Insure or Adapt? Household Balance Sheets and the Flood Risk Tradeoff

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Abstract

This paper studies how household balance sheets shape two key margins of climate-risk mitigation by homeowners: insuring and investing in adaptation. Using FEMA survey and NFIP administrative data, I show that floodproofing reduces realized damages and premiums, but insurance and adaptation respond to different financial margins. To interpret these patterns, I develop a dynamic heterogeneous-agent model with tenure choice, mortgage debt, public flood insurance, and lumpy adaptation investment. The model shows that insurance primarily protects liquidity-constrained households against short-run flood-state cash-flow risk, while adaptation is a wealth-protection investment chosen by households with sufficient equity and internal resources. This distinction implies that insurance and adaptation are not simple substitutes: raising premiums under risk-based pricing may reduce insurance coverage without inducing financially constrained households to adapt. The results highlight a central policy tradeoff for the NFIP: pricing flood risk accurately improves fiscal discipline, but without complementary support for adaptation finance, it may weaken household resilience precisely among those most exposed to balance-sheet constraints.

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1 Introduction

Flooding is the most costly natural disaster globally (Doocy et al., 2013; Razavi et al., 2020). In the United States flooding is estimated to cause between $179.8 to $496.0 billion dollars in damages annually (or 1-2% of 2023 GDP) (U.S. Congress Joint Economic Committee, 2024). Indeed, the distribution of people and assets across flood risk pose substantial economic risk in the US. As of 2017, 40.8 million people (13.3% of the population) are exposed to a 1-in-100 year fluvial (riverine) or pluvial (extreme rain) flood. This translates to a GDP exposure of $2.9 trillion[1] (15.3% of total GDP) or $5.5 trillion USD of infrastructure assets[2] (E. J. Wing et al., 2018). Notably, this does not include flooding from sea-level rise. With the shortfall in global carbon mitigation efforts, we can expect the physical impacts of climate change, and in particular flooding, to intensify.

Housing assets are of particular interest due to its physical immobility and hence inability to hedge against flood risk. That is, while housing can be bought and sold, it cannot be moved to a safer location. Focusing on the residential housing market, flood risk can have substantial implications on homeowner portfolios as housing is one of the largest assets making up their portfolio (Cocco et al., 2005). With real estate making up on average $\approx 40\% - 50\%$ of homeowner portfolios (Jones and Neelakantan, 2023). Naturally, flood risk will have substantial implications on homeowner balance sheets and welfare.

In responding to flood risk, homeowners have two options to reduce their risk exposure: (i) they may purchase flood insurance or (ii) they may invest in retrofitting their home to increase its structural resiliency against flooding (ie. basement floodproofing, elevating a house)[3], effectively *investing in adapting their housing asset*. I refer to these two options as insuring and investing in adaptation, respectively. These options differ across several dimensions. First, in purchasing flood insurance, homeowners are *transferring* this risk to the insurer. In contrast, by investing in adaptation homeowners effectively *reduce* their level of risk exposure[4]. Second, the cost structure of both options differ substantially: flood insurance requires recurring premium payments to the insurer to continue protection while adaptation require fixed lumpy investments and recurring maintenance costs. In this sense, insurance is a more flexible flood risk mitigation strategy while adaptation investment is irreversible. Lastly, flood insurance guarantees the household ex-ante the level of coverage they would receive should a flood occur. This contrasts flood adaptation, where the returns to the investment are only realized ex-post. Thus, agents who choose to adapt make an investment with uncertain returns. To limit the adverse effects of flooding on the residential real estate market, homeowners should be encouraged to invest in adaptation and *reduce* risk levels rather than transferring it to the insurer. However, recent data suggests that the proportion of households choosing to invest in adaptation are declining[5].

In this paper I argue that the underpricing of flood insurance premiums from the National Flood Insurance Program (NFIP) distorts homeowners incentives to insure and/or invest in adaptation and ask the question *how do income, asset holdings, and mortgage debt jointly shape households' decisions between insuring and adapting to flood risk in the United States?* In answer-

[1] GDP exposure is measured using the gross value-added at a 1-degree longitude/latitude resolution from the Global Gridded Geographically Based Economic dataset (G-Econ)

[2] Total value of assets are calculated using the National Structures Inventory estimated depreciated replacement value.

[3] See Figure 6, Figure 7 and Figure 8 for visual examples

[4] See Figure 9 for plot of depth-damage curve under different flood mitigation schemes.

[5] See Figure 10

ing this question, it will allow me to evaluate the effects of the NFIP's most recent pricing reform, Risk Rating 2.0, on welfare, insurance and adaptive investment uptake. I find that insurance uptake largely responds to liquidity strain and is predominantly used to smooth short-run liquidity risk in bad (flood) states. While adaptation investment uptake responds strongly to "skin in the game" or homeowners equity in their homes, subject to cost-feasibility constraints. Thus, insurance and adaptation respond to different incentives and margins of homeowner balance sheets. These results imply that raising insurance premiums under Risk Rating 2.0 will not raise aggregate adaptation investment and flood resilience, as raising premiums reduces available cash-on-hand and hence resources to invest in adaptation.

The remainder of this paper is organized as follows: in Section 2 of this paper I will provide institutional context of the NFIP and describing the market failure in question; in Section 3 I will provide a Literature Review and identify my contributions to the existing literature; in Section 4 I provide an Empirical Analysis, describing my data and stylized facts which motivate my modeling choices; in Section 5 I describe my model and define my equilibrium; in Section 6 I provide details of my calibration strategy; in Section 7 I describe my results; and in Section 8 I provide a conclusion.

2 Institutional Context: National Flood Insurance Program (NFIP)

The NFIP is a federally provided flood insurance program managed by the Federal Emergency Management Association (FEMA). As of 2018, the Program accounts for approximately 95 percent of all residential policies (Kousky et al., 2018). Specifically, there are 4.4 million residential policies in place, covering $1.168 trillion USD. The Program was enacted in 1968 in response to the unaffordability of private flood insurance or the lack of supply entirely in some regions. Due to the fat tail risk associated with flooding, private flood insurance premiums were deemed too expensive in the regions it was available. In response, the NFIP provided insurance with the mandate to (i) reduce the impact of flooding on private and public structures and (ii) provide *affordable* insurance to property owners. This affordability mandate manifested in the form of under-priced insurance premiums. While the Program is funded primarily by premiums, fees and surcharges paid by NFIP policyholders, the NFIP was not designed to handle the frequency and severity of storms and flooding experienced today. As a result, the Program's funding has been insufficient to pay its obligations and has borrowed upwards of $22 billion from the Treasury.

Flood insurance is not mandatory for all homeowners in the US, and is only required by homeowners residing in high risk flood zones (Special Flood Hazard Areas [SFHA's]) who have a federally-backed mortgage. However, the NFIP provides optional insurance to property owners, renters and businesses who live in a *NFIP community*. A community is defined as a local or state government that has agreed to adopt and implement local floodplain management regulations. The specific requirements of what these regulations entails depends on the type of flood hazard that FEMA has deemed that the community is exposed to[6]. However, such regulations may be included in zoning ordinances, building code, subdivision ordinances or "stand alone" floodplain management regulations. Of the 25,837 townships identified by FEMA, 22,740 are participating as a NFIP community, or $\approx$ 90.81% of townships [7] From Figure 11, we can see that almost all of the US have the *option* to participate

[6]See *Title 44 of the Code of Federal Regulations (44 CFR), Section 60.3*

[7]Figure 11 shows the spatial distribution of these participating communities.

in the NFIP. However, FEMA reports that only 4% of US household hold flood insurance, despite subsidized premiums.

Since the Program's inception, the pricing of these premiums have evolved substantially, though they have been subject to political economy-related constraints. Until the 1980's, the program used uniform pricing across the country which were set below actuarially fair levels. From the 1980's to the 2000's, the Program created Flood Insurance Rate Map's (FIRM's) and based the pricing of premiums based on which zones homes were located in, such that regions exposed to higher flood risk faced higher premiums. As the effects of climate change become more severe and the frequency of extreme weather events, in particular hurricanes, increased, the fiscal solvency of the program worsened. As of 2012, the Program had amassed over $17 billion in debt to the Treasury. This led to the Biggert-Waters Flood Insurance Reform Act (2012) (BW-12), which aimed to address this financial insolvency of the program by phasing out the use of FIRM's and move toward actuarially fair pricing of insurance. For many new premium transactions, subsidies were eliminated entirely, exposing buyers to full-risk premiums. Whereas existing premiums were scheduled to see annual increases of up to 25 percent per year until reaching full-risk rates.

However, the increase in NFIP rates saw substantial public backlash, and in 2014 Congress passed the Homeowner Flood Insurance Affordability Act (HFIAA), rolling back key provisions in BW-12 by restoring grandfathering of policies (ie. eliminated rate increases for existing policies) and refunding certain hikes. These policies highlighted this growing tension between the Program's fiscal sustainability versus affordability pressures. As a result of HFIAA (2014), holding risk levels fixed, NFIP premiums were still two to four times cheaper than private flood insurance, and as a result private flood insurance still could not compete after these pricing reforms (Fielding and Parsons, 2025). In 2021, FEMA again attempted to increase the fiscal solvency of the Program by introducing *Risk Rating 2.0*, where FEMA shifted to granular property-level pricing. Pricing under this regime used modern catastrophe models which factored in a property's distance to bodies of water, flood frequency and replacement costs. To date, this is the NFIP's largest pricing overhaul. The largest difference to BW-12 being the gradual transition in premium prices over time to actuarially sound levels. As demonstrated by Figure 12, all policies will not enforce full risk based pricing until 2070. A natural question which emerges from this policy change are the aggregate implications on insurance and adaptive investment uptake and distributional consequences of *who* changes their flood mitigation strategies and *how*. Under the assumption that insurance and adaptation are simple substitutes, we may reasonably conjecture that as premiums rise, homeowners will substitute towards adaptive investment. As I will demonstrate in this paper, the problem is more nuanced and understanding how homeowner balance sheets shape these margins of flood mitigation will have important implications on the effects of Risk Rating 2.0. In doing so, we are also able to quantify how NFIP's historical underpricing has distorted homeowners incentives to insure versus invest in adaptation.

3 Literature Review

This paper contributes to three main strands of literature: the macroeconomics of climate change and adaptation, the effects of climate risk on housing market outcomes, and the design of public flood insurance programs. Its central contribution is in integrating these strands within a dynamic heterogeneous-agent model where household balance sheets jointly shape insurance and adaptation decisions under flood risk.

A large macroeconomic literature studies the aggregate costs of climate change and optimal policy responses. Early work emphasizes mitigation policies that slow or reverse climate change through emissions pricing and regulation (Nordhaus, 1992, 1997; Golosov et al., 2014; Barrage, 2020; Barrage and Nordhaus, 2024). More recently, a growing literature focuses on adaptation as an additional margin through which economies respond to climate risk, particularly when mitigation is incomplete or delayed (Fried, 2021; Van Der Straten, 2023).

Most existing macro-adaptation models study adaptation at an aggregate or regional level and abstract from household balance sheets, housing finance, and credit constraints. As a result, they are ill-suited to analyze how adaptation incentives differ across households or how financial frictions shape adaptation choices. This paper contributes to this literature by introducing micro-founded heterogeneity in income, liquid assets, and mortgage debt, allowing adaptation to interact directly with household balance sheets. In addition, the model introduces underpriced public insurance as a policy distortion that alters adaptation incentives, a feature that is largely absent from existing macro-adaptation frameworks.

A related strand of literature studies how climate risk affects housing market outcomes. Empirical work shows that exposure to flood risk influences housing prices in the form of a price discount, transaction patterns, and household location decisions, often through capitalization, belief updating, and sorting mechanisms (Keys and Mulder, 2020; Baldauf et al., 2020; Bernstein et al., 2019). Complementary quantitative models study how climate risk and insurance interact with housing markets in equilibrium, highlighting the role of expectations and migration in influencing the distributional implications of climate risk in the US (Sun, 2025).

Taken together, this literature establishes housing as a central channel through which climate risk affects household welfare. However, most existing studies treat household responses to climate risk in reduced form or focus on extensive-margin adjustments such as migration, abstracting from endogenous mitigation behavior at the household level. In particular, private adaptation investments that reduce expected flood damages are typically absent or modeled implicitly. This paper fills this gap by endogenizing adaptation investment as a lumpy, durable household choice that directly affects the effective value of housing and interacts with insurance coverage and mortgage leverage.

Finally, this paper relates to the literature on public insurance provision and flood risk management, with particular emphasis on the US NFIP. Institutional and empirical work documents that the NFIP supplies nearly all residential flood insurance in the United States, but that coverage is incomplete and premiums are frequently set below actuarially fair levels due to affordability and political constraints (Kousky et al., 2018; Kousky, 2018; Wagner, 2022; Hennighausen et al., 2023). As a result, NFIP policies provide only partial protection against flood losses while simultaneously distorting price signals through subsidized premiums, contributing to cross-subsidization and persistent fiscal deficits.

Most existing models of flood insurance either abstract from household adaptation choices or treat insurance demand in isolation. In contrast, this paper studies insurance and adaptation as joint mitigation strategies chosen by households facing flood risk. By modeling insurance as a one-period contract that provides partial coverage at below-actuarially fair prices, the framework captures key institutional features of the NFIP and allows insurance affordability to distort incentives away from costly but resilience-enhancing adaptation investments. This interaction between insurance design, household balance sheets, and adaptation behavior is

central to understanding both individual welfare and aggregate flood resilience.

