Flooded House or Underwater Mortgage? The Macrofinancial Implications of Climate Change and Adaptation

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Abstract

I study how climate change affects housing markets, mortgage credit, and private adaptation in a general-equilibrium framework with overlapping generations. Households are exposed to physical climate risks that damage housing and degrade land, which is inelastically supplied. While exposure to future climate risk lowers expected resale values, realized climate damages reduce habitable land, driving house prices up over time through scarcity. This mechanism is robust to allowing substitution between land and structures. In frictionless markets, forward-looking prices support efficient private adaptation. However, constrained households underinvest in adaptation, implying that pricing alone may be insufficient. Unequal adaptation amplifies wealth inequality and accelerates land degradation. Over generations, the adaptation gap widens endogenously as tightening credit constraints further limit investment in resilience. A counterfactual shift from constrained homeownership to landlord-based ownership shows that separating adaptation investment from borrowing constraints can restore efficiency.

Keywords — Climate Change, Adaptation, Housing, Financial Assets, Financial Constraints, Flood Risk, Wealth Inequality.

JEL codes — E44, G51, Q54.

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I. Introduction

The urgency of climate change adaptation is becoming increasingly evident as climatic impacts intensify across the globe, and mitigation efforts remain inadequate in preventing temperatures from rising by more than 1.5-2 degree Celsius (UNEP, 2023). This raises the question how to address rising physical climate risks. While mitigation efforts seek to prevent further climate change by limiting global emissions, adaptation measures are implemented to reduce our vulnerability to existing climate impacts, moderating potential economic losses and damages (IPCC, 2021). A growing macro-literature studies whether we are adaptation to climate change and its macroeconomic and welfare consequences (see e.g. Burke et al., 2024; Bilal and Rossi-Hansberg, 2023; Hong et al., 2023; Fried, 2022), yet the role of finance remains underexplored. Physical climate risks may lead to significant economic losses (see e.g. Barrage and Nordhaus, 2024; Bilal and Känzig, 2024), but also directly impact real estate markets. A substantial finance literature investigates whether physical climate risks are priced into house values and whether they are factored into lending and insurance decisions (see e.g. Bernstein et al., 2019; Baldauf et al., 2020; Bakkensen and Barrage, 2021; Sastry, Forthcoming; Ge et al., 2022). However, it remains unclear how those market incentives, and potential financing frictions, shape private adaptation efforts.

In this paper, I study the implications of climate change on housing markets, mortgage credit, and private adaptation. What is the direct effect of climate change on house prices? Do households adapt efficiently given price signals? Are there any indirect feedback effects, as financial constraints prevent the most vulnerable households from reducing their exposure to climate risk, as access to credit crucially determines our ability to adapt? I take a long-term perspective and embed climate change in a general equilibrium framework with overlapping generations. Floods occur in each period, damaging housing and degrading habitable land. Houses are traded across generations, and, due to their forward-looking nature, house prices account for climate risk. I show that climate change affects house prices along two channels. First, the exposure to future climate risk reduces demand for housing, as future damages lower the expected resale value. However, as flooding events also degrade land, this reduces its long term usability and diminishes the housing supply over time. This scarcity effect puts upward pressure on house prices, and dominates in the general equilibrium if households are sufficiently risk averse with respect to their housing consumption, leading to an increase in house prices. I endogenize households' choice to invest in protective measures to adapt to climate change. Their private adaptation choice is largely influenced by house prices, as it reflects the value at risk to households. In frictionless markets, price signals support efficient adaptation, as they allow households to internalize the benefits of their adaptation investments for future generations. Pricing is insufficient, however, if households are financially constrained. This is because financially constrained households prefer to allocate a larger share of their constrained budget on present housing consumption rather than on investing into future resilience. As a consequence, financially constrained households protect a smaller fraction of their housing wealth. This underinvestment reinforces wealth inequality. It also increases the rate at which land degrades, causing households to become endogenously more constrained. Thus, over time, the difference between

the constrained and unconstrained choice of adaptation (i.e., the "adaptation gap") rises. I propose that a counterfactual shift from a model of constrained homeownership to a rental model with unconstrained owners can lead to more efficient adaptation. In perfectly competitive rental markets, landlords become the residual claimants and have both the financial means and the long-term incentive to internalize societies' benefits of adaptation.

I derive these insights from a simple model of housing and climate risk. The economy is populated by households, who live for two periods. Households have heterogeneous (and exogenous) skills, which determine household income, being either of the high-income or the low-income type. Households have preferences over a non-durable consumption good, which households consume when they are old, and housing, which they consume when they are young. Houses are traded across generations, with the young purchasing the the stock of houses from the old in each period. Housing is a risky investment, as the economy is exposed to physical climate risks.[1] Floods occur in each period and, with a certain probability, households experience losses due to the flood. All risk is thus idiosyncratic of nature. Floods not only destroy part of the housing stock, but also degrade land. Land degradation occurs over a quarter of the earth's ice-free land area. Climate change accelerates the rate and scale of ongoing land degradation processes and generates new degradation patterns (IPCC, 2019). For example, climate change intensifies land degradation through increased flooding, erosion, land subsidence and soil salinity, landslides, and rising sea levels which accelerates coastal erosion worldwide.[2] Such degradation processes can render previously habitable land unsuitable for (re-)development, adversely affecting its long-term usability. Within coastal areas, where land is often in inelastic supply due to geographic constraints (Saiz, 2010), land degradation processes thus cause habitable land to become increasingly scarce.

Since houses are traded across generations, house prices are forward-looking and reflect the physical risks it is being exposed to. In equilibrium, climate change affects house prices along two opposing channels. First, the exposure to physical climate risk weakens demand for housing, as future damages lower the expected resale value of housing. The future resale value of the house is thus discounted for the exposure to climate risk, which lowers current house prices (see e.g., Bernstein et al., 2019; Bosker et al., 2019; Baldauf et al., 2020). However, due to the degradation of land, housing becomes increasingly scarcer, reducing its availability in the economy over time. The reduction in supply puts upwards pressure on house prices. If households are sufficiently risk-averse with respect to their housing consumption, this scarcity effect dominates, causing house prices to rise in the long run equilibrium. Intuitive, the two opposing effects on house prices can be understood through geographical variation in climate risk exposure, where houses with a higher risk exposure trade at lower prices while houses with a lower risk exposure appreciate in prices over time. In other words, houses on higher elevation form a hedge against houses on lower elevation. This, however, also implies that migrating away from high-risk areas toward

[1] I focus on the risk of flooding from extreme weather events (e.g., pluvial floods, hurricanes and torrential rains) and rising sea levels. However, other physical climate events, such as wildfires, would generate similar effects.

[2] I focus on the case in which the change in land supply due to climate change is net negative, which is empirically most relevant. Already at present, soil is being lost from land that is tilled at a rate more than 100 times faster than new soil is naturally being formed. Moreover, due to climate change, erosion of coastal areas will increase worldwide, even with adequate implementation of measures to avoid, reduce and reverse land degradation IPCC (2019).

safer locations reinforces price appreciation in low-risk regions and accelerates decline in high-risk ones. I further show that allowing for substitution between land and structures, where households can partially offset land loss by using surviving land more intensively (e.g., by building taller or denser structures), only dampens the scarcity effect as long as the price response to land loss is positive but moderate.

I introduce private adaptation to climate change by allowing households to invest in self-protective measures that reduce their vulnerability to floods. There is a growing need for private adaptation to complement public adaptation investments as individuals often have a better understanding of the specific risks and vulnerabilities they face and, unlike broad public policies – which require political support – private adaptation measures can be tailored to their individual risk exposure and preferences. I model private adaptation investments as an intertemporal investment that households can undertake. Private adaptation measures, such as storm-proof windows, or flood-proof floors, do not change the probability of a flooding event occurring or the progression of climate risk, but reduce the damages households experience when hit by a flooding event. That is, adaptation investments shift the distribution of idiosyncratic damages leftwards. As a result, private adaptation measures mitigate the impact of flooding, thereby slowing the rate of land degradation.

Adaptation investments are costly, however, and households trade off the present costs and future benefits of adaptation, which are the avoided climate change damages. The private adaptation choice increases in the economy's climate risk exposure, as it determines the size of the damages households face in expectation. It also rises with house prices, which reflect the value at risk to households. Since house prices are forward-looking, they allow households to internalize the benefits of their adaptation investments for future generations. In other words, as in a decentralized information system, prices guide the optimal adaptation decision, reflecting the expected future benefits of reducing flood risk and maintaining the long-term value of housing. This prevents a "tragedy of the horizon" effect (Carney, 2015), and leads to efficient private adaptation in frictionless markets.

There are two nuances to this result. First, to guide households to invest optimally in adaptation, price signals must be correct. That is, climate risk must be accurately capitalized into house prices. If climate risk is mispriced — due to heterogeneity in beliefs about climate change (see e.g., Bakkensen and Barrage, 2021; Baldauf et al., 2020) or limited buyer sophistication (see e.g., Bernstein et al., 2019) — households underinvest in adaptation and remain vulnerable to climate impacts. Therefore, accurate climate risk pricing in housing markets is essential for incentivizing optimal adaptation. Second, the private optimum only coincides with the social optimum if market signals accurately reflect the social benefits of a having an additional unit of housing available for the next generation. This is the case when the welfare of future generations to be evaluated using markets discount rates (Stern, 2007; Nordhaus, 2007; Weitzman, 2007). If greater social weight was placed on the welfare of future generations, market prices would fail to reflect the value of adaptation investments to future generations and households would underinvest in adaptation from a social perspective.

In times of rising wealth inequality (Saez and Zucman, 2016; Zucman, 2019; Blanchet and Martínez-Toledano, 2023), it is essential to understand the heterogeneity in households' ability to respond to

rising climate risk. In the framework, households with positive savings lend to others that are unable to finance the purchase of housing from their income. Housing is pledged as collateral under the mortgage contract, but its liquidation value is affected by climate change. Mortgage creditors anticipate these potential losses and adjust their lending decisions accordingly. While borrowers can protect the liquidation value of the collateral by adapting to climate change, their adaptation investment is non-verifiable to mortgage creditors. Mortgage creditors thus form expectations about the private adaptation choice of their borrowers and do not allow the size of household debt to exceed the collaterals' expected liquidation value (Kiyotaki and Moore, 1997; Sastry, Forthcoming).

