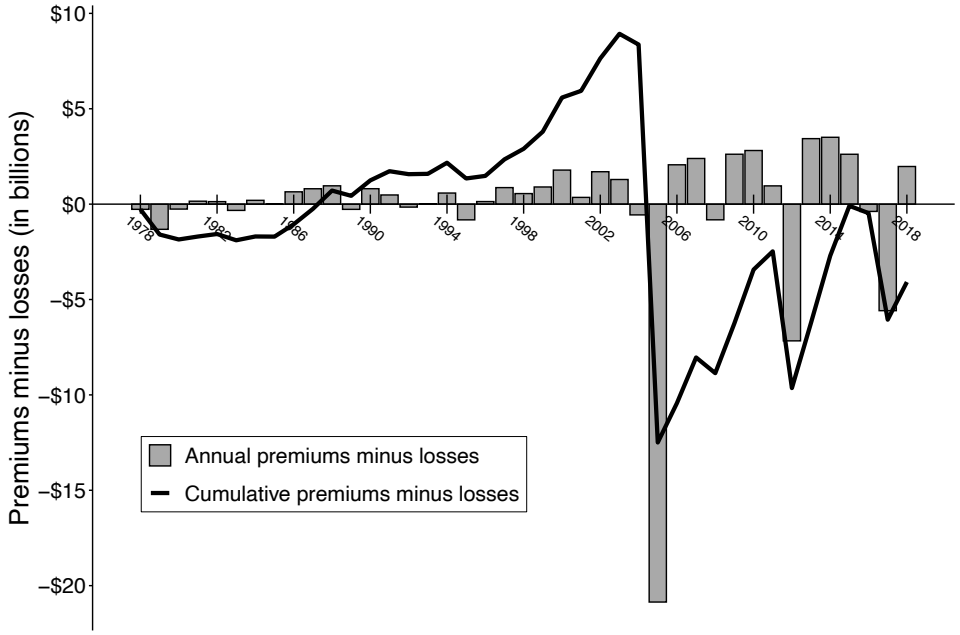
Figures and Tables

Figure 1: History of NFIP Policy Counts and Coverage



Notes: This figure shows the total number of policies sold and total dollar value of coverage written by the National Flood Insurance Program, for each year from 1978-2018. All dollar values are in 2018 USD. Data are from the Federal Emergency Management Agency.

Figure 2: History of NFIP Premiums and Losses



Notes: This figure shows the National Flood Insurance Program's annual premium shortfall or surplus. All dollar values are in 2018 USD. Data are from the Federal Emergency Management Agency.