4 Empirical Analysis

4.1 Data

I use four datasets in my analysis: (i) the FEMA National Household Survey (FEMA NHS), (ii) FEMA's NFIP (Redacted) Policies dataset, (iii) FEMA's NFIP (Redacted) Claims dataset and (iv) the National Oceanic and Atmospheric Administration's (NOAA's) Storm Events dataset.

The NHS is an annual survey administered by FEMA via landline and mobile telephone over a random sample of approximately 5,000 adult respondents. The survey includes a nationally representative sample, as well as hazard-specific over-samples for earthquakes, floods, wildfires and specific urban events. The NHS collects information on American households personal disaster preparedness, dis-aggregating across a subset of human-driven and climatic disasters, flooding being one of them. Yearly survey data files are available from 2017-2023. Due to differences in survey questions and differences in the level of detailed information, I only use the 2021-2023 files for analysis. This is consistent with the timing of the latest NFIP pricing premium change to *Risk Rating 2.0*.

The FEMA NFIP (Redacted) Policies dataset is provided by FEMA and contains over 50 million NFIP flood insurance policy observations beginning in 2009 from the NFIP system of record. Each observation is a policy transaction which have been redacted to remove personally identifiable information and geographic information (latitude / longitude) is truncated to one decimal place. However, the flood zone the observation is in, ZIP and county code as well as NFIP community that the observation resides in are all contained in the dataset. Each observation includes detailed information on the policy coverage, premium cost as well as structural attributes of the house which is being insured, including the building type, occupancy, base flood elevation, number of floors in the insured building as well as a binary indicator for whether the property is flood-proofed or not. Flood-proofed in this dataset is defined as "any combination of structural and non-structural additions, changes, or adjustments to structures which reduce or eliminate flood damage to a property". Additionally, the Program requires a flood-proofing certificate prior to considering the flood-proofing measure in the insurance premium calculation. Thus, floodproofing in this dataset reflects a lower bound, as not all floodproofed homes that are insured may necessarily have this certification.

Similarly, the FEMA NFIP (Redacted) Claims dataset again uses the NFIP system of records and contains approximately 2.5 million NFIP flood insurance claims from 1970 onward. Each observation again corresponds to an individual claim. The same restrictions of anonymity are preserved as in the NFIP policies dataset described above. This dataset contains the same level of detailed information on the structural attributes of the property for which the claim is filed in addition to the payout on the building structure claim and the contents claim.

Lastly, to get a sense of the spatial distribution of flooding across the US, I use the NOAA Storm Events dataset[8]. This dataset collects information from the National Weather Service

[8]In future iterations of this paper, I aim to get access to the Fathom Global Flood Map dataset for a more accurate sense of the distribution of flood risk in the US

(NWS) and meteorological data to classify extreme weather events and includes observations from 1950 onward. Specifically, each observation is a extreme weather event and details the location (to the county level), duration (if applicable), intensity and other physical measurements such as the atmospheric pressure, wind field diameter, etc. Of all the extreme weather event types, I subset for all flood types: coastal flood, flash flood, flood, heavy rain and lakeshore flooding[9]. While the dataset includes storm events from 1950, flood events are not separately recorded until 1996 onwards.

4.2 Stylized Facts

Fact 1: Flood risk is widespread across the continental US and increasing

Table 6 displays summary statistics of NWS recorded flood events between 1996-2010 and 2011-2024. The moments described in the Table are at the state level. Thus, on average, a given state in the continental US experienced 264 floods between 2011 and 2024. There are three key insights from this table: (i) the number of flood events has increased between 1996-2010 and 2011-2024 from 72,834 to 107,538; (ii) flooding has increased on the *intensive margin* in that states that previously experienced floods now experience floods more frequently, and (iii) flooding has increased on the *extensive margin* in that the number of counties who experienced a flood has increased between the 1996-2010 period and the 2011-2024 period. This suggests in a 13 year period, almost every county in the US experienced a flood. While these aggregate measures likely mask spatial heterogeneity in the *intensity* of flooding, on the *extensive* margin, $\approx$ 97% of the continental US are exposed to at least one 1-13 year flood.

Fact 2: Homeowner-driven (private) adaptation is economically meaningful

Using the NFIP redacted premiums and policies dataset, in Tables 7 and 8 I document that homeowners with NFIP insurance policies experience on average a 14 percentage point lower share of damage relative to the property's value compared to otherwise similar non-floodproofed homes and have premiums approximately 26 percent lower on average compared to otherwise similar homes[10]. Thus, adaptive investments reduce *both* the physical destruction caused by flooding *and* financial exposure. These result confirms that floodproofing provides resilience benefits, consistent with the view that adaptation mitigates realized losses rather than transferring them, as insurance does. This is also in line with the depth damage curve from De Ruig et al (2019) in Figure 9. Moreover, these results confirm that the NFIP program rewards homeowners who floodproof and obtain a floodproof certificate through reduced premium prices. Thus, while it may be the convention to view these two margins of flood mitigation strategies as substitutes, there are financial incentives which reward complementarity in choosing both.

Fact 3: Joint adoption of insurance and adaptation uptake is limited, but the two are positively associated

Households exhibit substantial heterogeneity in how they manage flood risk. In Table 9 I disaggregate the proportion of households who only insure, only adapt, insure and adapt or neither insure nor adapt. A large proportion (43.26%) of households undertakes neither insurance nor adaptation, while only 16.31% of homeowners adopts both insurance and adaptation and 16.25%-24.17% take up only insurance and adaptation, respectively. Despite

[9] See Table 5. for definition of how each of these events are defined by the NWS.

[10] I measure relative damage severity in the data as $\frac{\text{buildingDamageAmount}_i}{\text{buildingPropertyValue}_i}$ for each property claim i

the relatively low rate of joint adoption, insurance and adaptation are not used as simple substitutes. Using survey-weighted logistic regressions of insurance take up on adaptation and of adaptation and insurance, controlling for household characteristics, I estimate the conditional correlations between the two decisions. Conditional on observable characteristics, the two choices are positively associated. Homeowners that have invested in adaptation have $\approx$ 72% higher odds of being insured, conditional on controls while insured households have $\approx$ 73% higher odds of adapting[11].

These patterns indicate that households do not choose between physical mitigation and financial protection along a single margin. Instead, they sort into broader risk-management behavior, where more risk-aware or better-prepared households are more likely to adopt multiple forms of protection. At the same time, the relatively low prevalence of joint adoption suggests that the two instruments are not universally adopted together, consistent with the presence of costs or constraints that limit take-up along each margin.

Fact 4: Insurance and adaptation respond to different financial margins but reduced-form evidence alone cannot disentangle the underlying mechanisms

Insurance and adaptation decisions exhibit systematically different relationships with household financial characteristics. In Table 11 I produce two survey-weighted logistic regressions of insurance and adaptation uptake on household balance sheet items, flood experience using state and year fixed effects. I find that insurance demand is strongly associated with monthly mortgage payments, while adaptation investment is largely insensitive to mortgage obligations and instead strongly correlated with measures of financial preparedness, including income and emergency savings. This divergence suggests that the two forms of risk management operate along distinct economic margins. Insurance, which involves relatively small and recurring payments, behaves as a liquidity-based instrument tied to short-run budget constraints. In contrast, adaptation requires lumpy, upfront expenditures and therefore depends on households' balance-sheet capacity and ability to finance fixed costs.

A central challenge, however, is that key observables, primarily monthly mortgage payments, do not cleanly map into these underlying mechanisms. Mortgage payments reflect a combination of interest obligations, amortization, and housing values, and therefore simultaneously capture both short-run cash-flow strain and longer-run balance sheet characteristics such as leverage and equity-exposure. This ambiguity gives rise to two competing interpretations. Under a liquidity interpretation, higher mortgage payments tighten households' budget constraints, increasing the value of insurance while reducing the feasibility of costly adaptation investments. Under a balance-sheet interpretation, mortgage payments may instead proxy for leverage and "skin in the game," in which case greater exposure to housing losses may strengthen incentives to invest in adaptation.

The empirical patterns are more consistent with the liquidity-based interpretation for insurance: mortgage payments are strongly associated with insurance take-up but exhibit little relationship with adaptation. At the same time, adaptation is strongly linked to financial preparedness rather than mortgage obligations. However, because mortgage payments mechanically bundle these underlying forces, the data alone cannot cleanly distinguish between liquidity constraints and balance-sheet incentives. To overcome these data challenges I use a dynamic heterogeneous agent model to decompose which of these two channels dominate (short-run liquidity strain and balance-sheet equity exposure channels) across insurance and

[11] See Table 10 for regression table.

adaptative investment uptake, and to quantify the aggregate and distributional implications of raising insurance premiums as in *Risk Rating 2.0*.

5 Model

Time is discrete and infinite. The economy is composed of three sectors: (i) heterogeneous households, (ii) perfectly competitive rental companies and (iii) the federal government.

Households are infinitely lived, but face a probability μ_D of death. Upon dying, they are replaced by new households who are renters with no assets. Households derive utility from consumption of a non-durable good as well as *effective* housing services. Each period, households can choose to rent or own a house. The quality, or size, of the house is fixed at a level h. However, in purchasing a house, homeowners are exposed to idiosyncratic flood risk[12] which in the event of flood shocks, reduces their level of housing. That is, flood events act as a depreciation shock to the level of housing services households consume. To counteract the impact of these flood shocks, households may purchase insurance from the federal government, or invest in adapting (or "retrofitting") their house[13]. By doing so, households dampen the depreciation shock of flood events, although they cannot completely insure or adapt themselves away from the shock entirely. I define ex-post flood adjusted housing level as *effective housing*. In this sense, flooding and the adaptation / insurance decision impacts households value function differently.

Notably, each household faces the same probability of a flood event occurring and the same severity (size) of the flood shock. In other words, this is a model of one region. In this sense, renting acts as a form of self-insurance in this model. In addition to idiosyncratic flood risk, households also face idiosyncratic income risk. Thus, households are heterogeneous across two dimensions: income and flood risk.

A continuum of perfectly competitive rental companies govern the supply rental housing to households. The total housing stock is fixed at $\bar{H}$. Thus, the rental companies implicitly govern the supply of owner-occupied housing in addition to the supply of rental housing since:

$$\bar{H} = H_t^{ho} + H_t^r$$

As a result, while the total housing stock is fixed, the proportion of owner-occupied and rental housing is endogenous. Housing depreciates at a rate of δ_h. To counteract depreciation and keep the level of total housing supply fixed, homeowners incur a maintenance cost equivalent to the depreciated portion of housing ($\delta_h \cdot q_h$, where q^h is the price or value of owner-occupied housing). The maintenance cost of rental housing is absorbed by the rental companies and is internalized in the rent price.

The supply of insurance is governed by the Federal Government, synonymous to the National Flood Insurance Program (NFIP) in the US. The Government supplies insurance, matching demand at the *below* "full risk" price levels. Insurance is thus funded solely from the premiums and set-up fees collected by insured homeowners. When the premiums and fees are insufficient to payout insurance claims, an exogenous Treasury lends to the Federal Government.

[12] Flooding is modelled idiosyncratically as opposed to aggregately, in line with Fried (2023)

[13] In line with basement floodproofing or elevating one's house

5.1 Households

Preferences

Households maximize lifetime expected utility over non-durable consumption (c_t) and effective housing services ($\tilde{h}_t$):

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\gamma c_t^{1-\sigma} + (1-\gamma)\tilde{h}_t^{1-\sigma}\right]^{\frac{1}{1-\sigma}}$$

Thus, agents have constant elasticity of substitution between goods, where σ reflects the coefficient of relative risk aversion and γ is the share parameter[14].

Effective housing is defined as:

$$\tilde{h}_t = f(D_t, A_t^h)h$$

Where h is the level or quality of housing and $f(D_t, A_t^h)$ is the *climate resilience factor*. This factor is a function of the stochastic flood shocks, D_t and the stock of homeowner adaptive capital investment, A_t^h, such that:

$$f(D_t, A_t^h) = 1 - \phi_1 \cdot D_t^{1-A_t^h}$$

Thus, the function is decreasing in D_t and increasing in A_t^h. This maps intuitively to how flood shocks and floodproofing measures (ie. flood adaptation investment) impacts housing: when a flood occurs (ie. $D_t > 0$), the house becomes damaged and depreciates. However, the level of depreciation, or extent of the shock, depends on how floodproofed a house is. For example, a house retrofitted with a floodproofed basement will incur less damage than a house without. In this sense, $f(D_t, A_t^h)$ satisfies $\frac{\partial^2 f(D_t, A_t^h)}{\partial D_t \partial A_t^h} > 0$. To capture the evidence that housing with the highest level of adaptation (ie. housing elevation) still incur damage[15], $f(D_t, A_t^h)$ satisfies $\frac{\partial^2 f(D_t, A_t^h)}{\partial {A_t^h}^2} < 0$. ϕ_1 captures the residual damage share under full adaptation[16].

Since housing quality, h is fixed across all households, homeowners choices influence effective housing services and hence their utility through the climate resilience factor: the more a household chooses to invest in adaptation, the less flood damage will negatively impact utility in the event of a flood. In this sense, it is an ex-ante measure of protection. Adaptation investment will not increase utility directly upon investment, but it rather dampens the impact of flood shocks. This is synonymous to how adaptative investment is modeled in Fried (2021). Renters are not exposed to flood damage and thus $\tilde{h} = h$ for renters.