The ability of low-income households to adapt to climate change critically depend on their access to finance. When credit constraints bind, constrained households are unable to consume the optimal amount of housing. This has implications for their adaptation decision, as the marginal utility from spending an additional unit on housing – from which households derive utility in the present – is higher than the marginal utility from spending an additional unit on adaptation – which is an investment in future resilience. In essence, credit constrained households discount the benefits of future adaptation more heavily due to their limited ability to borrow against the future. As a result, credit constrained households optimally spend a relatively lower share of their resources on adaptation, thereby protecting a smaller fraction of their housing wealth. This has redistributive implications, since credit constrained households retain a relatively higher exposure to floods and face a relatively larger reduction in their housing wealth once the flood occurs. The underinvestment also creates intergenerational spillovers. Due to the underinvestment in adaptation, the economy faces larger climate-related damages, increasing the speed of land degradation. This raises housing scarcity, reducing welfare of future generations. Moreover, the further reduction in habitat endogenously tightens credit constraints for future generations. Over time, credit constrained households thus have increasingly lower incentives to invest in resilience, leading to a widening the private adaptation gap.

Credit constraints present a significant barrier to effective climate adaptation (IPCC, 2023), highlighting the need to address the unequal impacts of climate change. One such policy is to promote renting over homeownership for credit-constrained households. Through the reassignment of ownership in a rental model, landlords bear the responsibility for undertaking adaptation investments. Rental prices in a perfectly competitive markets adjust to reflect the rising scarcity of housing due to climate change. Since adaptation increases the resale value of housing in the future, these equilibrium price adjustment incentivize adaptation investments by landlords. Landlords thus have the financial capacity and the long-term incentive to invest efficiently in adaptation.Intuitively, renting functions as an equity-like arrangement where landlords bear the investment cost and capture the returns through higher rental income and preserved resale value. A counterfacutal shift to landlord-based ownership can thus support more efficient adaptation than mortgage markets, where adaptation is distorted by collateral limits.

I quantify the welfare effects of the underinvestment in adaptation over time, focusing on the Florida coastal area. Florida is at high risk of flooding due to sea level rise, and is projected to account for more than 40 percent of all houses at risk of flooding through sea-level rise in the United States as a

whole (Dahl et al., 2018). I provide a long-run simulation of the model under various climate change scenarios of projected socioeconomic global changes up to the year 2150 based on IPCC (2023). Under an intermediate climate change scenario, the difference between the private adaptation choice of credit constrained and unconstrained households grows to 7-12 percent. This represents the difference in the housing wealth that credit constrained households protect relative to unconstrained households.

While this underinvestment has implications for wealth inequality, as constrained households lose a relatively larger fraction of their housing wealth upon the realization of a climate impact, it also has implications for welfare more broadly. Under the most extreme climate change scenario, the marginal value of housing saved through adaptation, which reflects the amount of consumption household is willing to give up to preserve an additional unit of housing, rises to up to 11.7 percent. I determine the utility cost of the underinvestment in adaptation to quantify the inefficiency caused by credit constraints. This loss amounts to up to 3.5 percent of the home's market value, or approximately $15,700 per household. These findings highlight the long-term implications of constrained adaptation and signal the benefits of improving access to finance or shifting toward landlord-driven adaptation.

In an extension, I introduce an insurance market. Adaptation fundamentally differs from insurance, since adaptation aims at prevention, whereas insurance offers monetary compensation after losses occur. Hence, insurance does not affect the speed of land degradation. Rather, I show that insurance leads to moral hazard in adaptation (Fried, 2022). Even when priced actuarially fair, insurance allows households to limit the downside from a disaster in a way which is relatively cheaper than investing in adaptation, thus reducing households' willingness to undertake adaptation investments. As private climate risk insurance crowds out private adaptation, this leads to a faster reduction in the supply of habitable housing and increases inequality across generations. However, a trade-off emerges since a higher insurance coverage reduces the redistributive effects of climate change within generations due to the monetary compensation provided for damages. This underscores the relevance of considering distributional consequences, both across and within generations, in designing effective climate risk insurance schemes.

Roadmap The remainder of this paper is structured as follows. I discuss the related literature in Section II. In Section III, I introduce the theoretical framework with housing and climate risk. The conditions relevant for the definition of an equilibrium are derived in Section IV. I endogenous climate change adaptation in Section V. Section VI quantitatively assesses the welfare implications over time. In Section VII, I provide a model extension with climate risk insurance provision. Section VIII concludes.

II. Related literature

This paper contributes to the macro-finance and climate economics literatures by showing that the interaction between climate risk and credit frictions generates a dynamic adaptation gap that widens over generations. In contrast to previous work focusing on mitigation or static price effects, I endogenize adaptation, land scarcity, and intergenerational credit dynamics in general equilibrium.

This paper relates broadly to the literature studying the effects of climate change. This literature

can be divided into a stream focusing on quantifying the effect of a rise in temperatures on productivity, for example in agriculture, labour productivity or GDP growth more broadly (see e.g. Nordhaus, 1992, 1977; Mendelsohn et al., 1994; Deschênes and Greenstone, 2007; Schlenker and Roberts, 2009; Dell et al., 2012; Golosov et al., 2014; Burke et al., 2015; Barrage and Nordhaus, 2024; Cruz and Rossi-Hansberg, 2024; Bilal and Känzig, 2024) and a stream of literature studying the effect of sea level rise on real estate markets, which encompasses the pricing of physical climate risk in housing markets, and the effects of physical climate risk on mortgage - and insurance markets.

This paper contributes to this latter stream, particularly to the literature studying the pricing of physical climate risk in housing markets. These papers study empirically whether sea level rise risk is capitalized into housing markets in coastal areas. The majority of papers find evidence of a positive 'sea level rise discount', indicating that houses exposed to sea level rise risk trade at a lower price in the market (see e.g., Harrison et al., 2001; Bin et al., 2008; Keenan et al., 2018; Gibson et al., 2017; Bosker et al., 2019; Bernstein et al., 2019; Hino and Burke, 2020; Keys and Mulder, 2020; Baldauf et al., 2020; Giglio et al., 2021; Bakkensen and Barrage, 2021). This literature finds that factors as - amongst others - buyers' sophistication (Bernstein et al., 2019) and (heterogeneity in) climate change beliefs can explain (Baldauf et al., 2020; Murfin and Spiegel, 2020; Bakkensen and Barrage, 2021) variation in the sea level rise discount.Consistent with the aforementioned research, I show that demand for houses exposed to future climate risk is lower, which puts downwards pressure on current house prices. I contribute to the literature by considering the aggregate effect of climate change on house prices through rising scarcity. Specifically, I demonstrate that the materialization of climate-related damages reduces the supply of habitable houses. I derive the conditions under which this scarcity effect dominates in the general equilibrium, showing that this is the case when households are sufficiently risk-averse with respect to their housing consumption.

The evolution of house prices matters for mortgage market dynamics. Hence, there is a growing literature studying the effect of physical climate risk on mortgage markets. Issler et al. (2019) show that mortgage delinquency and foreclosure rates significantly increase after a wildfire. Bakkensen et al. (2022) find that homeowners with a larger exposure to SLR-risk are more likely to be leveraged due to heterogeneity in beliefs about climate risk. Bakkensen et al. (2022) further find that the underlying mortgage contracts have a longer maturity, and climate change pessimists are more likely to trade their climate risk exposure with banks via long-term debt contracts. Sastry (Forthcoming) shows that mortgage originators further offload flood risk to the government through flood insurance contracts, and to under-insured households through higher down payments. This indicates that mortgage originators only screen for flood risk when they retain residual exposures to it. Building on this latter result, I consider endogenous credit constraints in my theoretical framework. Specifically, mortgage originators take into consideration the exposure to climate risk, as this reduces the expected liquidation value of collateral pledged to the mortgage contract (cf. Kiyotaki and Moore, 1997). While this reduces financial risks, I show that such credit constraints fundamentally hinder homeowners from optimally investing in adaptation.

As physical climate risk rises, so do the costs of insuring oneself against these risks. Keys and Mulder (2024) document that insurance premia have risen sharply due to an increase in local disaster risk and the pass-through of reinsurance costs. Ge et al. (2022) show that higher insurance premia reduce transaction prices, with the effect being strongest for homes exposed to long-term sea level rise. Ge et al. (2022) suggest that insurance pricing can accelerate the incorporation of climate risk into asset markets. Boomhower et al. (2024) document that high exposure to wildfire risk not only leads to higher prices, but also to limited participation in insurance markets. Sastry et al. (2023) also find that traditional insurers increasingly exit the Florida-market. Importantly, Sastry et al. (2023) find that lower quality insurers enter the market to fill this gap. Mortgage lenders respond to the decline in insurance quality by selling a large portion of exposed loans to government sponsored enterprises, who bear an increasing share of insurance counterparty risk. While it is essential to ensure that premia accurately reflect climate risk exposures, I show that climate risk insurance leads to moral hazard in adaptation, even if insurance premia reflect the accurate climate risk exposure. This is because insurance limits the downside from a disaster in a way which is relatively cheaper than investing in adaptation, reducing households' willingness to undertake those investments, which is consistent with Fried (2022).

It is essential to consider adaptation when quantifying climate-related losses and their impact. Hence, a growing macro-literature studies adaptation to climate change. Bradt and Aldy (2023) and Hsiao (2023) focus on public adaptation. Bradt and Aldy (2023) estimate the magnitude and distribution of benefits from public adaptation infrastructure. Hsiao (2023) shows that public adaptation intervention hinders long-run resilience against flood risk by creating coastal moral hazard, which leads to lock-in and delays inland migration. Since public adaptation relies on collective efforts which require political support, and individuals typically have a better understanding of the unique risks and vulnerabilities they face, there is a growing need for private adaptation. Specifically, private adaptation measures can be tailored to meet the specific needs of individuals, which may not be adequately addressed by public policies. Fried (2022) develops a macro heterogeneous-agent model to quantify the interactions between adaptation, federal disaster policy, and climate change. Fried (2022) shows that moral hazard effects from disaster aid reduce adaptation in the U.S. economy, but federal subsidies for investment in adaptation more than correct for the moral hazard. Hong et al. (2023) analyze how private and public sectors should adapt to manage disaster risks to the capital stock when they learn about the adverse consequences of global warming for disaster arrivals. Hong et al. (2023) highlight that adaptation is more valuable under learning. In a similar spirit, Balboni et al. (2023) show that climate change impacts will be moderated as flood-affected firms in Pakistan learn from the experience of increasingly frequent disasters and increasingly relocate to safer areas.[3] However, Albert et al. (2021) show that spatial capital and labour market frictions constrain the reallocation process of capital and labour from agriculture to manufacturing in Brazil.