Flood Shocks and Adaptation

The flood damage shocks, D_t, follow a simple Bernoulli distribution:

$$D_t = \begin{cases} 0, & \text{with probability } 1-\lambda \\ \xi, & \text{with probability } \lambda \end{cases}$$

[14] This utility specification is akin to Sun (2025)
[15] See Figure 9
[16] Derivation to demonstrate this can be found in the Appendix 10.8

Where ξ reflects the severity or size of the flood shock and λ reflects the probability of a flood occurring. I assume that $\xi > 1$ for $f(D_t, A_t^h)$ to be well-behaved[17]. By the law of large numbers, a fraction λ of homes experience a flood in t. A flood occurs at the beginning of the time period t. Thus, homeowners choices are made ex-post of the flood shock.

There are several choices households can make to reduce the impact of flood shocks: (i) they may invest in adaptation at a price $p^a(A^h)$, which improves their flow utility in the event of a flood and minimizes the extent of damage, (ii) they may purchase flood insurance from the NFIP at a price p_t^π or (iii) self-insure by becoming renters.

Adaptation investment is a homogeneous, lumpy good, which is modeled as a quality ladder, where there are discrete "rungs" of resilience that households can invest in. Let the set of adaptation levels be:

$$\mathcal{A} = \{0, A^{h,low}, A^{h,high}\}$$

where $a^h \in \mathcal{A}$ denotes the adaptation rung currently chosen by the household. A higher a^h corresponds to a greater resilience against flood shocks. There are three rungs of adaptive investment: (1) no investment ($a^h = 0$), (2) $A^{h,low}$, which corresponds to basement floodproofing (broadly) and (3) $A^{h,high}$, which corresponds to housing elevation, the most resilient form of retrofitting. Moving up the ladder requires a transition cost which depends on the current level of adaptive capital, $a^h \in \mathcal{A}$, and is represented by $p^a(a^h)$.

Adaptation evolves discretely over time. In each period, a household can:

- Upgrade to the next rung, by making a payment $p^a(a^h)$
- Maintain its current rung by paying a maintenance cost proportional to the depreciation of the adaptive capital, $\delta_a \cdot p^a(a^h)$, where $0 < \delta_a < 1$
- Downgrade by letting protection lapse. When no maintenance cost is paid nor the transition cost to upgrade up the ladder, homeowners move down one rung, resulting in lower resilience.

Investments are therefore lumpy and partially irreversible: households cannot sell back past investments, but may choose to forgo future maintenance. When a household sells or defaults, it is assumed that houses are depreciated to the baseline level of adaptation investment ($a^h = 0$), thus new entrants into homeownership begin at the baseline rung.

Lastly, I assume that adaptation investments are available at exogenously given costs. Households take these costs as given. I do not model the supply side of adaptation capital, rather I impose the assumption that $\frac{\partial p^a(a^h)}{\partial a^h} > 0$, such that the cost of adaptation is increasing in the size of the investment. This captures the heterogeneity in costs of floodproofing measures. Particularly in that more resilient floodproofing measures (ie. elevating a house) is more expensive than basement floodproofing.

Insurance

Households can purchase flood insurance (π_t) to transfer part of their flood risk to the government. Insurance contracts are one-period in length and are non-storable. At the beginning of period t, the household chooses whether or not to buy insurance at a premium price p^π, for period $t+1$. Therefore, the decision to purchase insurance is an extensive margin choice,

[17] See Appendix 10.9 for additional context

$\pi_t \in \{0, 1\}$. There is no intensive margin decision of insurance coverage. If in period $t + 1$ a flood does not occur, households receive no payout. If in period $t + 1$ a flood does occur, the household receives an indemnity equal to a portion κ of the realized damage. Where $\kappa \in (0, 1)$. Thus, insurance partially covers repair costs but does not eliminate them entirely. Reflecting the cap on the amount of coverage that the NFIP offers in reality.

When a flood occurs, the fraction of housing stock that is damaged for a given A_t^h is:

$$\phi_1 \xi^{1-A_t^h}$$

Thus, the realized damages in monetary terms is given by

$$\phi_1 \xi^{1-A_t^h} h q^h$$

If insured, the payout is

$$\text{Indemnity}_t = \kappa \cdot \phi_1 \xi^{1-A_t^h} h q^h$$

The remaining uninsured damages are then $(1 - \kappa) \cdot \phi_1 \xi^{1-A_t^h} h q^h$. Regardless of the level of adaptation investment or insurance uptake, households must repair the remaining damages in the event of a flood shock. If a household has insurance, this is equivalent to a payment of $(1 - \kappa) \cdot \phi_1 \xi^{1-A_t^h} h q^h$. If a household does not, this is equivalent to a payment of $\phi_1 \xi^{1-A_t^h} h q^h$.

From this formulation, the interactions between adaptation investment and insurance are clear: the higher the level of adaptation capital a household has, the lower the realized damages from climate shocks are. Therefore, higher levels of adaptation not only impact homeowners flow utility, but also loosen the budget constraint by reducing the realized damages that the household must repair. An implication of this is that it also reduces the insurance payout due to the lower damages. Since both damages and premiums are decreasing in the adaptation rung, insurance and adaptation act as joint risk-management tools: adaptation reduces the size of losses and insurance transfers part of the remaining losses to the insurer.

Income

Households receive stochastic labour income, y_t, each period. Income evolves according to the following AR(1) process

$$\ln(y_{t+1}) = \rho \ln(y_t) + \varepsilon_{t+1}$$

Where $\varepsilon_t \sim N(\mu, \sigma_\varepsilon^2)$. This formulation captures persistent idiosyncratic earnings risk. Since there is a continuum of households, aggregate labour income is non-stochastic, but individual income realizations shape household savings and risk-management choices.

Savings

Households can save in a one-period risk-free asset, a_t, at the risk-free rate r_t^f. Borrowing against future income is not permitted, so the only form of leverage in the model arises from mortgage borrowing at the time of home purchase.

Housing Tenureship

Households may choose to be renters ($s_t = r$) or homeowners ($s_t = ho$) in any given period. Only homeowners are exposed to flood risk. Thus to reiterate, renting is a form of self-insurance against flood risk. Every period, households choose their housing tenureship

for the next period, s_{t+1}.

Renters pay rent q_t^r every period to the rental companies in exchange for rental housing. Should a renter decide to become a homeowner, they must make a down payment equal to a fraction α of the house price q_t^h. The remainder is financed through mortgage borrowing from exogenously competitive lenders, generating an initial stock of debt. New homeowners enter period $t+1$ with no adaptive capital nor insurance. Beginning in $t+1$ they may choose to adapt or insure.

Homeowners hold an illiquid housing asset of value q_t^h. As homeowners, they make fixed mortgage payments m_t every period in addition to maintenance costs equivalent to the rate of housing depreciation, δ_h. In a given period, homeowners may choose to become renters starting the next period. Doing so involves transaction costs. Sellers must pay a fraction ψ_s of the selling price. If a household is unable to continue making mortgage payments, they may default on their loan. If they do so, they face a higher transaction cost, ψ_d such that $\psi_d > \psi_s$. In the event of default, the competitive lenders seize and sell the house, returning any positive amount from the sale, net of the outstanding mortgage and transaction costs, back to the defaulter. The defaulter enters the next period as a renter.

Default in my model is endogenous and equity-driven: it occurs when continuation under foreclosure weakly dominates both staying and selling. In practice, this condition coincides with negative home equity after transaction costs, consistent with the option-theoretic view of mortgage default. However, because households must also cover repairs and maintenance before selling, liquidity constraints can tilt the decision margin, making the mechanism closer to the hybrid strategic/liquidity default emphasized in the post-2008 literature (Campbell and Cocco, 2015; Guiso et al., 2013).

Mortgage Payments

To purchase a house of price q_t^h, a renter must pay a down payment of αq_t^h and must finance the remainder with a mortgage (M_t) from an external lender. A mortgage contract is defined as a tuple (M_0, r_t^b, ω). Where M_0 is the initial mortgage balance, r_t^b is the mortgage interest rate and ω is the amortization rate. Households take these mortgage contracts as given. The only assumption imposed is that $r_t^b > r_t^f$. That is, borrowing faces a larger interest rate than saving.

The initial mortgage balance is

$$M_0 = (1-\alpha)q_t^h$$

Or, the value of the house less the down payment. Each period the homeowner services the loan by paying interest at rate r_t^b and amortizing a fixed fraction $\omega \in (0, 1]$ of the current balance. Thus, the per-period payment, m_t, is

$$\begin{aligned} m_t &= r_t^b M_t + \omega M_t \\ &= (r_t^b + \omega) M_t \end{aligned}$$

and the balance evolves deterministically as

$$M_{t+1} = (1-\omega) M_t$$

Therefore, $\frac{1}{\omega}$ controls the effective duration of the mortgage.

Optimization Problem of Renters

Renters can either remain renters (rr), paying q_t^r and making consumption-savings decisions. Or, they can purchase a house (rh), making their standard consumption-savings choice but also incurring the cost of the down payment:

$$V(y, a, s = r) = \max \left(V^{rr}(y, a), V^{rh}(y, a) \right)$$

Where V^{rr} is the value function if the household decides to remain a renter and V^{rh} is the value function should a household choose to purchase a house. Recall that renters are not exposed to climate risk, therefore $\tilde{h} = h$. The value of a renter who decides to remain a renter is given by:

$$V^{rr}(y, a) = \max_{c, a' \geq 0} u(c, h) + \beta(1 - \mu_D) \sum_{y' \in Y} V(y', a', s' = r) \Pi(y'|y)$$

subject to

$$c + \frac{a'}{1 + r^f} + q^r h \leq y + a$$

Where Y is the set of all possible income realizations and $\Pi(y'|y)$ governs the transition probabilities between income levels. The value of a renter who decides to purchase a house is given by:

$$\begin{aligned} V^{rh}(y, a) = \max_{c, a' \geq 0} u(c, h) + \beta(1 - \mu_D) \sum_{y' \in Y} [\lambda V(y', a', D' = \xi, A^{h'} = 0, M' = \underline{M}, \pi' = 0, s' = ho) \\ + (1 - \lambda) V(y', a', D' = 0, A^{h'} = 0, M' = \underline{M}, \pi' = 0, s' = ho)] \Pi(y'|y) \end{aligned}$$

subject to

$$\begin{aligned} c + \frac{a'}{1 + r^f} + \alpha q^h h \leq y + a \\ \underline{M} = (1 - \alpha) q^h h \end{aligned}$$

New homeowners enter the next period with no adaptive capital nor insurance. Thus, should a climatic shock occur the next period, they must incur the entire damage cost. Home sellers and defaulters absorb the cost of a climatic shock should they choose to sell their house in a period where a flood occurs. Meaning they must repair their house in order to sell. As such, home buyers purchase a house at full quality $h = \tilde{h}$. Hence, the mortgage terms and down payment are defined using h

Optimization Problem for Homeowners

Homeowners can decide to remain as homeowners (hh), sell their house and become a renter (hr) or default (d). This decision governs their home tenureship starting in the next period.

$$V(y, a, D, A^h, M, \pi, s = ho) = \max \left\{ V^{hh}(y, a, D, A^h, M, \pi), V^{hr}(y, a, D, A^h, M, \pi), V^d(y, a, D, A^h, M, \pi) \right\}$$

The value function of homeowners who decide to remain homeowners (hh) is:

$$\begin{aligned} V^{hh}(y, a, D, A^h, M, \pi) = \max_{c, a', \pi', A^{h'}} u(c, \tilde{h}) + \beta(1 - \mu_D) \sum_{y' \in Y} [\lambda V(y', a', \xi, A^{h'}, M', \pi', s' = ho) \\ + (1 - \lambda) V(y', a', 0, A^{h'}, M', \pi', s' = ho)] \Pi(y'|y) \end{aligned}$$

subject to

$$c + \frac{a'}{1+r^f} + C^a(A^{h'}|A^h) + p^\pi \pi' + \phi_1 D^{1-A^h} hq^h + m + \delta_h q^h \leq y + a + \pi\kappa\phi_1 D^{1-A^h} hq^h$$

$$A^{h'} \in \{A^h_{i-1}, A^h_i, A^h_{i+1}\}$$

$$a' \geq 0$$

$$C^a(A^{h'}|A^h) = \begin{cases} \delta_a p^a(A^{h'}) & \text{if } A^{h'} = A^h_i \\ p^a(A^{h'}) & \text{if } A^{h'} = A^h_{i+1} \\ 0 & \text{if } A^{h'} = A^h_{i-1} \end{cases}$$

$$\pi' \in \{0, 1\}$$

$$m = (r^b + \omega)M$$

Let i denote the index for A^h in $\mathcal{A}$. Homeowners are restricted between upgrading to the next rung of adaptive capital in the next period (ie. $A^{h'} = A^h_{i+1}$), maintaining their current level of adaptive capital (ie. $A^{h'} = A^h_i$) or downgrading (ie. $A^{h'} = A^h_{i-1}$). If the homeowner is at the lowest rung of adaptive capital, then $A^h_i = A^h_{i-1}$ and so the homeowner must either maintain the current rung of adaptive capital or upgrade. Likewise, if the homeowner is at the highest rung of adaptive capital, then $A^h_i = A^h_{i+1}$, in which case the homeowner must either maintain the current level of adaptive capital or downgrade. Costs, $C^a(A^{h'}|A^h)$, are heterogeneous depending on the homeowners action, hence they depend on the current rung of adaptive capital (due to the indexing) and the future rung of adaptive capital. If a homeowner upgrades to a higher rung of adaptive capital, they pay the price $p^a(A^{h'})$. However, if a homeowner maintains the current level of capital, they only pay a maintenance cost proportional to the depreciation rate of adaptive capital, $\delta_a p^a(A^{h'})$. If a homeowner chooses to downgrade, then then face no cost. Thus, homeowners who decide to remain homeowners make climate risk-management choices jointly in their consumption-savings choice.

The problem of a homeowner who decides to become a renter (hr) is:

$$V^{hr}(y, a, D, A^h, M, \pi, s = ho) = \max_{c, a' \geq 0} u(c, \tilde{h}) + \beta(1 - \mu_D) \sum_{y' \in Y} [V(y', a', s' = r)]\Pi(y'|y)$$

subject to

$$c + \frac{a'}{1+r^f} + \phi_1 D^{1-A^h} hq^h + \delta_h q^h \leq y + a + (q^h \tilde{h}(1 - \psi_h) - M) + \pi\kappa\phi_1 D^{1-A^h} hq^h$$

In selling their home, homeowners must pay off their mortgage in order to rent again. Given they become renters beginning in the next period, the seller must still pay the maintenance cost in the current period.

The problem of the homeowner who defaults (d) is the same problem as a renter, but their house is seized and is sold on the market. Any positive amount is returned net of the outstanding mortgage.

$$V^d(y, a, s = ho) = \max_{c, a' \geq 0} u(c, \tilde{h}) + \beta(1 - \mu_D) \sum_{y' \in Y} [V(y', a', s' = r)]\Pi(y'|y)$$

subject to,

$$c + \frac{a'}{1+r^f} + \phi_1 D^{1-A^h} h + \delta_h q^h \leq y + a + \max(q^h \tilde{h}(1 - \psi_d) - M, 0) + \pi\kappa\phi_1 D^{1-A^h} h$$

5.2 Federal Government

The federal government is the sole provider of flood insurance, consistent with the National Flood Insurance Program (NFIP) in the US which provides $\approx 95\%$ of flood insurance (Kousky et al., 2018). Specifically, the government offers one-period flood insurance, paying out a fraction κ of the of the total damage, $\phi_1 D_t^{1-A_t^h} h$, in the event of a flood shock ($D_t = \xi$). To remain consistent with the NFIP, the government agent supplies insurance at a fraction $(1-\nu)$ *below* the actuarially fair, adaptation-adjusted premium price.

I follow the standard-deviation principle from actuarial risk theory (Buhlmann, 1970; Kaas et al., 2008) such that the government prices flood insurance at the discounted expected loss plus a risk loading proportional to the standard deviation of losses[18]. Because realized flood losses are highly volatile and require ex-post transfers from the Treasury when premium revenues are insufficient, premium pricing include a risk-loading term proportional to the standard deviation of losses, which captures the shadow cost of aggregate fiscal risk rather than private insurer risk aversion.

Thus, the formulation for p^π is given by[19]:

$$\begin{aligned} p^\pi &= \mathbb{E}[L] + \theta SD(L) \\ &= \frac{1-\nu}{1+r_t^f}\left(\lambda + \theta\sqrt{\lambda(1-\lambda)}\right)\kappa\phi_1\xi^{1-A_t^h}q^h \end{aligned}$$

Where L is the size of the loss and θ is the risk-loading parameter. To account for the setup fees that the NFIP charges upon new insurance policyholders, I also assign a cost π^{setup} that new insurance holders have to pay. Thus:

$$p^\pi = \begin{cases} \frac{1-\nu}{1+r_t^f}\left(\lambda + \theta\sqrt{\lambda(1-\lambda)}\right)\kappa\phi_1\xi^{1-A_t^h}q_t^h + \pi^{setup} & \text{if } \pi_t = 0 \\ \frac{1-\nu}{1+r_t^f}\left(\lambda + \theta\sqrt{\lambda(1-\lambda)}\right)\kappa\phi_1\xi^{1-A_t^h}q_t^h & \text{if } \pi_t = 1 \end{cases}$$

The objective of the federal government, consistent with the NFIP, is to provide affordable insurance. Thus, they do not face any optimality problem. The government gains revenue from the premiums they charge and incur costs in the form of the insurance payout for agents in the event of a climate shock. Thus, the program's profit evolves as follows:

$$R_{t+1} = R_t + \sum_{i\in\mathcal{I}} p_{i,t}^\pi - \sum_{i\in\mathcal{I}} \kappa\phi_1 D_t^{1-A_{i,t}^h} q_i^h$$

Where $\mathcal{I}$ is the measure of insured homes at time t[20].

[18] While this method is not commonly found in the macroeconomics literature, but remains a common method for actuarial premium calculation in the actuarial literature. Under expected utility theory, this standard deviation principle can also be viewed as a second-order Taylor approximation to the certainty equivalence of a risk-averse insurer with mean-variance preferences: $CE \approx \mathbb{E}[L] + \frac{1}{2}A \cdot Var(L)$, where L is the loss and A is the absolute risk aversion. Since $SD(L) = \sqrt{Var(L)}$, this principle is a simpler way of capturing a markup when A is constant. Actuaries often replace the variance by the standard deviation to make the markup scale invariant. This simplification still satisfies the desired monotonicity and homogeneity properties.

[19] See Appendix 10.10 for derivation of p^π

[20] In reality, when the NFIP cannot cover its expenses due to a large storm, it borrows from the treasury and incurs interest. I have not modeled interest accrual on net debt

5.3 Perfectly Competitive Rental Companies

Rental companies are perfectly competitive and risk neutral and set the proportion of rental housing every period[21]. At date t, a rental company enters with stock $(1-\delta_h)H^r_{t-1}$. It then chooses next period's stock H^r_t subject to an adjustment cost, $\frac{\eta}{2}q^h_t(H^r_t - H^r_{t-1})^2$ and receives rent net of per-unit maintenance, $(q^r_t - \chi)H^r_t$. By the law of large numbers, a fraction λH^r_t of rental properties experience a climatic shock and incurs damage costs of $\phi_1 \xi q^r_t$. Rental companies pay dividends of

$$x^r_t = q^h_t(1-\delta_h)H^r_{t-1} - q^h_t H^r_t - \frac{\eta}{2}q^h_t(H^r_t - H^r_{t-1})^2 + (q^r_t - \chi)H^r_t - \lambda H^r_t \phi_1 \xi q^r_t$$

to shareholders. Thus, the objective of the company is to maximize its total market value:

$$V^{rc}_t(H^r_{t-1}) = \max_{H^r_t} \frac{q^h_t(1-\delta)H^r_{t-1} - q^h_t H^r_t - \frac{\eta}{2}q^h_t(H^r_t - H^r_{t-1})^2 + (q^r_t - \chi)H^r_t + -\lambda H^r_t \phi_1 \xi q^r_t + V^{rc}_{t+1}(H^r_t)}{1 + r^f_t}$$

Taking the first order condition of the company's objective function gives rise to the rental price of housing as an expression of the price of owner-occupied housing and rental housing stock in periods $t-1$ t and $t+1$:

$$q^r_t(1 - \lambda\xi\phi_1) = \chi + q^h_t + \eta q^h_t(H^r_t - H^r_{t-1}) - \frac{(1-\delta_h)q^h_{t+1} + \eta q^h_t(H^r_{t+1} - H^r_t)}{1 + r^f_{t+1}}$$

This formulates the supply of rental housing. The demand for rental housing arises from the households choice, s.

5.4 Stationary Recursive Equilibrium

Given interest rates, (r^f, r^b), and a vector of adaptation investment prices $p^a(a) \forall a \in \mathcal{A}$, a *stationary recursive equilibrium* consists of time-invariant housing market prices $\{q^h, q^r\}$, time invariant insurance premium $\{p^\pi\}$ value and policy functions for renters, $\{V, c, a', s'\}$, value and policy functions for homeowners $\{V, c, a', s', \pi', A^{h'}\}$, value and the policy function for rental companies, $\{V^{rc}, H^r\}$ and a joint stationary distribution $\mu(y, a, s, D, A^h, M, \pi)$[22] such that:

1. Given prices $(q^h, q^r, p^a(a), p^\pi)$ and interest rates (r^f, r^b), the renters and homeowners policy functions solve their value functions
2. Taking prices as given, the rental companies policy function solves their value function.
3. μ is invariant under the households policy functions and exogenous shocks:

$$\mu = \mathcal{T}(\mu; q^h, q^r)$$

4. The housing market clears:

$$H^{s,r} = H^{d,r}$$
$$H^{d,ho} + H^{d,r} = \bar{H}$$

Where $H^{d,r} = \int [s'(\Theta) = r] d\mu(\Theta)$

[21] The rental companies are modeled synonymously to the rental companies in (Arslan et al., 2024)

[22] Henceforth I denote the set of states $(y, a, s, D, A^h, M, \pi) = \Theta$

5. Rental price consistency: the rental price satisfies the steady-state user-cost relation[23]:

$$q^r = \frac{\chi + \frac{r^f + \delta_h}{1+r^f} q^h}{1 - \lambda \xi \phi_1}$$

6. Flood insurance is *below* actuarially fair, with premium price:

$$p^{\pi}(A^h, \pi) = \begin{cases} \frac{1-\nu}{1+r^f} \left(\lambda + \theta \sqrt{\lambda(1-\lambda)} \right) \kappa \phi_1 \xi^{1-A^h} q^h + \pi^{setup} & \text{if } \pi = 0 \\ \frac{1-\nu}{1+r^f} \left(\lambda + \theta \sqrt{\lambda(1-\lambda)} \right) \kappa \phi_1 \xi^{1-A^h} q^h & \text{if } \pi = 1 \end{cases}$$

6 Calibration

A model period t is one year. Table 1 presents the internally and externally calibrated parameters. I normalize the model by annual household income, so that house prices, mortgage payments, insurance premiums, and adaptation costs are measured relative to income[24].

I approximate the AR(1) income process using the Rouwenhorst method with five income levels. Consistent with Arslan et al. (2024), I set $\rho = 0.92$ and $\sigma_\varepsilon = 0.31$, values that are standard in the heterogeneous-agent macro literature and discipline idiosyncratic labor income risk to match the persistence and dispersion observed in U.S. micro data. The unconditional mean of income is normalized to $1 - \rho = 0.08$

I set the probability of climate shocks, λ, to 0.1, to capture 1-10 year floods. The intention of this research is *not* to capture infrequent, large floods, in which FEMA provides emergency disaster funding to households. As Fried (2021) concludes, this introduces an additional substantial moral hazard problem. To abstract away from this, and to capture the aggregate impact of higher frequency smaller floods, I set $\lambda = 0.1$. To discipline my model, I use NFIP microdata to calibrate the other two key climate-related parameters: the residual damage fraction with full adaptation (ϕ_1) and the flood shock severity multiplier (ξ)[25].

I normalize the total stock of housing $\bar{H} = 1$. Thus, H^{ho} and H^r can be naturally interpreted as the share of owner-occupied housing and the share of rental housing. The depreciation rate of housing, δ_h, is set to 5% per year (ie. $\delta_h = 0.05$). This is consistent with Arslan et al. (2024). The transaction costs from selling or foreclosing a house, ψ_h and ψ_e, are set to 7% and 25% of the sale value of the house, respectively. These values are consistent with Arslan et al. (2024). I set the down payment proportion, α equal to the conventional amount of 20% (ie. $\alpha = 0.2$). I calibrate the model assuming a 30-year mortgage term, implying that ω is set to $\frac{1}{30}$.

The adaptive capital market is set entirely externally to the economy. I define $\mathcal{A} = \{0, A^{h,low}, A^{h,high}\} = \{0, 0.2, 0.6\}$. The prices are respectively set to $p^a(A^h) = \{0.0, 0.5, 1.5\}$. These values are set abstractly.

Lastly, I use NFIP microdata to calibrate the insurance-related parameter: the NFIP payout share / coverage (κ)[26].