This paper contributes to the literature on climate change adaptation by taking into consideration

[3]I abstract from migration as adaptation mechanism in this paper. Cruz and Rossi-Hansberg (2024); Bilal and Rossi-Hansberg (2023); Desmet and Rossi-Hansberg (2015); Muis et al. (2015) the adaptation incentives in dynamic spatial models. For example, Cruz and Rossi-Hansberg (2024) examine responses to local temperature changes through costly trade, migration, and technological innovations, while Bilal and Rossi-Hansberg (2023) focus on migration and capital investment decisions. These papers highlight that migration may reduce substantially the welfare impact of climate change.

the role of financial markets in driving private adaptation decisions. I show that the capitalization of climate risk in house prices influences the incentives of households to adapt to climate change. Specifically, in frictionless markets, price signals lead to efficient adaptation, as household internalize the effect of their adaptation investments on future generations. However, I show that pricing may not always be sufficient, as households may not have sufficient means to adapt to optimally to climate change. Indeed, credit-constrained households optimally underinvest in climate change adaption.[4] I highlight the dynamic feedback effect of credit constraints in the context of climate change adaptation. Specifically, credit constraint households remain more exposed to climate risks due to the underinvestment in adaptation. Upon an impact, their underinvestment reinforces wealth inequality. It also leads to a further reduction in future habitat. As habitat becomes increasingly scarcer in supply, next generations become more constrained and therefore underinvest to an even larger extent. This leads to a widening of the private adaptation gap over time. I propose that a societal shift from constrained homeownership to a rental model with unconstrained owners could overcome the dynamic underinvestment problem and lead to more efficient adaptation.

Finally, this paper relates to the literature studying the effects to climate change policies on inequality. Känzig (2023) shows that a carbon taxes disproportionately affects the poor, as these households have a high energy share within their consumption bundle, and tend to work in sectors which are more impacted by carbon pricing policies. Pedroni et al. (2022), Belfiori and Macera (2024) and Belfiori et al. (2024) study how inequality can be optimally accounted for in climate mitigation policies.

III. A Simple Framework of Housing and Climate Risk

Time is discrete and denoted by $t \in \{0, 1, ..., \infty\}$. The economy is characterized by two overlapping generations, each consisting of a unit mass of households. Households derive utility from consuming housing and a non-durable good, which is freely traded on world markets.[5] At the start of each period, a flood occurs. This event hits a fraction of households, damaging their housing capital. All risk is idiosyncratic, and the economy's aggregate climate risk exposure rises deterministically over time.

A. Households

Households live for two periods. When young, households purchase housing capital, denoted by L, from the old generation at a relative price p (the price of the consumption good is normalized to 1).[6] Additionally, young households hold financial assets, and can invest in mortgage debt. Once old, households channel their savings, which consist of the proceeds from selling their house, as well as the return earned on

[4] This aligns with the findings of Rampini and Viswanathan (2013); Rampini (2019), who show that firms facing financing constraints are less likely to invest in durable assets.

[5] Appendix C extends the model with a production sector and shows that endogenizing the production of the non-durable good does not alter the main results.

[6] While I focus on owner-occupied housing, the model implicitly embeds a rental market. When the rental market is perfectly competitive, households are indifferent between renting and buying housing. I explore this feature in Section V.D.3.

their savings, to the purchase of the non-durable consumption good, denoted by c. There is an initial generation at $t = 0$, which is endowed with the supply of houses, $\bar{L}_0$.

A.1 Preferences

Households have preferences over housing and the non-durable consumption good[7], which are given by the following quasi-linear utility function

$$U\left(c_{i,t+1}, L_{i,t}\right) = c_{i,t+1} + v\left(L_{i,t}\right)$$

$v\left(L_{i,t}\right)$ captures the utility that household i obtains in period t from owning $L_{i,t}$ housing capital. I assume that $v'(\cdot) > 0, v''(\cdot) < 0$. Households maximize expected lifetime utility.

A.2 Skills and Income

Households have heterogeneous (and exogenous) skills, which determine household income. There are two skill levels. I denote high skills and income by h and low skills and income by l. A fraction ϕ of households is high-skilled, and is endowed with $\bar{h}$ high-skilled labour. The remaining households are low-skilled, denoted by l, and are endowed with $\bar{l}$ manual labour.
Young workers supply labour to the firm and earn an income of $y_{i,t} = \{q_t\bar{h}, w_t\bar{l}\}$, where q_t (w_t) denotes the high-skilled (low-skilled) wage per unit of labour.

B. Climate Risk and Housing Capital

The economy is exposed to physical climate risks and floods occur in each period from extreme weather events (e.g., pluvial floods, hurricanes and torrential rains) and gradual changes like sea-level rise. Let $\gamma_{t+1} \in [0, 1]$ denote the probability that a given household experiences damages from a flood in period, $t+1$. This probability is common among households and increases deterministically over time. By the law of large numbers, γ_{t+1} corresponds to the fraction of households experiencing climate-related damages in any period $t + 1$. Following Fried (2022), I model idiosyncratic climate damages. Let $\xi_{i,t+1} \in [0, 1]$ denote the idiosyncratic losses of a given household, i, in period, $t + 1$, which follows some distribution, $F\left(\xi_{i,t+1}\right)$ that is i.i.d. across households. This reflects that flooding events may hit certain households harder than others. However, since idiosyncratic risk can be diversified, only the expectation of losses matters for pricing. Denote by $\mu \in [0, 1]$ the expected loss, as a fraction of housing capital, conditional on being hit by a flood. This represents the common, non-diversifiable component of losses. Then, the expected idiosyncratic losses are given by:

[7] As I am interested in the dynamic effects of climate risk on adaptation incentives rather than intergenerational wealth transmission, I abstract from bequests. This removes automatic persistence in ownership across generations and isolates how climate risk and financial constraints shape households' adaptation incentives.

$$\begin{aligned}\mathbb{E}\left(\xi_{i,t+1}\right) &= \mathbb{E}\left(\xi_{i,t+1}\middle|\text{Hit by the flood}\right)\cdot\mathbb{P}\left(\text{Hit by the flood}\right)\\ &= \mu\gamma_{t+1}\end{aligned}$$

Climate-related damages reduce the amount of housing that can be resold. For a given household i, the housing capital remaining in period $t+1$ is given by:

$$L_{i,t+1} = \left(1-\xi_{i,t+1}\right)L_{i,t}$$

Physical climate events not only destroy part of the housing stock, but also degrade land. Land degradation occurs over a quarter of the Earth's ice-free land area and climate change accelerates the rate and scale of ongoing land degradation processes and generates new degradation patterns. Climate change will further exacerbate land degradation processes through increasing floods, erosion, soil salinity, landslides, and sea level rise IPCC (2019). These degradation processes can render previously habitable land unsuitable for development, thereby adversely affecting its long-term usability.

Denote the supply of livable land (cf. Burzyński et al. (2019)) in a given period by $\bar{L}_t$. Consistent with the macroeconomic literature analyzing land and long-run economic - and house price growth, I assume that the supply of livable is fixed in the long run.[8] As a result of land degradation, the supply of houses evolves dynamically over time and follows the law of motion:

$$\begin{aligned}\bar{L}_{t+1} &= \int_0^1 \left(1-\xi_{i,t+1}\right)di\cdot\bar{L}_t\\ &\overset{\text{LLN}}{=}\left(1-\mu\gamma_{t+1}\right)\cdot\bar{L}_t\end{aligned}$$

Hence, by the law of large numbers, the supply of habitable land falls in each period $t+1$ by a fraction $\mu\gamma_{t+1}$. As land degrades, rebuilding housing in the affected part of the region becomes impossible. While new homes could be constructed in unaffected parts of the regions, this would still mean that the same number of households must share a smaller amount of land. An alternative way to interpret this supply reduction is as an increase in housing costs, which arise from increased construction expenses in safer areas or potential regulatory restrictions on development in flood-prone zones.

[8] See for example Ricardo (1817), who shows that economic growth benefits landlords disproportionatly due to the fixed nature of land. Nichols (1970) includes land as fixed production factor in a Solow model to show that house prices grow at the same rate as output in the steady state. Also Hansen and Prescott (2002) build a one-good, two-sector overlapping generations (OLG) model land is in fixed supply. More recently, Grossmann et al. (2025) consider a two-good, two-sector infinitely-lived agent model in which the land development sector becomes inactive in the long run. Combined with differences in the intensity by which land is used in different sectors, the fixed nature of land explains the rise in real house prices in the long run as observed in the data. Finally, Saiz (2010) shows empirically that the fraction of undevelopable land is higher in areas where there are regulatory or geographical constraints. This is particularly true for coastal cities, such as Miami, San Francisco, and New Orleans.

C. *Housing Market Dynamics and Financial Markets*

There is one housing market on which all home purchases and sales take place. The market opens after the flood, which occurs at the start of the period. Define $S_{i,t}$ as the net savings of a young household, i in period t, after the purchase of housing capital:

$$S_{i,t} = y_{i,t} - p_t L_{i,t}$$

This can be positive or negative, depending on whether a given household i is a net lender or borrower:

$$S_{i,t} \begin{cases} \geq 0 & \text{net lender} \\ < 0 & \text{net borrower} \end{cases}$$

Households earn the risk-free rate of return, r, on their savings, which the economy takes as given.[9] Households may lend to others who have insufficient resources to finance the purchase of their housing capital. Lending takes place against collateral, and the housing capital purchased backs the mortgage contract. However, destroyed housing capital has zero liquidation value, indicating that borrowers risk default. Therefore, borrowers hence pay the risky rate of return, $\hat{r}_{t+1} \geq r$.Default occurs when that mortgage is "under water". That is, when the revenue from selling the undamaged housing capital is smaller than the value of the amount borrowed (including interest):

$$p_{t+1} L_{i,t+1} \leq (1 + \hat{r}_{t+1})(-S_{i,t})$$

Define the loan-to-value ratio as

$$LTV_{i,t+1} = \frac{(1 + \hat{r}_{t+1})(-S_{i,t})}{p_{t+1} L_{i,t}}$$

The condition implicitly defines a threshold on the climate damages above which a homeowner defaults:

$$\hat{\xi}_{i,t+1} = 1 - LTV_{i,t+1}$$

Accordingly, the probability of default is given by

$$\chi_{i,t} = \mathbb{P}\left(\xi_{i,t+1} \geq \hat{\xi}_{i,t+1}\right) = \left(1 - F\left(\hat{\xi}_{i,t+1}\right)\right)$$

[9] This reflects that the non-durable consumption good is traded on world markets. Appendix C shows that allowing r to be determined domestically in a simple production extension leaves the main results unchanged.