[23] See Appendix 10.11 for derivation of the rental price
[24] See Appendix 10.12 for the Steady State Algorithm
[25] See Appendix 10.13 for details on the calculation
[26] See Appendix 10.14 for details on this calculation

Model Parameters			
Parameter	**Description**	**Value**	**Note**
	Set Externally		
σ	Relative Risk Aversion	2	
β	Discount factor	0.95	
γ	Share parameter	0.8	Sun (2025)
ρ	Persistence for AR(1) for y_t	0.92	Arslan et al. (2024)
σ_ε	SD of error for y_t	0.31	Arslan et al. (2024)
μ	Mean of error for y_t	0	
λ	Probability of Climate shock	0.10	1-10 year flood
ϕ_1	Climate Damage Scaler	0.1153	NFIP Claims Dataset (1982-2024)
ξ	Size of Damage Shock	2.59	NFIP Claims Dataset (1982-2024)
$\bar{H}$	Total Stock of Housing	1	
α	Down Payment Proportion	0.2	20% down payment
ω	Duration of mortgage	$\frac{1}{30}$	30-year mortgage
δ_h	Housing Capital Depreciation (Maintenance)	0.05	Arslan et al. (2024)
ψ_h	House Sale Transaction Cost	0.07	Arslan et al. (2024)
ψ_e	Foreclosure Transaction Cost	0.25	Arslan et al. (2024)
κ	Insurance Payout Share	0.5622	NFIP Claims Dataset (1982-2024)
ν	Insurance Price Distortion	0.2	
μ_D	Probability of Death	0.015	
	Set Internally		
δ_a	Adaptive Capital Depreciation (Maintenance)	0.04	
θ	Risk-loading Parameter	0.13	
π^{setup}	Insurance Setup Fees and Surcharges	0.03	
χ	Rental Companies Maintenance Cost	0.05	

Table 1: Parameters (externally set and internally calibrated)

Parameter	**Description**	**Value**	**Note**
	Set Externally		
r^f	Risk-free interest rate	0.04	US Treasury (2024)
r^b	Risky interest rate	0.067	FHFA (2023)
p^c	Price of consumption	1 (Numeraire)	
$[p^{a,low}, p^{a,high}]$	Price of adaptation	$[0.0, 0.5, 1.5]$	
	Set Internally		
p^π	Price of insurance	-	See above. Below Actuarially Fair Pricing:
q^h	Price of Owner-Occupied Housing	5.04	Jointly determined with q^r via market clearing
q^r	Price of Rental Housing	0.464	Jointly determined with q^h via market clearing

Table 2: Prices

7 Results

This section presents the main quantitative results of the model and decomposes how different dimensions of household balance sheets, primarily short-run liquidity strain and equity exposure, generate distinct incentives for insurance and adaptation, leading to heterogeneous mitigation behavior across households. To decompose whether insurance and/or adaptation are responding to cash-flow strain and/or equity exposure, I use and define the beginning-of-period cash on hand $(y + a)$ and the loan-to-value (LTV) ratio $(\frac{M}{q^h})$. Using these model-generated variables, I evaluate the distribution of insurance and adaptation investment uptake and place my quantitative results in a regression framework to estimate the marginal effects. Table 3 below contains a table of my targeted moments[27].

Statistic	Data	Model	Note
Homeownership rate	65%	57.34%	Data: FRED (Q2 2025)
Share of Flood Insured Homeowners	32.79%	30.95%	Data: FEMA NHS (2021-2023)
Share of Homeowners w/ Mortgage	36%	35.54%	Data: FRED (2023)
Share of Floodproofed Homeowners	40.10%	54.46%	Data: FEMA NHS (2021-2023)

Table 3: Targeted Moments

7.1 Liquidity Strain vs. Equity Exposure Channel Decomposition

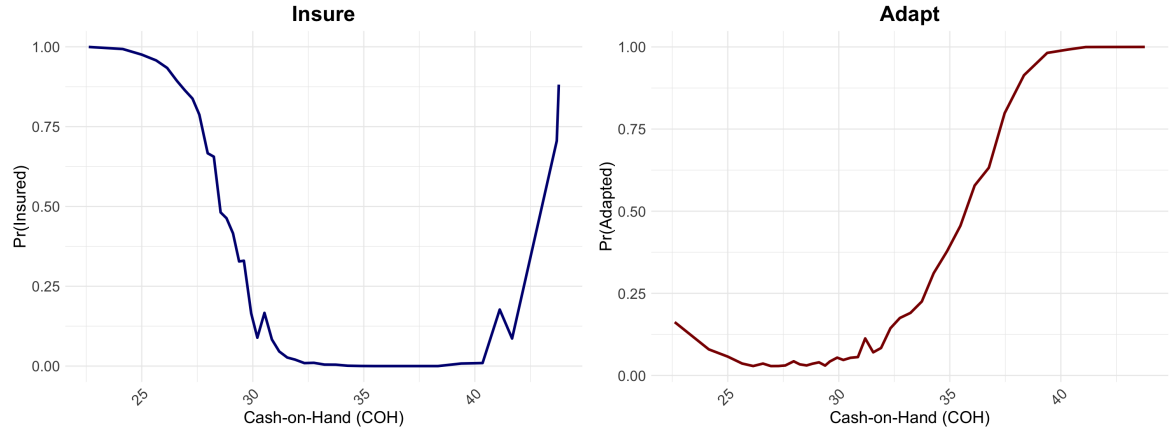


Figure 1: Distribution of Households Who Insure (Left) or Adapt (Right) Across Cash-on-Hand

First, in Figure 1 I plot how insurance and adaptive investment uptake are distributed across the cash-on-hand distribution to evaluate how liquidity strain influences flood mitigation behaviour. Insurance demand is non-monotonic in COH. At low levels of liquidity, households exhibit high insurance uptake, as insurance provides protection against short-run consumption risk following a flood shock. As COH increases, insurance demand declines, reflecting a reduced need for liquidity smoothing. However, at sufficiently high levels of COH, insurance demand rises again, as households use insurance to protect high-value housing assets. In contrast, adaptation increases monotonically with COH. Since adaptation requires

[27] Calibration and targeted moments are currently a work in progress.

a lumpy upfront investment, it is only feasible for households with sufficient internal resources. Wealthier households are therefore more likely to invest in adaptation in order to reduce expected damages. These results imply that liquidity constraints are a key determinant of adaptation, while insurance primarily serves as a tool for managing short-run financial risk. Taken together, these findings indicate that insurance and adaptation do not operate along a common liquidity margin. Instead, they perform distinct roles: insurance smooths consumption in adverse states, while adaptation reduces exposure to those states ex ante.

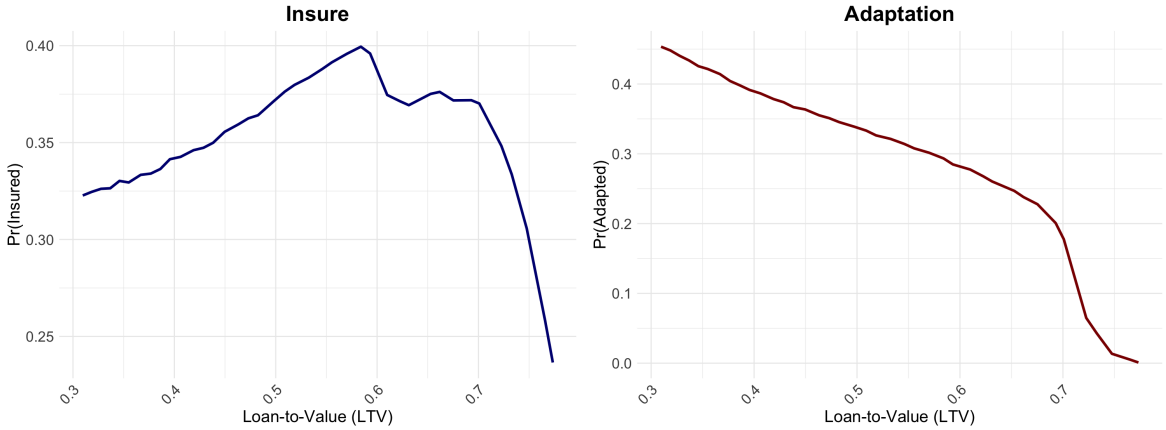


Figure 2: Distribution of Households Who Insure (Left) or Adapt (Right) Across LTV

Next, to evaluate how these flood mitigation strategies respond to equity exposure, I plot how insurance and adaptive investment uptake are distributed across the LTV distribution in Figure 2. The model also delivers distinct predictions with respect to equity exposure, or leverage. Insurance demand is again non-monotonic in leverage. At intermediate levels of leverage, insurance demand is relatively high, reflecting both exposure to housing risk and limited ability to self-insure. However, as households accumulate equity (i.e., as LTV declines), insurance demand falls, as households substitute toward adaptation. Adaptation, by contrast, increases strongly with equity. As households build equity, a larger share of housing wealth is at risk in the event of a flood. This generates a "skin in the game" effect: lower leverage increases the incentive to protect the asset through adaptation. At high levels of leverage, adaptation is limited both by weak incentives and by constrained financial capacity. These results imply that adaptation is fundamentally a wealth-protection investment, while insurance primarily addresses short-run exposure.

To evaluate the joint distribution of liquidity strain and equity exposure, I produce heatmaps of insurance uptake and adaptation investment uptake across the cash-on-hand and LTV deciles in Figure 3. Examining Figure 3 reveals substantial heterogeneity in mitigation behavior. Households sort into different strategies depending on their balance sheet position. Insurance is concentrated among households that are financially fragile, particularly those with low liquidity but not extremely high leverage. These households face high exposure to short-run income shocks and rely on insurance to stabilize consumption. In contrast, adaptation is concentrated among households with both high liquidity and low leverage, who have the resources and incentives to protect their housing wealth. This sorting implies that insurance and adaptation are not simple substitutes. Instead, they are chosen along different financial margins, and aggregate behavior reflects the composition of households across these dimensions.

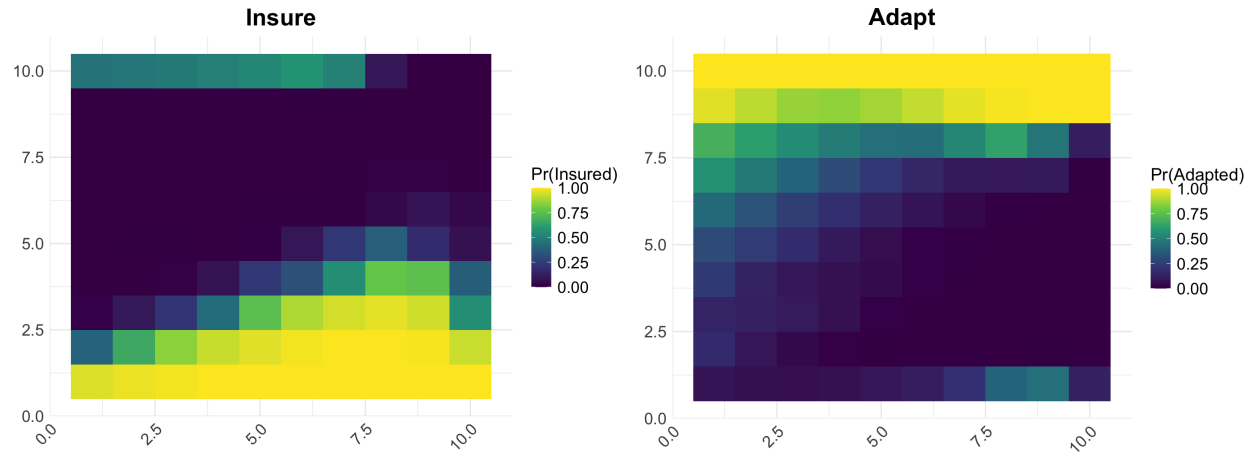


Figure 3: Joint Distribution of Households Who Insure (Left) or Adapt (Right) Across COH and LTV

Lastly, to quantify the mechanisms driving insurance and adaptation choices, I estimate a reduced-form regression on simulated data generated by the model. The objective is to isolate how liquidity constraints and leverage jointly shape mitigation behavior, and to provide a direct mapping between the model's internal state variables that is empirically undetectable due to the monthly mortgage payment variable mixing liquidity strain and balance sheet items. However, rather than using the beginning-of-period cash-on-hand, I use the share of cash-on-hand devoted to mortgage payments, defined as $COH_PS_i = \frac{m_i}{COH_i}$. The regression is estimated on the stationary distribution of households obtained from the model simulation. Specifically, the specification I run is:

$$P_x = \Lambda(\beta_0 + \beta_1 LTV + \beta_2 COH_PS + \beta_3 COH_PS \times LTV), \qquad x \in \{\text{Insure}, \text{Adapt}\}$$

The average marginal effects generated from the model can be found in Table 4. The estimated average marginal effects reveal two distinct channels. First, leverage reduces insurance uptake but increases adaptation. Holding liquidity constant, higher LTV corresponds to lower effective equity exposure, reducing the incentive to protect housing wealth through adaptation. Conversely, as households accumulate equity, they shift away from insurance and toward adaptation, consistent with a "skin in the game" mechanism. Second, liquidity strain increases insurance uptake but reduces adaptation. Households with a high mortgage payment burden relative to available resources face elevated short-run consumption risk in the event of a flood. As a result, they rely more heavily on insurance as a form of liquidity smoothing. At the same time, these households are less able to finance the upfront costs of adaptation, leading to lower adaptation investment.

	Insure	Adapt
LTV	-3.22***	2.34***
	(0.002)	(0.002)
COH_PS	1.99***	-1.91***
	(0.0009)	(0.0005)

Notes: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 4: Average Marginal Effects

To study the interaction effects, I plot the 25th ("low") and 75th ("high") percentiles of the predicted conditional probabilities to insure and adapt in Figure 4. The interaction between leverage and liquidity strain reveals that the effect of balance sheet composition is

state-dependent. At low levels of liquidity strain, mitigation decisions respond strongly to leverage, with households adjusting behavior based on their exposure to housing wealth. However, as liquidity strain increases, this relationship weakens substantially. In the region of high cash-flow pressure, insurance uptake becomes largely insensitive to leverage, indicating that households prioritize short-run solvency concerns over balance sheet composition. This is evident in the predicted probability plots, where differences across leverage states collapse at high levels of COH payment share. This pattern implies that liquidity constraints effectively dominate decision-making in financially stressed regions of the state space, shutting down the leverage channel. In contrast, when households are unconstrained, both liquidity and leverage jointly shape behavior. These results provide direct evidence that insurance primarily responds to cash-flow risk, while the role of leverage is conditional on the absence of binding liquidity constraints.

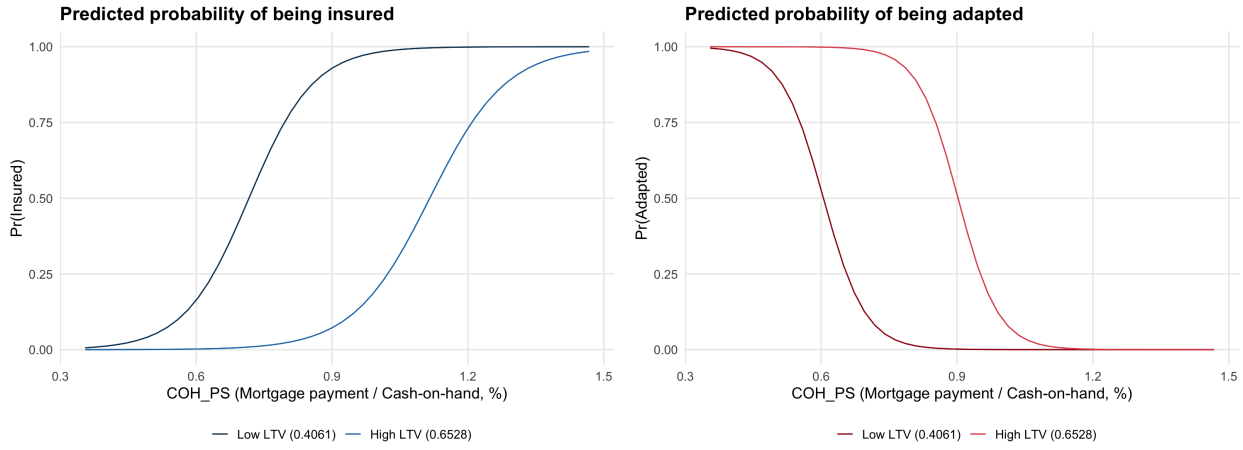


Figure 4: Conditional Predicted Probabilities of Insuring and Adapting

7.2 Insurance and Adaptive Investment: Complements or Substitutes

To quantify whether insurance and adaptive investment act as complements or as substitutes within the homeowners problem. In my model, insurance operates as an *ex-post* transfer mechanism in that when a shock occurs, the insured homeowner receives a payout proportional to the loss, smoothing consumption and preserving liquidity. In that sense, insurance mitigates income risk after damages occur. In contrast, adaptive investment acts as an *ex-ante* mitigation measure. By improving floodproofing (ie. by investing in adaptation), adaptation directly increases the resilience of the housing asset and reduces the expected physical loss in a future shock. Thus, adaptive investment mitigates exposure risk in that it lowers the conditional loss probability and limits the fraction of hosing that must be repaired following a shock. Since the two instruments address different parts of the risk process (ie. one reduces the loss itself and other transfers the financial consequences of the loss), their interaction is theoretically ambiguous. This ambiguity is muddled further since insurance premiums are declining with adaptive investment, adding a dimension of complementarity to the two flood mitigation measures. Thus, adaptation may make insurance less valuable if it already prevents losses (ie. making them substituonary), but it may also make insurance more valuable given the lower premiums faced (ie. making them complementary).

To assess whether they are complementary or substituonary, I compute a supermodularity index based on the model's value function. Following Topkis (1978) and Milgrom and Shannon (1994), two instruments are Edgeworth complements if the value function $V^*(\pi, A^h; x)$

exhibits increasing differences in π and A^h:

$$\frac{\partial^2 V^*(\pi, A^h; x)}{\partial \pi \partial A^h} > 0$$

where x denotes the other state variables. I approximate this cross-partial on the discrete states as:

$$\begin{aligned} SM(x) =& [V^*(\pi = 1, A^h = 0.6; x) - V^*(\pi = 0, A^h = 0.6; x)] \\ & - [V^*(\pi = 1, A^h = 0.2; x) - V^*(\pi = 0, A^h = 0.2; x)] \end{aligned} \tag{1}$$

This difference measures how the value of insurance changes as adaptation rises[28] If $SM(x) > 0$, then adaptative investment increases the marginal value of insurance, meaning they are complements. If $SM(x) < 0$, then adaptation decreases the marginal value of insurance, meaning they are substitutes. If $SM(x) \approx 0$, adaptation has little influence on the value of insurance, meaning they behave independently. Thus, (6) captures the structural interaction between ex-ante adaptation and ex-post risk transfer via insurance.

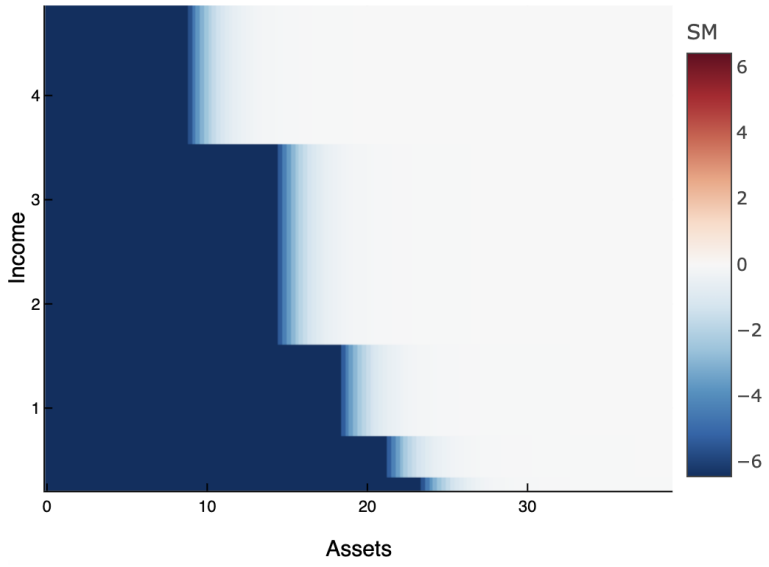


Figure 5: $SM(x)$ across the income and asset grids

In Figure 5 I plot the value of (6) across the income and asset gridso characterize how the interaction between insurance and adaptation varies over the household balance sheet. The results indicate that the relationship between the two instruments is state-dependent and governed by liquidity constraints. In regions of low income and low asset holdings, the supermodularity index is negative, implying that insurance and adaptation act as substitutes. In these states, households face binding liquidity constraints and are unable to finance the lumpy upfront costs associated with adaptation. As a result, insurance provides a comparatively low-cost mechanism to manage flood risk by smoothing ex-post losses. Conditional on adaptation already being in place, however, the marginal value of insurance declines, as the residual risk exposure, and hence the need for financial protection, is reduced.

As households move to higher levels of income and assets, this substitutability weakens and the interaction between the two instruments approaches zero. In these regions, households

[28]Results are robust to using $A^h = 0.6$ and $A^h = 0.0$ as well as $A^h = 0.2$ and $A^h = 0.0$ as the "high" and "low" values of adaptive investment.

are sufficiently unconstrained to finance both adaptation and insurance, and the marginal benefit of combining the two instruments becomes limited. Adaptation substantially reduces expected damages, while insurance transfers a smaller remaining portion of risk, leading to diminishing gains from joint adoption. Thus, rather than operating as strict substitutes or complements, insurance and adaptation behave as substitutes in constrained regions of the state space and become approximately independent as financial constraints relax.

These results highlight that the interaction between ex-ante risk reduction and ex-post risk transfer is mediated by household balance sheets. In particular, liquidity constraints play a central role in determining whether households rely on insurance as a substitute for adaptation or are able to adopt both instruments without strong interaction effects.

7.3 Counterfactual 1: Actuarially Fair Insurance Premium Pricing

Currently a work in progress.

8 Conclusion

This paper studies how households manage climate risk when housing is both a consumption good and a leveraged asset. In the context of flood risk, households face two fundamentally different mitigation margins: insurance, which transfers risk ex post, and adaptation, which reduces exposure ex ante. I develop a dynamic heterogeneous-agent model with mortgage debt, tenure choice, and lumpy adaptation investment to examine how these margins interact with household balance sheets and to evaluate the consequences of public insurance design under the National Flood Insurance Program (NFIP).

The central finding is that insurance and adaptation respond to distinct (and interacting) dimensions of household financial positions. Insurance demand is primarily driven by short-run liquidity considerations: households with high cash-flow strain rely on insurance to smooth consumption risk following flood shocks. In contrast, adaptation investment is governed by balance-sheet exposure and financial capacity: households with greater equity and sufficient internal resources invest in resilience to protect housing wealth. These two channels, liquidity strain and equity exposure, generate systematic heterogeneity in mitigation behavior across the state space and imply that insurance and adaptation are not simple substitutes.

A key implication of the model is that the relationship between insurance and adaptation is state-dependent. For liquidity-constrained households, insurance and adaptation act as substitutes, as the high upfront costs of adaptation render it infeasible and insurance provides a lower-cost alternative for managing risk. As financial constraints relax, this substitutability weakens and the two instruments become approximately independent, with households able to adopt both but with diminishing marginal gains from doing so. This mechanism reconciles the empirical observation that joint adoption is limited yet positively correlated across households, and highlights the role of financial frictions in shaping risk-management choices.

These insights have direct implications for the design of flood insurance policy. In particular, the model shows that increasing insurance premiums toward actuarially fair levels, as in Risk Rating 2.0, does not necessarily induce substitution toward adaptation. Instead, higher premiums tighten household liquidity constraints, reducing the ability of constrained

households to finance adaptation investment. As a result, policies that rely solely on correcting insurance pricing distortions may generate unintended consequences, including reduced homeownership, limited increases in adaptation, and concentrated welfare losses among financially vulnerable households.

More broadly, this paper highlights the importance of integrating household finance into the analysis of climate risk and adaptation. By modeling the joint role of income risk, liquidity constraints, and leverage, the framework provides a tractable way to study how climate shocks propagate through household balance sheets and housing markets. It also underscores that the effectiveness of climate policy depends critically on how it interacts with these underlying financial frictions.

Several extensions remain for future work. On the empirical side, further work is needed to strengthen the identification of liquidity versus balance-sheet channels using microdata. On the quantitative side, incorporating richer credit markets, endogenous borrowing, or regional heterogeneity in flood risk would allow the model to better capture the spatial and institutional complexity of flood exposure. These extensions would further enhance our understanding of how climate risk interacts with household behavior and policy design.

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10 Appendix

10.1 Visual Examples of House Floodproofing Measures

In this Appendix I provide visual examples for three floodproofing measures: (i) basement floodproofing using a sump pump; (ii) exterior retrofit using a commercial product (the Garrison Flood Control Hammerhead System); and (iii) housing elevation.

(i) Basement Floodproofing (Sump Pump)

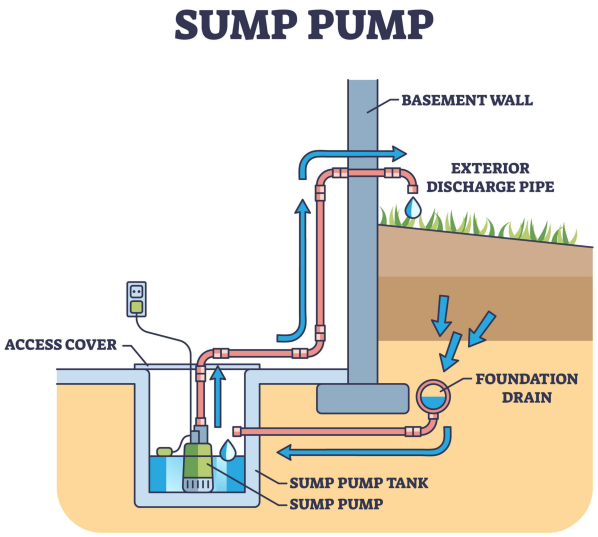


Figure 6: Basement Floodproofing (Sump Pump) Infographic

Note: A sump pump is a mechanism which detects rising water levels and pressure to ensure that these levels do not rise too high. A "sump" is a constructed pit typically constructed below the main surface of a basement floor which holds the sump pump. The pump is equipped with valves which sense rising water levels and/or pressure. When the level or pressure gets too high, the sump pump automatically ejects the excess water out the basement and away from the property using a discharge line.