IV. Equilibrium

A. Household Optimization Problem

Households maximize utility subject to the budget constraint and a limited liability constraint:

$$\begin{aligned}\max_{c_{i,t+1},L_{i,t},S_{i,t}} \mathbb{E}\left(U(c_{i,t+1},L_{i,t})\right) &= \mathbb{E}_t\left(c_{i,t+1}\right)+v\left(L_{i,t}\right)\\ s.t. \quad y_i &\leq p_t L_{i,t}+S_{i,t}\\ c_{i,t+1} &\leq \max\{p_{t+1}(1-\xi_{i,t+1})L_{i,t}+(1+\hat{r}_{t+1})S_{i,t},0\}\\ c_{i,t+1},L_{i,t} &\geq 0.\end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.[10]

A.1 Optimal Demand for Housing Capital

The optimal demand for housing capital in a given period t determines its price:

Lemma IV.1. *The demand for housing capital of each household i in period t is given by*

$$L_t^* = v'^{-1}\left((1+r)p_t-(1-\mu\gamma_{t+1})\,p_{t+1}\right)$$

Accordingly, the price of housing capital in a given period, t, becomes

$$p_t = \frac{(1-\mu\gamma_{t+1})p_{t+1}+v'\left(L_t^*\right)}{(1+r)}$$

This is a standard asset pricing equation, indicating that the price of housing capital today is equal to the discounted value of the benefits from owning housing. The benefits of owning housing consist of two parts. First, there are marginal benefit to owning housing capital, which is captured by $v'\left(L_t^*\right)$ (the 'dividend'). Second, the owner reaps the revenue from selling the undamaged housing capital at the start of the next period (the 'resale value'). The revenue per unit of housing capital owned is given by the future house price, p_{t+1}, which is discounted for the fraction of expected damages. As a result, demand for housing weakens and current house prices are thus discounted for the exposure to future climate risk (e.g., Bernstein et al., 2019; Baldauf et al., 2020; Bosker et al., 2019). Hence, house prices decline in *future* climate risk, γ_{t+1}.

[10] Note that there is no no-bubble constraint in the framework. In overlapping generation models, bubbles arise when agents purchase an asset purely for resale value, rather than for the real return it provides. However, in this model, house prices remain tied to their fundamental value due to several elements. First, perfect foresight ensures that households correctly anticipate the evolution of climate risk, land degradation, and future house prices, preventing speculative expectations that could fuel a bubble. Moreover, housing provides direct utility to households rather than being solely a speculative asset. As a result, house prices in the long term reflect the expected future benefit of homeownership, which is constrained by the marginal utility of housing consumption rather than speculative resale value. This ensure that the transversality condition remains satisfied.

A.2 Demand for Household Debt

Household debt follows residually. Households with net savings lend to others households while households with negative savings take out a mortgage.

B. Equilibrium and Market Clearing

A competitive equilibrium is an allocation $\{c_{t+1}, L_t, S_t\}_{t=0}^{T}$ and prices $\{p_t\}_{t=0}^{T}$, such that in each period, t, given prices, households maximize lifetime utility and all markets clear.

B.1 Housing market

Total housing demand equals total housing supply, so that $\int_0^1 L_{i,t}^* di = \bar{L}_t$. Therefore, housing market equilibrium requires

$$\bar{L}_{t+1} = (1 - \mu\gamma_{t+1})\,\bar{L}_t.$$

The housing market clearing condition pins down the equilibrium price of housing capital:

$$p_t^* = \frac{(1 - \mu\gamma_{t+1})\,p_{t+1} + v'\left(\bar{L}_t\right)}{1 + r}$$

Forward substitution gives

$$p_t^* = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} (1 - \mu\gamma_{\iota+1})$$

Hence, as the housing stock is traded across generations, and households have perfect foresight, house prices are forward-looking. The expression reveals that climate change influences house prices through an additional channel, which is the rising scarcity of housing. Households are risk averse with respect to housing consumption - which can be considered a relatively more essential good than their non-durable consumption. This risk aversion is reflected by the concavity of $v(L)$ in housing, L. When the supply of housing decreases due to climate-related damages, the remaining housing supply becomes scarcer. This increases the value households place on owning an additional unit of housing, as reflected by a rise in the marginal utility of owning housing. A higher marginal utility of owning housing raises the willingness to pay, thus driving up house prices. Hence, while houses exposed to climate *risk* face a price discount in the market, climate-related *damages* (i.e., the materialization of climate risk) drive up contemporaneous house prices.

Proposition 1. *Let climate risk increase in all future periods by a factor $\sigma > 1$ (i.e., future climate risk*

is given by $\{\sigma\gamma_{t+1}, ..., \sigma\gamma_{\infty}\}$*). The price of housing capital rises in* σ *if*

$$\underbrace{-\frac{v''(\bar{L}_j) \cdot \bar{L}_j}{v'(\bar{L}_j)}}_{RRA} \geq 1 \tag{1}$$

Proof: See Appendix A.1

If households are sufficiently risk-averse with respect to their consumption of housing - that is, households are more risk-averse with respect to their housing consumption than their consumption of the non-durable consumption good -, the scarcity effect dominates in the general equilibrium. This leads to a rise in house prices in the long run. While the initial loss of habitable land has a negligible effect on the utility households derive from owning housing, the continued reduction in the housing supply raises the marginal utility of owning housing, producing an increasingly strong upward pressure on house prices over time.

High vs Low Risk Regions The two opposing effects on house prices can be intuitively understood through geographical variation in climate risk exposure. I consider a region with two distinct types of housing stocks in Appendix B.1, with a fraction of all houses are located on high elevation (e.g., on a hill) and the remaining houses are located on low elevation. House prices adjust in equilibrium to ensure that households are indifferent between purchasing housing in the region with a high or low risk exposure. The differences in risk exposure results in implicit price segmentation, since houses with a higher risk exposure trade at a lower price than houses with a lower risk exposure. Intuitively, this implies that houses on higher elevation are a hedge against houses on lower elevation. Over time, the composition of the housing stock in the region changes, as houses with a lower risk exposure have a higher likelihood to remain. As houses with high risk becomes increasingly scarce, this shifts demand to low-risk housing, pushing up prices.

Corollary 1. *Within a region, houses on higher elevation trade at higher prices than those on lower elevation. In aggregate, house prices rise over time.*

Land vs Housing Structures The baseline model implicitly assumes that housing equals land, where land is in fixed supply but degrades with climate risk. This implies a perfectly inelastic housing supply in both the short and long run, such that climate damages increase housing prices through land scarcity. I consider a setting that distinguishes between land L_t and effective housing services H_t, allowing households to partially offset land loss by using surviving land more intensively (e.g., by building taller or denser structures) in Appendix B.2. Physical climate risk reduces the effective supply of land, as in the baseline model, and structure intensity is adjusted to its static optimum given remaining land. Housing services, which are delivered competitively, follow from a Cobb-Douglas aggregator (Combes et al., 2021).

In equilibrium, effective housing services are proportional to land supply. Therefore, land loss reduces housing services. However, if households are sufficiently risk-averse with respect to their housing consumption, the marginal value of housing rises to reflect increased scarcity, in line with Proposition

1. This induces greater structure intensity on remaining land. When the price response is positive but moderate, the increase in structure intensity dampens the scarcity effect. Only if housing prices respond sufficiently elastically can higher structure intensity offset physical land loss.

Corollary 2. *Effective housing services decline with land loss if and only if the elasticity of housing prices with respect to land supply, $\epsilon_{p,\bar{L}}$, satisfies*

$$\epsilon_{p,\bar{L}} \equiv \frac{\partial log(p_t)}{\partial log(\bar{L}_t)} > -\frac{(1-\alpha)}{\alpha}.$$

In the remainder of this analysis, I abstract from structures and focus on one type of housing stock within the given region.

B.2 Financial market

Aggregate income of young households must in equilibrium equal the aggregate investment in housing. Hence,

$$\int_0^1 y_i di = p_t \bar{L}_t,$$

where the aggregate labour income of the young is:

$$\int_0^1 y_i di = \phi q + (1-\phi)\, w.$$

In equilibrium, the total savings of labour income must be large enough to cover the purchase of the stock of houses. This indicates that at least one type of households must have positive savings. Since high-skilled households earn higher wages, these households are net lenders. Low-skilled are either net lenders or net borrowers and the volume of mortgage credit in the economy, m, is given by

$$m_t = \max\left\{0, (1-\phi)\left(p_t \bar{L}_t - w\right)\right\}$$

i.e., the size of mortgage credit in the economy is equal to the value of the housing stock owned by low-skilled households, net of their income.

Corollary 3. *The volume of credit rises in climate risk.*

V. Adapting to Climate Change

In this Section, I introduce private adaptation to climate change, allowing households to invest in self-protective measures that increase their resilience and reduce vulnerability to flooding. Private adaptation measures, such as storm-proof windows, flood-proof floors, or the fortification of one's home do not alter the probability of climate-related damages in a given period (γ_t) or the progression of climate risk ($\gamma_{t+1}, ..., \gamma_\infty$). Rather, by investing in adaptation, households reduce the idiosyncratic losses they

experience due to flooding. As a result, household's private adaptation measures directly influence the rate at which inhabitable land degrades, and thus the speed at which the housing supply shrinks.[11]

A. Climate Change Adaptation

Households invest in climate change adaptation at the time they purchase housing capital. Denote by $x_{i,t} \in [0,1)$ the choice of adaptation of household i in period t. This investment comes at a cost. Specifically, the investment costs are given by $\psi(x_{i,t}, L_{i,t}) = \frac{1}{2} L_{i,t}(x_{i,t})^2$. The costs increase with the amount of housing capital, as larger houses require more significant investments, such as a greater number of storm-proof windows, to achieve the same level of protection (Fried, 2022). Moreover, the investment rise at an accelerating rate in the choice of adaptation, indicating that even the most ambitious investments cannot entirely prevent climate-related losses and damages (UNEP, 2022). For simplicity, I assume that the adaptation infrastructure fully depreciates at the end of each period. That is, households must reinvest in adaptation in every period.[12]

By adapting to climate change, households protect themselves against climate-related damages in the next period. Let the choice of adaptation, $x_{i,t}$, represent the fraction of idiosyncratic losses which are prevented due to the investment in resilience. Adaptation thus leads to a leftward shift in the distribution of losses by $x_{i,t} \cdot \mu\gamma_{t+1}$. In expectation, the losses experienced by a given household, $\xi_{i,t+1}$, are given by:

$$\mathbb{E}\left(\xi_{i,t+1}\right) = \left(1 - x_{i,t}\right) \mu\gamma_{t+1}$$

A household with $x_{i,t} = 0$ does not undertake any measures to reduce idiosyncratic losses, while $x_{i,t} \to 1$ indicates that the household has perfectly adapted to climate change and has nearly eliminated all expected losses. Define x_t as the aggregate private investment in adaptation, i.e.

$$x_t = \int_0^1 x_{i,t} di$$

By its virtue of preserving housing capital, climate change adaptation reduces the rate at which the supply of inhabitable houses declines. More specifically, when households adapt to climate change, the

[11] Even when measures are implemented to avoid or reverse land degradation, there will be some residual degradation with high likelihood (IPCC, 2019).