(ii) Exterior Retrofit via Garrison Flood Control Hammerhead System



Figure 7: Photos of the Garrison Flood Control Hammerhead System

(iii) Housing Elevation

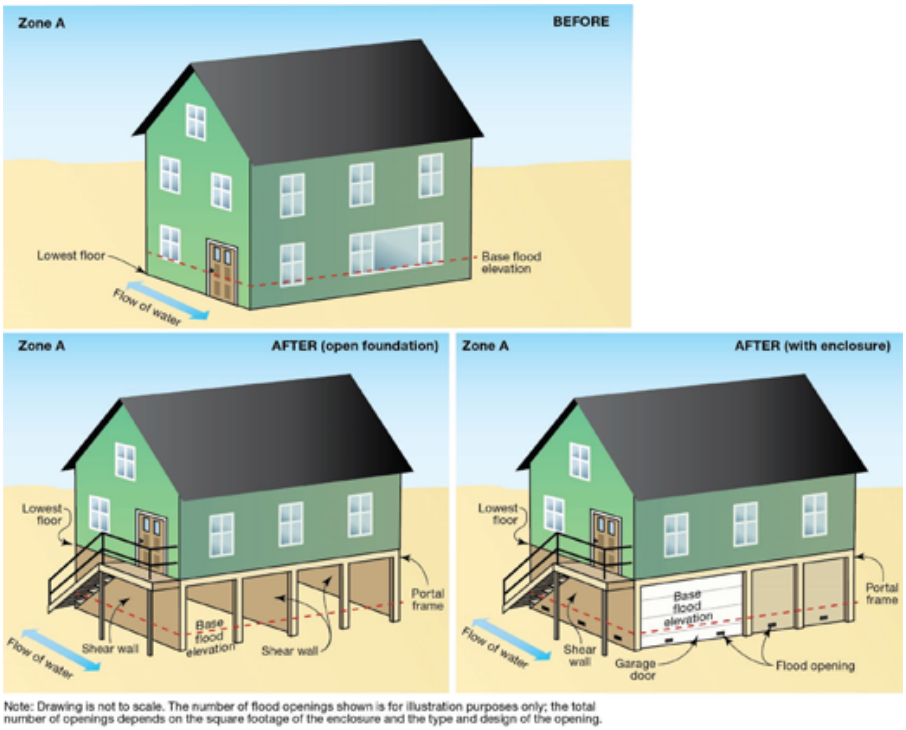


Figure 8: Housing Elevation Investment Diagram

10.2 Effectiveness of Adaptation Measures in Reducing Flood Damages

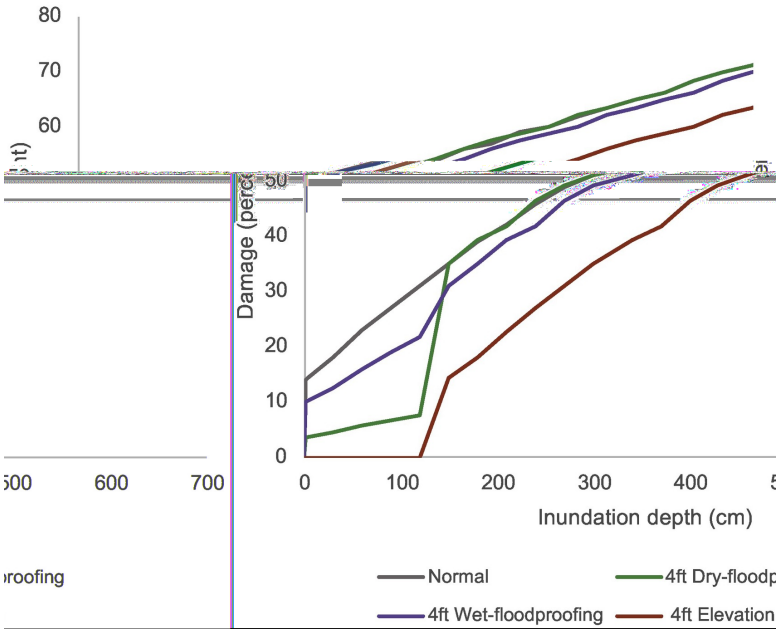


Figure 9: Depth Damage Curve For Various Adaptation Measures for a Residential Single Family Dwelling

Note: This plot shows the amount of damage as a percentage of the total replacement value of the building for each centimeter of inundation, for residential housing with different adaptitive investment or floodproofing measures. This plot is from De Ruig et al (2019) and the plot is generated using data from the Los Angeles region.

10.3 Declining Aggregate Adaptation Choices

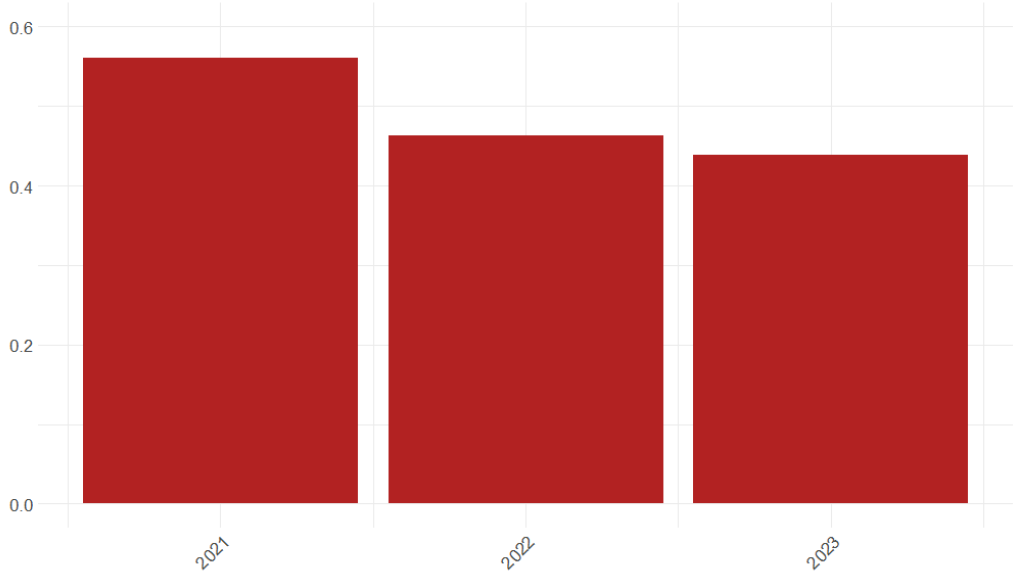


Figure 10: Share of Homeowners in the FEMA NHS Who Report Investing in Adaptation (2021-2023)

10.4 NFIP Community Status Map

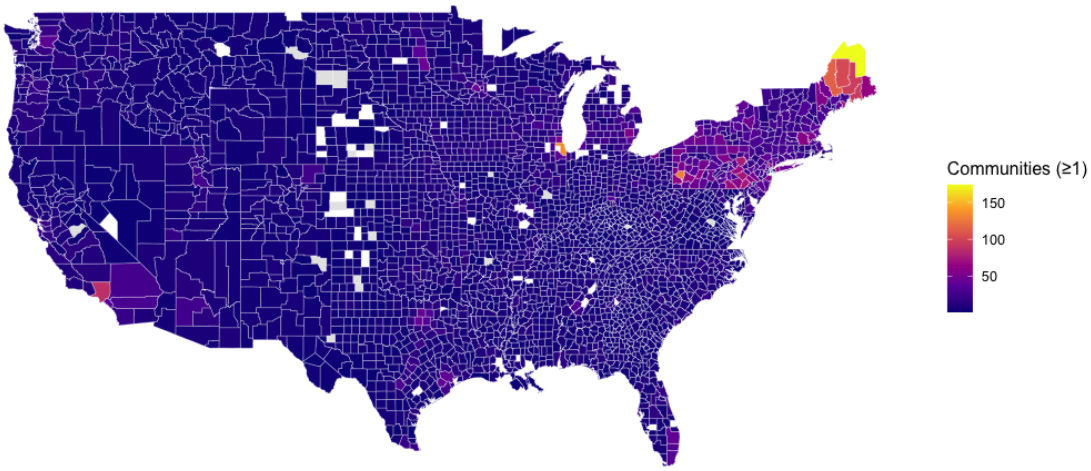


Figure 11: Number of Participating NFIP Communities Per County

10.5 NFIP Risk Rating 2.0

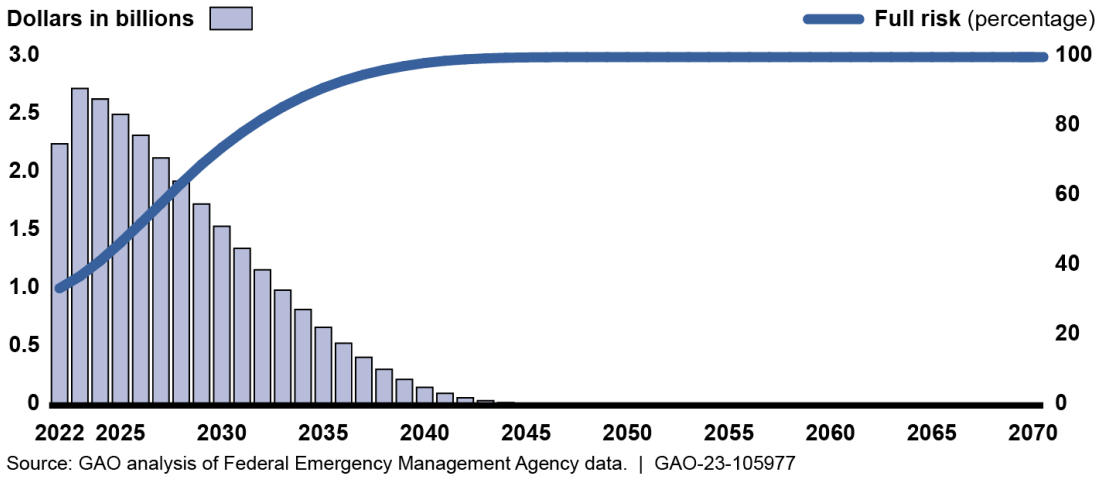


Figure 12: Timeline of NFIP Debt and Actuarial Soundness of NFIP Premium Pricing. Source: US Government Accountability Office (2023)

10.6 NOAA Storms Dataset

Coastal Flood	Flooding of coastal areas due to the vertical rise above normal water level caused by strong, persistent onshore wind, high astronomical tide, and/or low atmospheric pressure, resulting in damage, erosion, flooding, fatalities, or injuries. Coastal areas are defined as those portions of coastal land zones (coastal county/parish) adjacent to the waters, bays, and estuaries of the oceans.
Flash Flood	A life-threatening, rapid rise of water into a normally dry area beginning within minutes to multiple hours of the causative event (e.g., intense rainfall, dam failure, ice jam). Ongoing flooding can intensify to flash flooding when intense rainfall results in a rapid surge of rising waters. Includes dangerous small stream or urban flooding and dam or levee failures. Professional judgment is used to distinguish when it transitions to a general Flood event.
Flood	Any high flow, overflow, or inundation by water which causes damage. Generally refers to inundation of a normally dry area caused by increased water level in an established watercourse, or ponding of water, posing a threat to life or property.
Heavy Rain	An unusually large amount of rain which does not cause a Flash Flood or Flood event but causes damage, such as roof collapse or other human or economic impacts. Heavy Rain should not be used to record low-impact or isolated flood events.
Lakeshore Flood	Flooding of lakeshore areas due to the vertical rise of water above normal level caused by strong, persistent onshore wind and/or low atmospheric pressure, resulting in damage, erosion, flooding, fatalities, or injuries. Lakeshore areas are defined as portions of land zones adjacent to the waters of the Great Lakes and other lakes with assigned Marine Zones.

Table 5: Definitions of Flood-Related Event Types

10.7 Stylized Facts

	N	Mean	Median	Min.	Max.	Variance	Counties Affected	% Counties Affected
1996-2010	72,834	198.0	164.0	4.0	608.0	26,664.0	3,121	96.9%
2011-2024	107,538	264.0	250.0	10.0	482.0	19,876.0	3,133	97.2%

Table 6: NOAA Flood Events Summary Statistics by Time Period

	Dependent variable:
	Damage Ratio
Floodproofed (indicator)	-0.140^{***}
	(0.0213)
Water Depth	0.00158
	(0.00098)
Number of Floors	-0.0561^{*}
	(0.0314)
Occupancy Type	-0.0106
	(0.0134)
Year of Loss	0.00945^{*}
	(0.00572)
State FE	Yes
Constant	-18.64
	(10.37)
Observations	1,890,633
R^2	0.000007
Adjusted R^2	-0.000025
Residual Std. Error	77.23 (df = 1,890,571)
F Statistic	0.220 (df = 61; 1,890,571)
Note:	$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

Table 7: Regression of Damage Ratio on Floodproofing and Controls

	Dependent variable:
	Log(Premium)
Floodproofed (indicator)	-0.2633^{***}
	(0.0298)
Total Building Coverage	$8.37e{-}08^{***}$
	(1.17e−10)
Total Contents Coverage	$3.06e{-}06^{***}$
	(3.52e−09)
Base Flood Elevation	$1.09e{-}05^{***}$
	(4.73e−07)
Lowest Floor Elevation	$-3.48e{-}05^{***}$
	(6.22e−07)
Lowest Adjacent Grade	2.29e−07
	(1.49e−07)
CRS Class Code	0.0407^{***}
	(0.00014)
Flood Zone FE	Yes
Deductible Code FE	Yes
Constant	5.321^{***}
	(0.00221)
Observations	9,663,636
R^2	0.283
Adjusted R^2	0.283
Residual Std. Error	0.606 (df = 9,662,542)
F Statistic	$40{,}930^{***}$ (df = 93; 9,662,542)
Note:	$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

Table 8: Regression of Log Premiums on Floodproofing and Controls

Insure Only	**Adapt Only**	**Insure and Adapt**	**Neither Insure Nor Adapt**
16.25%	24.17%	16.31%	43.26%

Table 9: Insurance and Adaptation Uptake Shares

	(1) Adaptation	(2) Insurance
Adapted		0.545***
		(0.056)
Insured	0.548***	
	(0.056)	
State fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	12,281	12,281

Robust standard errors in parentheses. Dependent variables are indicators for household adaptation (column 1) and insurance take-up (column 2). All specifications include income, mortgage payment, emergency savings and flood experience controls. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 10: Insurance and Adaptation: Conditional Associations

	Insured	**Adapted**
Emergency savings	0.055^{***} (0.009)	0.201^{***} (0.009)
Flood experience	0.205^{***} (0.013)	0.159^{***} (0.013)
Mortgage payment: \$501–1,000	0.111^{***} (0.011)	-0.004 (0.012)
Mortgage payment: \$1,001–2,000	0.130^{***} (0.011)	-0.015 (0.012)
Mortgage payment: \$2,001–3,000	0.208^{***} (0.016)	-0.026 (0.016)
Mortgage payment: \$3,000+	0.212^{***} (0.022)	-0.063^{**} (0.022)
Income: \$10k–49k	-0.036 (0.022)	0.039^{*} (0.023)
Income: \$50k–99k	0.010 (0.022)	0.075^{***} (0.023)
Income: \$100k–149k	0.053^{**} (0.024)	0.105^{***} (0.024)
Income: \$150k–199k	0.061^{**} (0.025)	0.089^{***} (0.026)
Income: \$200k+	0.099^{***} (0.038)	0.152^{***} (0.039)
State fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	12,281	12,281
R^2	0.098	0.077

Notes: The omitted categories are mortgage balance below \$500 and income below \$10k. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 11: Regression of Insurance and Adaptation Choice Across Household Balance Sheet Items for Homeowners

10.8 Derivation of ϕ_1 as the residual damage share under full adaptation

In the model, effective housing services is defined as

$$\tilde{h} = f(D_t, A_t^h)h, \qquad f(D_t, A_t^h) = 1 - \phi_1 D_t^{1-A_t^h}, \quad A_t^h \in [0, 1]$$

Then, the fractional damage or proportional loss in housing services is governed by the climate resilience factor, $f(D_t, A_t^h)$. More specifically, this proportional loss induced by a flood is

$$\phi_1 D_t^{1-A_t^h}$$

Under full adaptation ($A_t^h = 1$), this fractional damage becomes:

$$\phi_1 D_t^{1-1} = \phi_1 D_t^0 = \phi_1$$

Thus, ϕ_1 is the residual damage share that remains even when the household is fully adapted. This captures the information from the depth damage curves in Figure 9 in that even under the most intensive adaptive investment schemes, households still incur some damage.