[12] The main insights are not sensitive to this assumption. Suppose that adaptation infrastructure only depreciates when the household experiences damages due to flooding (with probability γ, but remains intact if the household is not hit (with probability $(1-\gamma)$. In this case, households who are not affected by the flood sell both the house and the adaptation infrastructure. Assuming that the adaptation infrastructure is marketable, yet inseparable from the house, and trades at its fair value, households still invest optimally in adaptation. This is because the house price reflects the expected value of selling the adaptation infrastructure along with it. Due to the forward-looking nature of house prices, households implicitly account for the expected value of their adaptation investment for all future generations. Note that, as the marginal benefits of adaptation investment increase when it can be resold, households optimally invest more in adaptation than in the full-depreciation benchmark.

supply of inhabitable houses evolves according to the following law of motion:

$$\begin{aligned}\bar{L}_{t+1} &= \int_0^1 (1-\xi_{i,t})\, di \cdot L_t \\ &\overset{\text{LLN}}{=} (1-(1-x_t)\mu\gamma_{t+1})\, \bar{L}_t\end{aligned}$$

The investment in adaptation in period t prevents some of the reduction in the housing supply in the subsequent period, $t+1$. Therefore, adaptation constitutes an intertemporal investment, leaving the current housing supply, $\bar{L}_t$, unaffected. Consequently, adaptation does not increase the utility of owning housing capital, $v(L)$. Instead, by reducing the damage to housing, adaptation ensures that more of the housing stock stays intact and can be resold in the next period. This gives older households more resources to spend on non-durable goods. Adaptation also benefits future generations. By protecting the housing stock, it ensures that more houses remain available for them to live in and derive utility from. In this way, adaptation investments also benefit future households by preserving housing availability.

Note on Insurance Markets Investing in adaptation fundamentally differs from purchasing insurance, since adaptation aims at prevention, whereas insurance offers monetary compensation after losses occur. While purchasing insurance is an effective measure to reduces the impact of climate risk on household wealth, the ex-post compensation provided cannot alleviate the reduction in the supply of inhabitable houses. Demand for insurance is not separable from households' adaptation choice, however, as climate-related damages directly affect the value of the insured good (Mayers and Smith Jr, 1983). Hence, climate risk insurance affects the private choice of adaptation in the general equilibrium. I explore this in more detail in a model extension, in Section VIII.A.

B. Unconstrained Private Choice of Adaptation

*B.*1 Household Optimization Problem

When households adapt to climate change, the household maximization problem is given by

$$\begin{aligned}\max_{c_{i,t+1},L_{i,t},S_{i,t},x_{i,t}} \mathbb{E}\left(U(c_{i,t+1},L_{i,t})\right) &= \mathbb{E}_t\left(c_{i,t+1}\right) + v\left(L_{i,t}\right) \\ s.t. \quad y_i &\leq \left(p_t + \frac{1}{2}x_{i,t}^2\right) L_{i,t} + S_{i,t} \\ c_{i,t+1} &\leq \max\left\{p_{t+1}\left(1-\xi_{i,t+1}\right) L_{i,t} + \left(1+\hat{r}_{t+1}\right) S_{i,t}, 0\right\} \\ c_{i,t+1}, x_{i,t}, L_{i,t} &\geq 0\end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.

B.2 Optimal Demand for Housing and Adaptation

When households adaptation to climate change, this affects their demand for housing capital. First, by reducing vulnerability to climate risk, investments in adaptation ensure that a larger fraction of housing capital remains undamaged. This increases the per unit revenue of selling housing once households turns old, thus raising housing demand. However, the investment in adaptation absorbs part of households' savings, leaving less resources to be allocated to housing consumption.

Lemma V.1. *When households adapt to climate change, the demand for housing capital of a given household, i, in a given period, t, is given by*

$$L_t^* = v'^{-1}\left((1+r)\left(p_t + \frac{\theta}{2}x_{i,t}^{*2}\right) - \left(1-(1-x_{i,t}^*)\mu\gamma_{t+1}\right)p_{t+1}\right)$$

and the price of housing capital in a given period, t, is given by

$$p_t = \frac{\left(1-(1-x_{i,t}^*)\mu\gamma_{t+1}\right)p_{t+1} + v'(L_t^*)}{(1+r)} - \frac{1}{2}x_{i,t}^{*2}$$

The above expression indicates that the total amount spent per unit of housing capital, i.e., $p_t + \frac{1}{2}x_{i,t}^{*2}$, must equal the discounted value of the benefits from owning housing capital. This expression reveals the trade-off between the present costs and future benefits of adaptation, as adaptation requires an upfront investment cost while it only generates benefits to households once they sell their housing. This trade-off determines the private choice of adaptation in equilibrium, with households investing in adaptation as long as its marginal benefits outweigh its marginal cost.

Lemma V.2. *The optimal private choice of adaptation of a given household i is given by*

$$x_{i,t}^* = \frac{\mu\gamma_{t+1}\cdot p_{t+1}}{(1+r)}$$

The optimal private choice of adaptation increases in climate risk exposure (γ_{t+1}), as well as in the expected losses when hit by the flooding event, μ, since both parameters increase the expected damages to the housing capital owned. Therefore, a rise in households' climate risk exposure strengthens their incentives to invest in adaptation over time.

The optimal private choice of adaptation is crucially influenced by house prices, as the house price reflects the value at risk from flooding to households. Price signals, therefore, play a crucial role in determining private adaptation decisions. As discussed in Section IV.B., house prices are forward-looking. They not only reflect the reduction in households' climate risk exposure due to adaptation efforts but also incorporate the benefits adaptation provides for future generations. By investing in adaptation, households preserve more of the housing stock for the future, making housing less scarce over time. This reduced scarcity weakens the rise in the marginal utility of owning housing. Since this intergenerational benefits is capitalized into house prices, households—guided by price signals—effectively internalize the

long-term benefits of their adaptation investments.[13] Hence, price signals prevent the "tragedy of the horizon" effect, i.e., where a short-term focus of economic agents overlooks long-term climate risks and their impacts on future generations (Carney, 2015).

To illustrate this point, suppose that an unconstrained social planner maximizes utilitarian welfare , i.e.

$$\max_{x_{S,t}} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[-(1+r)\frac{1}{2}\bar{L}_t \cdot x_{S,t}^2 + v(\bar{L}_t)\right]$$

subject to

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} (1-(1-x_{S,\iota})\mu\gamma_{\iota+1})$$

This gives:

$$x_{S,t}^* = x_{i,t}^*$$

Proposition 2. *The optimal private choice of adaptation is efficient.*

Proof: See Appendix A.2

Households determine their private choice of adaptation based on market signals. Consequently, Proposition 2 is sensitive to two underlying assumptions. First, within this framework, climate risk is accurately capitalized into house prices. Although empirical studies show that climate risk is gradually being incorporated into house prices (see e.g., Baldauf et al., 2020; Bernstein et al., 2019; Bosker et al., 2019), it is crucial to assess whether prices in the housing market sufficiently reflect the actual climate risk exposure of a given region. If climate risk is not properly accounted for in market pricing — due to factors such as heterogeneity in beliefs about climate change (see e.g., Bakkensen and Barrage, 2021; Baldauf et al., 2020) or buyers' limited sophistication (see e.g., Bernstein et al., 2019) prices may fail to signal the risks faced by households. As a result, households would underinvest in adaptation, leaving them vulnerable to the impacts of climate change. The accurate pricing of climate risk in housing markets is therefore crucial to incentivize households to adapt optimally.

Second, for Proposition 2 to hold, market signals must accurately reflect the social benefits of a having an additional unit of housing available for the next generation. If a social planner maximizes utilitarian welfare and weights the utility of different generations using market discount rates, the private optimum and social optimum coincide. However, if the social planner assigns a larger weight to the welfare of future generations (i.e., a discount rate lower than the market discount rate), the value of preserving an additional unit of housing would have a higher social value than market prices reflect. In this case, households would underinvest in adaptation from a social perspective.

[13] Note that there is no moral hazard in adaptation by borrowers. This is because borrowers bear the full consequences of their adaptation decisions - as a higher adaptation investment increase the revenue when selling the house. Moreover, there is no information asymmetry on the size of the damages between borrowers and lenders, and borrowers repay the mortgage (or default) right after the flood occurs and housing markets open. Hence, there is no agency problem when households borrow.

Corollary 4. *If the social planner evaluates the welfare of future generations using a discount rate of* $r^{SP} \in [0,1]$ *with* $r^{SP} < r$*, unconstrained households* ***underinvest*** *in adaptation. Denote by* Ω *the social adaptation gap, which is defined as the difference between the private choice of adaptation and the social optimum. In a given period,* t*, the size of the social adaptation gap is given by*

$$\Omega_t = \frac{\mu\gamma_{t+1}}{(1+r)} \cdot \sum_{j=t+1}^{\infty} \left(\left(\frac{1}{1+r^{SP}} \right)^t - \left(\frac{1}{1+r} \right)^t \right) \left[-(1+r)\frac{1}{2}x_j^2 + v'(L_j) \right] \prod_{i=t+1}^{j-1} \left(1-(1-x_i)\,\mu\gamma_{i+1}\right)$$

The choice of the appropriate social discount rate has received large attention in the climate change economics literature (see e.g., Stern, 2007; Nordhaus, 2007; Weitzman, 2007), yet disagreements remain at the heart of the climate policy debate (Nordhaus, 2013).[14] While determining the appropriate discount rate for mitigation efforts – which aim to protect the global climate as a public good – can be complex (Heal and Millner, 2014), this is fundamentally different in the context of adaptation. Unlike the global climate, which is not traded in the market, housing, a private and marketable asset. Because private adaptation directly protects assets with observable market values, equilibrium prices can provide guidance for adaptation investment decisions.