10.9 Assumption: $\xi > 1$

In the model, the climate resilience factor is defined as

$$f(D_t, A_t^h) = 1 - \phi_1 D_t^{1-A_t^h}, \quad A_t^h \in [0, 1]$$

When a flood occurs such that $D_t = \xi$, the proportional damage share is:

$$\phi_1 \xi^{1-A_t^h}$$

For the function to behave monotonically such that more adaptation weakly reduces damages, it must be that

$$\frac{\partial}{\partial A_t^h}\left(\phi_1 \xi^{1-A_t^h}\right) \leq 0$$

Differentiating this damage share with respect to adaptive investment gives

$$\phi_1(-\ln(\xi))\xi^{1-A_t^h}$$

Since $\phi_1 > 0$, it must be that $\xi > 1$ for the function to remain monotonic. If $\xi = 1$, then $\ln(\xi) = 0$ and adaptation will have no effect on damages. If $0 < \xi < 1$, then $\ln(\xi) < 0$ and the function will behave such that adaptation would increase damages. Thus, $\xi > 1$ ensures that the adaptive investment technology respects the intended comparative statics.

10.10 Derivation of p^π

Conditional on a flood occurring, the building loss (before insurance) is:

$$L^{gross}(A_t^h) = \phi_1 \xi^{1-A_t^h} q_t^h$$

and 0 if no flood occurs. Since the policy covers a fraction κ of the loss,

$$L(A_t^h) = \kappa \phi_1 \xi^{1-A_t^h} q_t^h$$

Therefore, the random payout next period is:

$$\tilde{L}_{t+1} = \begin{cases} L(A_t^h), & \text{with prob. } \lambda \\ 0 & \text{with prob. } 1-\lambda \end{cases}$$

Due to the Bernoulli distribution of flood risk, the random payout follows a Bernoulli mixture such that

$$\mathbb{E}[\tilde{L}_{t+1}] = \lambda L(A_t^h)$$
$$SD(\tilde{L}_{t+1}) = \sqrt{\lambda(1-\lambda)} L(A_t^h)$$

Thus,

$$p^\pi = \lambda L(A_t^h) + \theta\sqrt{\lambda(1-\lambda)} L(A_t^h) = \left(\lambda + \theta\sqrt{\lambda(1-\lambda)}\right) L(A_t^h)$$

To reflect the pass that insurance chosen today becomes effective the next period, I discount by $(1 + r^f)$. Additionally, to implement that the NFIP under-prices insurance, I introduce ν which reflects the degree of insurance pricing distortion. Such that the expression becomes:

$$p^{\pi} = \frac{1-\nu}{1+r_t^f}\left(\lambda + \theta\sqrt{\lambda(1-\lambda)}\right) L(A_t^h)$$

Thus, substituting in the expression for $L(A_t^h)$, the pricing expression becomes:

$$p^{\pi} = \frac{1-\nu}{1+r_t^f}\left(\lambda + \theta\sqrt{\lambda(1-\lambda)}\right) \kappa\phi_1\xi^{1-A_t^h} q^h$$

10.11 Derivation of q^r

Each firm chooses this period's rental stock H_t^r to maximize the present value of dividends:

$$V_t^{rc}(H_{t-1}^r) = \max_{H_t^r} \frac{q_t^h(1-\delta)H_{t-1}^r - q_t^h H_t^r - \frac{\eta}{2}q_t^h(H_t^r - H_{t-1}^r)^2 + (q_t^r - \chi)H_t^r + -\lambda H_t^r\phi_1\xi q_t^r + V_{t+1}^{rc}(H_t^r)}{1+r_t^f}$$

The first order condition of the problem gives:

$$(q_t^r - \chi) - q_t^h - \eta q_t^h(H_t^r - H_{t-1}^r) - \lambda\phi_1\xi q_t^r + \frac{1}{1+r_{t+1}^f}\frac{\partial V_{t+1}^{rc}}{\partial H_t^r} = 0 \tag{2}$$

Then, the envelope condition gives:

$$\frac{V_{t+1}^{rc}}{\partial H_t^r} = q_{t+1}^h(1-\delta_h) - \eta q_{t+1}^h(H_{t+1}^r - H_t^r) \tag{3}$$

Substituting (8) into (7) and rearranging to isolate q_t^r gives:

$$q_t^r(1-\lambda\xi\phi_1) = \chi + q_t^h + \eta q_t^h(H_t^r - H_{t-1}^r) - \frac{(1-\delta_h)q_{t+1}^h + \eta q_{t+1}^h(H_{t+1}^r - H_t^r)}{1+r_{t+1}^f} \tag{4}$$

Then, I invoke steady state such that $q_{t+1}^h = q_t^h = q^h$, $q_{t+1}^r = q_t^r = q^r$, $r_{t+1}^f = r_t^f = r^f$, $H_{t+1}^r = H_{t-1}^r = H_t^r = H^r$. Then, (9) becomes:

$$\begin{aligned} q^r(1-\lambda\xi\phi_1) &= \chi + q^h - \frac{(1-\delta_h)q^h}{1+r^f} \\ q^r &= \frac{\chi + \frac{r^f+\delta_h}{1+r^f}q^h}{1-\lambda\xi\phi_1} \end{aligned} \tag{5}$$

Thus, (10) gives the user cost relation pricing for rental housing.

10.12 Steady State Equilibrium Algorithm

This appendix describes the computational algorithm used to solve the partial-equilibrium steady state equilibrium:

1. **Initialization**: I load all structural parameters, define discrete grids for assets, income states and adaptation rungs. Then, I supply my initial guesses:
    - For my value function, I supply a zero guess for every state.

- For my initial prices, I set $q^{h,guess} = 4$. Using the steady-state user cost formula from equilibrium condition 6 (in section 4.4), the corresponding initial guess for the rental cost of housing is $\frac{4}{9} \approx 0.444$

2. **Household Problem: Value Function Iteration**

- *Renters*: Since renters are not exposed to climate risk, they have a smaller state space. Therefore, for $s = 1$ (ie. renters), I define the state space $(Y \times A)$. For each state, I solve for their next period tenureship (s'), consumption (c) and savings choice (a'). I first solve for the optimal c and a' for each sub-value function (V^{rr}, V^{ho}). Then, the choice for next period tenureship comes from which sub-value function, using the optimal c and a', which delivers the highest value. Naturally, the policy choice for c and a' are then the ones corresponding to the highest sub-value function.
- *Homeowners*: Homeowners $(s = 2)$ have a richer state space: $(Y \times A \times D \times \mathcal{A} \times M \times \pi)$. For each state, I solve for the homeowners next period tenureship, (s'), consumption, (c), savings (a'), next period insurance choice (π') and next period adaptation rung $(A^{h'})$. The tenureship, consumption and savings choices are identified the same way as for renters. However, because homeowners make π' and $A^{h'}$ choices, for the V^{hh} sub-value problem, I find the maximum V^{hh} by looping through cases where $\pi' = 0, 1$ and correspondingly for the $A^{h'}$ options. Since these are low-dimension discrete choices, this does not add drastic complexity. That is, for each possible π' and $A^{h'}$, I calculate the optimal c and a' using the Golden Search method. The combination of policies which delivers the highest value for V^{hh} is the optimal choices and value for this problem. Then, the next period tenureship is chosen by selecting whichever sub-value problem delivers the highest value (V^{hh}, V^{hr}, V^{d}). The remaining policy choices are those that correspond to the highest value sub-value problem.
- I continue iterating the value function problem for renters and homeowners until it converges to my tolerance rule of $\max\{\max|V^{rent,new} - V^{rent,old}|, \max|V^{ho,new} - V^{ho,old}|\} < tol$, where $tol = 1e-6$

3. **Simulation:**

- I initialize a large panel of N households over a degenerate distribution, where they all start out as renters with middle-income and modest assets (income index = 3, asset index = 5). I set $N = 10,000$.
- I draw income and climate shocks for T periods from the calibrated processes. I set $T = 5,000$
- Using the initial degenerate distribution and simulation of income and climate shocks, I simulate my households forward using the policy functions from step 2.

4. **Market Clearing:**

- Using the simulation from step 3, I define my "burn-in" period as $t > 2500$ (ie. from period 2500 onwards). Then, I compute the post-burn in market flows of buyers, sellers and defaulters to determine the supply and demand for owner-occupied housing.
- I iterate steps (2)-(3), applying the output to a bracketing function until I find a set of two possible $q^{h,guess}$ which delivers negative and positive excess demand for owner-occupied housing.

- Once this bracket of possible $q^{h,guess}$ is pinned down, the corresponding $q^{r,guess}$ is applied using the steady-state user cost relation (condition 5 of the steady state definition). I then apply Brent's optimization method to find q^{h*}.
- Once q^{h*} is found such that the owner-occupied market clears, q^{r*} is found using the user cost formula in condition 5 of the steady state equilibrium definition.

10.13 Calibration of ϕ_1 and ξ

i) Residual damage with full adaptation (ϕ_1): Let `buildingDamageAmount` denote the assessed building damage and `buildingPropertyValue` the pre-flood building value. I restrict to "floodproofed" homes (floodproofed as pre-defined by NFIP)[29], and define:

$$\phi_1 \equiv \mathbb{E}\left[\frac{\texttt{buildingDamageAmount}}{\texttt{buildingPropertyValue}} \,\middle|\, \text{Floodproofed Homes}\right].$$

Using NFIP claims data from 1982-2024, $\phi_1 \approx 0.1153$, meaning that floodproofed homes lose about 11.5% of their value in a flood.

ii) Flood shock severity (ξ): In the model, effective housing is defined as:

$$\tilde{h}(A^h, D) = 1 - \phi_1 \cdot D^{1-A^h}, \quad A^h \in [0,1],$$

where A^h is the adaptation level and D is the climate shock. Suppose there is a climatic shock, then for unadapted homes ($A^h = 0$),

$$\tilde{h}(0, \xi) = 1 - \phi_1 \cdot \xi.$$

This implies that the average loss for unadapted homes, d_0, satisfies:

$$d_0 = \phi_1 \cdot \xi.$$

Both d_0 and ϕ_1 are directly estimated from the NFIP data: d_0 is the mean damage ratio for unadapted homes, while ϕ_1 is the mean damage ratio for fully adapted homes. Dividing one by the other yields:

$$\xi = \frac{d_0}{\phi_1}.$$

Thus, ξ is interpreted as the *damage multiplier*: it measures how much worse the damage is for an unadapted home relative to a fully adapted home. Using the NFIP claims data from 1982-2024, $\xi \approx 2.6$, meaning that unadapted homes experience on average about 2.6 times the loss severity of fully adapted homes.

$$d_0 \equiv \mathbb{E}\left[\frac{\texttt{buildingDamageAmount}}{\texttt{buildingPropertyValue}} \,\middle|\, \text{Unadapted Homes}\right].$$

Then:

$$d_0 = \phi_1 \cdot \xi \quad \Rightarrow \quad \xi = \frac{d_0}{\phi_1}.$$

From the NFIP data, $d_0 \approx 0.30$ and $\phi_1 \approx 0.1153$, giving:

$$\xi \approx \frac{0.30}{0.1153} \approx 2.599.$$

This implies that unadapted homes experience about $2.6\times$ the effective damage severity of fully adapted homes.

[29] Link: https://www.fema.gov/openfema-data-page/fima-nfip-redacted-claims-v2

10.14 Calibration of κ

Let `netBuildingPaymentAmount` be the NFIP payout for building damages. I compute:

$$\pi_{\text{val}} \equiv \mathbb{E}\left[\frac{\texttt{netBuildingPaymentAmount}}{\texttt{buildingPropertyValue}} \,\middle|\, \text{Claims Occurred}\right].$$

From the NFIP claims data:

$$\kappa \approx 0.5622,$$

meaning that, conditional on a claim, NFIP pays on average about 56% of the building's pre-flood value.