C. Equilibrium and Market Clearing

When households adapt to climate change, this changes the housing - and financial market clearing conditions.

Housing market Total housing demand equals total housing supply, so that $\int_0^1 L_{i,t}^* di = \bar{L}_t$. Therefore, housing market equilibrium requires

$$\bar{L}_{t+1} = \left(1 - (1 - \int_0^1 x_{i,t}^* di)\mu\gamma_{t+1}\right) \bar{L}_t.$$

The housing market clearing condition pins down the equilibrium price of housing capital:

$$p_t^* = \frac{\left(1 - (1 - \int_0^1 x_{i,t}^* di)\mu\gamma_{t+1}\right) p_{t+1} + v'\left(\bar{L}_t\right)}{1+r} - \frac{1}{2}\int_0^1 x_{i,t}^{2*} di$$

[14] Following the Ramsey rule, the relationship between the equilibrium real return on capital, r^*, and the growth rate of the economy, g^* is given by $r^* = \varrho + \kappa \cdot g^*$, where ϱ denotes the pure rate of time preference, g denotes the growth rate of per capita consumption and κ denotes the elasticity of consumption (Nordhaus, 2007). Stern (2007) argues that it is immoral to evaluate the welfare of future generations using a social discount rate based on market discount rates. Rather, the author favours an a priori approach, with $\varrho = 0.1\%$, $\kappa = 1$ and $g^* = 1.3\%$. This gives a real return of capital equal to $r^* = 1.4\%$. Nordhaus (2008) argues that economists have no particular expertise in what is morally right, but must ensure that models replicate reality. Therefore, Nordhaus (2007) advocates a market based approach with $\varrho = 1.5\%$, $\kappa = 2$, and $g^* = 2\%$. This gives a real return on capital equal to $r^* = 5.5\%$. Weitzman (2007) proposed his guess of consensus estimates among economists studying climate change. This gives $\varrho = 2\%$, $\kappa = 2$ and $g^* = 2\%$, translating into a real return on capital equal to $r^* = 6\%$. However, arguing that uncertainty is key to the climate problem, Weitzman (2007) favors a discount rate that declines sharply over time. Even seemingly small differences in proposed social discount rates can translate into large differences in the recommended intensity of climate change mitigation policies (Heal and Millner, 2014).

Forward substitution gives

$$p_t^* = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[-(1+r)\int_0^1 x_{i,j}^{2*} di + v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} \left(1 - \left(1 - \int_0^1 x_{i,\iota}^* di\right) \mu\gamma_{\iota+1}\right)$$

Due to the forward-looking nature of house prices, adaptation efforts reduce the speed at which the housing supply declines. This reduced scarcity dampens the rise in the value households place on owning housing. If Condition (1) holds (see Proposition 1), this scarcity effect dominates in equilibrium. Then, adaptation helps mitigating the effect of climate risk on house prices.

Corollary 5. *Investments in adaptation reduces the rate at which house prices rise.*

Financial market Aggregate income of young households must in equilibrium equal the aggregate investment in housing and adaptation. Hence,

$$\int_0^1 y_i di = \left(p_t + \frac{1}{2}\int_0^1 x_{i,t}^{2*} di\right) \bar{L}_t,$$

In this case, the volume of mortgage credit in the economy, m, is given by

$$m_t = \max\left\{0, (1-\phi)\left(\left(p_t + \frac{1}{2}\int_0^1 x_{i,t}^{2*} di\right) L_t - w\right)\right\}$$

Corollary 6. *Investments in adaptation reduces the rate at which the volume of mortgage credit rises.*

D. Endogenous Credit Constraints

Borrowers are protected by limited liability, which can create incentives for highly indebted households to strategically default. In the baseline model, housing capital is collateralized in order to prevent this. However, the collateral itself is exposed to climate risk, as floods directly reduce both the quantity and value of housing that can be pledged. Because of the deterministic nature of climate risk, mortgage creditors anticipate these potential losses and adjust their lending accordingly. Rational lenders therefore ensure that household debt (including interest) does not exceed the expected liquidation value of undamaged housing capital in the next period (Kiyotaki and Moore, 1997; Sastry, Forthcoming).

The expected liquidation value of the collateral depends on the economy's climate risk exposure and the adaptation efforts undertaken by borrowers. By investing in adaptation, borrowers can mitigate potential losses, thereby directly influencing the liquidation value of the collateral. Adaptation investments are made privately, however, and mortgage creditors are unable to individually verify the investment households have made after credit has been extended.[15] Mortgage creditors thus form expectations on

[15] Even if creditors could, it is nearly impossible to verify that adaptation measures are maintained and remain functional at the time of the flood.

the choice of adaptation of borrowers, denoted by $\mathbb{E}(\bar{x}_{l,t})$. The credit constraint then becomes:

$$(1+\hat{r}_{t+1})(-S_{l,t}) \leq (1-(1-\mathbb{E}(\bar{x}_{l,t}))\,\mu\gamma_{t+1})\,p_{t+1}\cdot L_{l,t}$$

where

$$S_{l,t} = w - \left(p_t + \frac{1}{2}x_{l,t}^2\right) L_{l,t} < 0$$

The left-hand side of the equation represents mortgage credit demanded by borrowers, which depends on current house prices, p_t, borrowers' choice of adaptation, $x_{l,t}$, and their demand for housing, $L_{l,t}$. The right-hand side reflects the expected liquidation value of the undamaged collateral. This liquidation value is influenced by the economy's climate risk exposure, γ_{t+1}, the expected choice of adaptation of borrowers, $\mathbb{E}(\bar{x}_{l,t})$, and future house prices, p_{t+1}. Since there is no aggregate uncertainty, mortgage creditors have perfect foresight on future house prices.

Climate change impacts the credit constraint through multiple channels. Consider first the expected liquidation value of the collateral. While future house prices rise due to the reduced housing supply, house prices are fully recursive and, therefore, this is entirely reflected in the current house price. In other words, as the price at which a given unit of housing capital can be resold rises, this also increases the costs of buying that unit of housing in the first place (see Prop. 1). Additionally, higher climate risk exposure increases the need for adaptation measures, driving up investment costs. Hence, a rise in climate risk increases the down payment required from borrowers, tightening the credit constraint over time.[16]

D.1 Equilibrium with Credit Constraints

As indicated in Section IV.B., high-skilled households are net lenders in equilibrium. Low-skilled households are either net lenders or net borrowers. When these households borrowers, they maximize expected utility subject to the budget constraint, limited liability constraint, and the credit constraint:

$$\begin{aligned}
\max_{c_{l,t+1},L_{l,t},S_{l,t},x_{l,t}} \quad & \mathbb{E}\left(U(c_{l,t+1},L_{l,t})\right) = \mathbb{E}_t\left(c_{l,t+1}\right) + v\left(L_{l,t}\right) \\
s.t. \quad & w \leq \left(p_t + \frac{1}{2}x_{l,t}^2\right) L_{l,t} + S_{l,t} \\
& c_{l,t+1} \leq \max\left\{p_{t+1}\left(1-\xi_{l,t+1}\right) L_{l,t} + \left(1+\hat{r}_{t+1}\right) S_{l,t}, 0\right\} \\
& -(1+\hat{r}_{t+1})S_{l,t} \leq (1-(1-\mathbb{E}(\bar{x}_{l,t}))\mu\gamma_{t+1})\,p_{t+1}L_{l,t} \\
& c_{l,t+1}, L_{l,t}, x_{l,t} \geq 0
\end{aligned}$$

[16] Sastry (Forthcoming) documents empirically that lenders screen for flood risk and, when they retain residual exposures to it, require higher down payments.

D.2 Optimal Demand for Housing and Adaptation

Due to credit constraints, low-income households have limited financial resources to finance the purchase housing capital and their investment in adaptation. In equilibrium, low-income households borrow up to the point where the constraint binds:

Lemma V.3. *The demand for housing capital of credit constrained, low-income households is given by:*

$$L^*_{l,t} = \frac{(1+r_{t+1})w_t}{(1+r_{t+1})\left(p_t + \frac{1}{2}x^2_{l,t}\right) - (1-(1-\mathbb{E}(\bar{x}_{l,t}))\,\mu\gamma_{t+1})\,p_{t+1}}$$

where $\mathbb{E}(\bar{x}_{l,t}) = x^*_{l,t}$ *in a symmetric equilibrium. The choice of adaptation of credit constrained, low-skilled households,* $x^*_{l,t}$*, is given by*

$$x^*_{l,t} = \frac{\mu\gamma_{t+1}\cdot p_{t+1}}{(1+r_{t+1})(1+\lambda_t)}$$

with $\lambda_t \geq 0$ *the shadow price of the credit constraint.*

When credit constraints bind, households cannot afford the optimal amount of housing capital and therefore consume less housing. Due to the quasi-linearity of preferences and diminishing marginal utility of housing, the marginal utility of housing becomes higher for constrained households than for the unconstrained ones. This is captured by a strictly positive shadow price of the constraint, λ_t, which reflects the utility gain of relaxing the constraint by one unit.

The binding constraint distorts the intertemporal allocation decision, which has important implications for adaptation. Adaptation is a forward-looking investment: it increases the resale value of housing by mitigating future climate-related damages. Because credit households must finance adaptation jointly with housing capital, but are liquidity constrained, their effective marginal cost of adaptation is higher. As these households are limited in the extent to which they can borrow against the future, they discount the benefits of adaptation more heavily, essentially behaving as if they are more impatient. As a result, constrained households optimally allocate a larger share of their limited budget to housing capital, which provides utility in the present, and invest *less* in adaptation, which is an investment in resilience against future climate risks.

Proposition 3. *Credit constrained, low-income households adapt relatively less to climate change:*

$$x^*_l < x^*$$

Proof: See Appendix A.3

Proposition 3 has several key implications. Since the adaptation choice, $x_{l,t}$, represents the *fraction* of idiosyncratic losses prevented, the underinvestment in adaptation by credit-constrained households means that these households protect a smaller share of their housing wealth. Consequently, these households remain more vulnerable to climate risks. When a flooding event occur, credit-constrained

households experience a disproportionately larger expected loss of housing wealth, reinforcing existing wealth inequality. In addition, the underinvestment in adaptation by credit-constrained households accelerates the reduction in the supply of habitable land. This exacerbates scarcity over time and generates intergenerational spillovers: future generations face scarcer housing supply and their welfare is therefore lower.[17] Denote by Λ_t the private adaptation gap, which is defined as the optimal private choice of adaptation relative to the constrained choice of adaptation:

$$\Lambda_t = \frac{x^*_{h,t}}{x^*_{l,t}} = (1 + \lambda_t)$$

Proposition 4. *When the utility function of housing ($v(L)$) is characterized by constant relative risk aversion (CRRA), the private adaptation gap rises in climate risk.*

Proof: See Appendix A.4

The private adaptation gap widens over time as habitable land becomes increasingly scarce. The mechanism is dynamic: underinvestment by one generation raises housing scarcity and therefore increases the marginal utility of housing for the next generation. This results in a higher shadow price of the credit constraint. In essence, housing becomes increasingly important relative to future consumption, causing credit-constrained households to allocate a growing share of their resources toward housing consumption rather than toward adaptation investment. This leads to a persistent widening of the private adaptation gap across generations.

Robustness to Alternative Preference Specifications In the main framework, I assume quasi-linear preferences. With quasi-linearity, income does not affect the housing choice of unconstrained households, as housing is the concave part of utility. Once financial constraints bind, constrained households consume less housing and therefore optimally underinvest in adaptation. I show that the distributional implications of Propositions 3 and 4 are robust to the specification of household preferences. Specifically, I verify the robustness of the result to introducing utility curvature in non-durable consumption using CRRA utility, and by introducing non-seperability of the utility function using CES preferences. The preference specification and numerical solution methods are detailed in Appendix B.3. In line with the baseline model, and under either preference specification, the optimal adaptation choice ($x^*_{i,t}$) is strictly increasing in income and the slope $x^*_{i,t}(y_i)$ is steeper in more severe climate scenarios.

Rental Markets and Effective Adaptation Credit constraints prevent households from effectively reducing their vulnerability to climatic impacts, leading to underinvestment in adaptation. Would the economy as a whole benefit if credit-constrained households relied on households with deeper pockets

[17] Due to the rising scarcity of houses, the value at risk increases. Therefore, unconstrained households invest more in adaptation in an economy where a fraction of households is credit constrained, compared to an economy where a fraction of households is credit constrained, compared to an economy without binding credit constraints. However, this does not represent inefficient overinvestment. The adaptation choice of unconstrained households remains first-best, as they simply respond to the rising marginal benefits of housing for future generations as habitable land becomes scarcer.

individuals to mitigate climate impacts? I explore whether it is more efficient for credit-constrained households to rent housing, rather than purchasing it.

In a perfectly competitive rental market, the rental price (per unit of housing L_t), denoted Υ_t, must be such that (unconstrained) households are indifferent between renting or buying housing. Then, the rental price satisfies

$$\Upsilon_t = v'\left(\bar{L}_t\right)$$

Hence, the model implicitly incorporates a rental market, where $v'\left(\bar{L}_t\right)$ represents the imputed rent. The rental price rises over time due to the increased scarcity of habitable land. Nevertheless, it is through the reassignment of ownerships that credit-constrained households become better off by renting housing rather than purchasing it.

When households rent rather than buy, the ownership of housing capital remains with the landlord. This removes the need for credit-constrained households to take out a mortgage, allowing them to consume the optimal level of housing without facing credit constraints. The responsibility for investing in adaptation then shifts to the landlord. Adaptation increases the resale value of housing in the future. In a perfectly competitive rental market, rents reflect the full value of protected housing, including these benefits of adaptation. This price signal incentivizes landlords to invest efficiently in resilience. The rental model thereby also overcomes the information problem due to non-verifiable adaptation by allowing prices to reflect the underlying value of the adaptation investment.

In this sense, the rental contract functions as an equity-like arrangement, where landlords – as residual claimants, bear the investment cost and capture the returns through higher rental income and preserved resale value. In contrast to mortgage markets, where adaptation investments by credit-constrained households are distorted by collateral limits, rental markets can thus foster more efficient adaptation where landlords effectively shield credit-constrained households from the climatic impacts they would otherwise face.

Proposition 5. *If perfectly competitive, rental markets leads to more effective adaptation.*

Proof: See Appendix A.5

VI. Quantitative Assessment and Counterfactual Analysis

I quantify the welfare effects of the underinvestment in adaptation over time. For this purpose, I focus on the version of the model which incorporates firms (see Appendix C). I provide a parameterization based on the U.S. economy in the year 2010 and I simulate the model up to 2150 for Florida's coastal area.[18] Given the overlapping generation structure of the model, each time period equals 30 years. I conduct counterfactual analysis to demonstrate welfare effects under different climate change scenarios as

[18]The projections of climate change used are relative to a 1995-2014 baseline. Hence, the climate risk parameter has a value of 0 between 2000 and 2010.

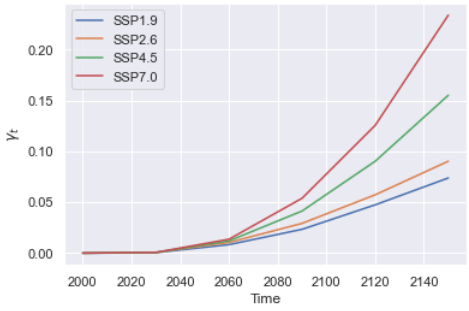


FIGURE 1: THE EVOLUTION OF γ_t UNDER THE SSP1-1.9, SSP1-2.6, SSP2-4.5 AND SSP3-7.0 SCENARIO.

projected by IPCC (2023), similar to (Bilal and Känzig, 2024; Cruz and Rossi-Hansberg, 2024; Bilal and Rossi-Hansberg, 2023). Specifically, I simulate the model under low greenhouse gas emission-scenarios (SSP1-1.9, SSP1-2.6), under an intermediate greenhouse gas emission-scenario (SSP2-4.5) and a high greenhouse gas emission-scenario (SSP3-7.0).[19]

A. The Evolution of Climate Risk

To determine the evolution of climate risk, I assume that γ_t represents the fraction of homes in Florida's coastal area which are at risk of flooding due to future sea level rise. Specifically, I focus on properties that would be flooded for 10 feet of sea level rise. Florida is a low-lying state at the east coast of the United States, and is at high risk of flooding due to sea level rise. Within the next 30 years, approximately 64,000 homes in Florida will be at risk of chronic flooding and 12,000 of those homes are located in the Miami Beach area. This number is expected to grow rapidly, to more than 1 million homes by the end of the century. This implies that Florida alone would account for more than 40 percent of the houses at risk of flooding due to sea level rise in the United States as a whole (Dahl et al., 2018). To evaluate property-level exposure to sea level rise in Florida's coastal areas, I rely on the estimates provided by Bernstein et al. (2019).[20] I focus on aggregate exposure estimates, measuring the total number of properties at risk of flooding for varying levels of future sea level rise.[21] These estimates provide the number of properties expected to be flooded for different levels of future sea level rise. To approximate the evolution of the fraction of houses at risk of flooding due to future sea level rise (γ_t) under different scenarios of sea level

[19]The SSP$x-y$ scenarios describe different climate futures depending on socio-economic trends underlying the scenario (x) and the approximate level of radiative forcing (in watts per square meter) resulting from the scenario in the year 2100 (y). Under SSP1-1.9 (SSP1-2.6), global warming remains approximately below 1.5 (2.0) degrees Celsius above 1850-1900 in the year 2100, which is the target of the Paris Agreement. This scenario requires net zero CO2 emissions by 2050 (in the second half of the century). SSP2-4.5 is in line with the aggregate Nationally Determined Contribution emission levels by 2030. Under this scenario, global warming reaches approximately 2.7 degrees Celsius above 1850-1900 by the end of the century. SSP3-7.0 is a medium to high climate change scenario. Under this scenario, global warming reaches approximately 3.6 degrees Celsius above 1850-1900 by the end of the century.

[20]Bernstein et al. (2019) use geographic mapping software to assess each property's vulnerability to sea level rise. Specifically,the authors combine geolocation data of individual properties with projections from the National Oceanic and Atmospheric Administration (NOAA) sea level rise calculator, which identifies regions expected to be underwater under different sea level rise scenarios.

[21]The estimates cover scenarios from 1 to 10 feet of sea level rise. For example, Bernstein et al. (2019) find that 7.2 percent of properties in Florida's coastal areas would be flooded under 3 feet (0.914 meters) of sea level rise, while 50.7 percent would be flooded under 6 feet (1.83 meters).

Table 1: Parameter Values

Parameter	Description	Value	Source/Target
A	TFP in final-good production	1	Normalization
$\tilde{h}$	Inelastic supply of high-skilled labour	35	Credit allocation target
$\tilde{l}$	Inelastic supply of low-skilled labour	20	Credit allocation target
$\bar{L}$	Initial stock of houses	1	Normalization
α	Capital share in final-good production	0.32	BEA (2010)
η	Relative productivity of intangible inputs	0.67	Credit allocation target
μ	Fraction of damages to housing capital	1	Complete losses due to SLR
μ_K	Fraction of damages to tangible capital	0.7	$\mu/\mu_K = 0.7$ (Fried, 2022)
ρ	Substitution parameter	0	Cobb-Douglas Production
ϕ	Fraction of high skilled labour	0.3	U.S. Census Bureau (2010)
$\tilde{\omega}$	Bargaining power of innovators (scaled)	0.58	Capital structure target

Table 2: Targeted Moments

Target	Description	Data	Model
Credit allocation target	Household debt/(Household + corporate debt)	0.68	0.65
Capital structure target	Corporate debt/(Corporate debt + equity)	0.26	0.29

rise, I use the NASA Sea Level Projection Tool (Garner et al., 2021; Fox-Kemper et al., 2021; Garner et al., in prep.). This tool visualizes the median projections of global and regional sea level rise, relative to a 1995-2014 baseline. These projections are based on IPCC (2023). Projections are provided for various regions and cities in Florida. As there is relatively little variability in their projection, I focus on the projections for the Miami-beach area.[22] By the end of the century, this region is expected to experience sea level rise of 0.71 meters under an intermediate greenhouse gas emission scenario (SSP2-4.5). The evolution of the fraction of houses at risk of flooding due to future sea level rise, under the different SSP$x-y$ trajectories, is depicted in Figure 1. Under the intermediate climate change scenario, approximately 15 percent of homes are at risk of flooding due to sea level rise by the mid of the next century.

B. Other Parameters and Functional Form Specifications

Other parameter values are specified in Table 1. I use a number of internally and externally calibrated parameters. Externally calibrated parameters are reported as of 2010 for the Unites States.[23] I internally

[22] Projections are provided for Virginia Key, Lake Worth Piert, Trident Pier (Port Canaveral), Dayone Beach, Mayport (Bar Pilots Doc), Fernandina Beach, Vace Key, Key West, Naples, Fort Myers, St. Petersburg, Clearwater Beach, Cedar Key, Apalachicola, Panama City, St. Andrews Bay, and Pensacola. By the end of the century, these regions are expected to experience a sea level rise between 0.64 and 0.73 meters by the end of the century under an intermediate greenhouse gas emission scenario (SSP2-4.5).

[23] The capital share in final-good production is based on net capital share of gross domestic income, as reported by the Bureau of Economic Analysis (BEA). The net capital share is calculated as gross domestic income less consumption of fixed capital, taxes on production and imports less subsidies, less compensation of employees, divided by gross domestic income less consumption of fixed capital, taxes on production and imports less subsidies. All values are reported by the Bureau of Economic Analysis (BEA). The fraction of high-skilled labour is 0.3 and is measured as the fraction of U.S. citizens of 25 years and that have completed at least 4 years of college education. This data is provided by the U.S. Census Bureau.

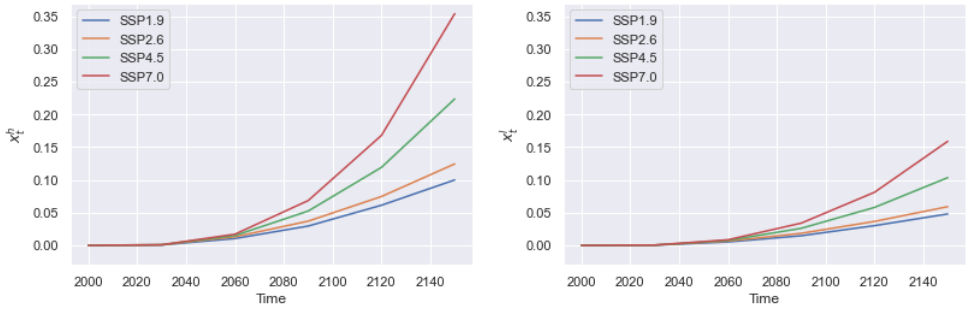


FIGURE 2: THE EVOLUTION OF THE OPTIMAL CHOICE OF ADAPTATION, x_t^h (LEFT) AND THE CONSTRAINED CHOICE OF ADAPTATION, x_t^l,(RIGHT), UNDER THE SSP1-1.9, SSP1-2.6, SSP2-4.5 AND SSP3-7.0 SCENARIO.

calibrate the supply of labour and the relative productivity of the distinct types of capital. Specifically, I choose the value of these parameters to target the ratio of household to (non-financial) corporate debt in the U.S. economy in 2010 (Federal Reserve Board, 2010).[24] The bargaining power of the entrepreneurs is set to match an aggregate capital structure target of the U.S. economy, given by the size of the (non-financial) corporate debt market relative to the market value of equity plus (non-financial) corporate debt (Fred, 2010).[25] I normalize the supply of houses and set it equal to one in 2010. The expected idiosyncratic damages conditional on suffering losses from the climate impact, μ, is equal to one, as the simulation focuses on sea level rise. I target a ratio of damages to housing relative to productive capital of 0.7, which is based on Fried (2022). Finally, I set ρ equal to zero, such that the production technology is Cobb-Douglas, and the functional form of the utility of housing is $v(L) = ln(L)$.

C. The Evolution of Private Adaptation

To solve the model, I assume a steady state is reached by 2150, which is last year for which sea level rise projections are available. That is, I assume that climate risk remains constant after this period and solve the model backwards from this point. I compare the simulations of an economy with climate change and in which households are financially unconstrained to those of an economy where credit constraints hinder households efforts to adapt to climate change. Let left panel of Figure 2 shows the evolution of the optimal private choice of adaptation, x_t^h, which increases in the economy's climate risk exposure. The fraction of idiosyncratic losses which unconstrained households choose to prevent by investing in resilience rises to approximately 35 percent under the most severe climate change scenario and by the mid of the next century. At the same time, the adaptation gap widens, as becomes clear from the right panel of Figure 2. This panel depicts the evolution of the constrained private choice of adaptation, x_t^l, over time. Depending on the severity of the climate change scenario, the difference between the private adaptation choice of credit constrained and unconstrained households grows to 5-20 percent. Essentially,

[24]Data on the financial accounts of the United States for non-financial sectors is available via the Federal Reserve Board. See https://www.federalreserve.gov/releases/z1/dataviz/z1/nonfinancial_debt/table/.

[25]Data on non-financial corporate debt as a percentage of the market value of corporate equities in the United States is available via the Federal Reserve bank of St. Louis. See https://fred.stlouisfed.org/series/NCBCMDPMVCE.

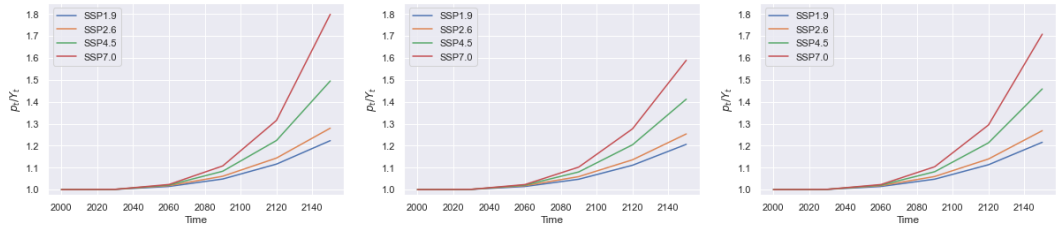


FIGURE 3: THE EVOLUTION OF HOUSE PRICES TO INCOME (INDEXED TO 1 IN 2000) UNDER THE DIFFERENT SSP$x-y$ SCENARIOS, FOR THE MODEL WITH CLIMATE CHANGE ONLY (LEFT), THE MODEL WITH EFFICIENT ADAPTATION (MIDDLE) AND UNEQUAL ADAPTATION (RIGHT) TO CLIMATE CHANGE.

this represents the difference in the housing wealth these households protect.

D. The Evolution of the House Prices

In the model, climate risk leads to an endogenous decline in the supply of inhabitable houses. Consistent with Proposition 1, this drives up house prices over time. The left panel of figure 3 illustrates this effect by plotting the ratio of house prices to income in the model with climate change only, which rises by approximately 50–80 percent under medium to severe climate scenarios by the middle of the next century. Adaptation moderates the decline in housing supply by allowing households to invest in damage-limiting measures, thereby weakening the scarcity effect on prices. The middle panel shows that when households adapt efficiently, the increase in the house price-to-income ratio is more moderate, rising by 40–60 percent over the same horizon. By contrast, in the unequal adaptation scenario (right panel), where not all households can preserve their housing stock effectively, the ratio still rises by approximately 45–70 percent. This highlights the aggregate importance of efficient adaptation in housing scarcity and moderating long-run price increases.

E. The Evolution of the Wealth Inequality

Credit constraints prevent low-income households from consuming the optimal amount of housing and from investing optimally in adaptation. This has implications for their accumulation of wealth. While low-income households invest less in both housing and adaptation relative to unconstrained households, they also reap relatively fewer benefits from selling the undamaged fraction of their housing due to underinvestment. Define Δc^{λ}_{t+1} as the consumption equivalent difference between the time $t+1$ capital gain on housing (i.e., the difference between the future sales price and the investment in housing) for high-income households versus low-income households. Figure 4 demonstrates that wealth inequality (in consumption-equivalent terms) increases due to the underinvestment channel. Specifically, consumption inequality rises by 7–8 percent under medium to severe climate scenarios by the middle of the next century due to this underinvestment.[26] This rise in consumption-equivalent wealth inequality is entirely driven by credit constraints. Consequently, shifting from a model of constrained homeownership to a

[26]By comparison, the Gini coefficient –, a common measure of wealth inequality –, has risen by approximately 9.8 percent over the past 60 years.



FIGURE 4: THE EVOLUTION OF CONSUMPTION INEQUALITY DUE TO THE CREDIT CONSTRAINT CHANNEL, Δc^{λ}_{t+1} (INDEXED TO 1 IN 2000), UNDER THE DIFFERENT SSP$x-y$ SCENARIOS.

rental market with unconstrained landlords could fully offset this inequality effect. By transferring the responsibility for adaptation investments to deep-pocketed landlords, credit-constrained households are shielded from excessive climate-related housing damages. Therefore, landlord-based adaptation becomes crucial for moderating the redistributive consequences of climate change.

F. Welfare Implications

Credit constraints prevent low-income households from investing efficiently in climate adaptation. This has implications for wealth inequality, as these households lose a relatively larger fraction of their housing wealth upon the realization of a climate impact. It also has implications for welfare more broadly.

To assess the welfare implications of the underinvestment channel, I determine how much utility a low-income household gains per unit of housing saved through better adaptation. I define the marginal value of housing saved through adaptation as the product of the marginal utility of housing and the marginal effect of adaptation on housing preservation. This reflects the full marginal benefit of adaptation, and can be interpreted as the willingness to pay for preserving an additional unit of housing through adaptation. Panel A of Table 3 reports the marginal value of housing preserved through adaptation under the distinct climate change scenarios. The first row reports the marginal value in consumption equivalent units, representing the amount of consumption a household would be willing to forgo to obtain a marginal increase in the amount of preserved housing. The second row reports the same value relative to a household's consumption. Even a small increase in adaptation yield sizable welfare gains. By the mid of the next century, a household would be willing to trade up to 11.7 percent of their consumption (or 13.4 percent of their income) for a marginal increase in preserved housing. The fourth row expresses the value of saved housing as a fraction of the market value of the entire home. This share rises from 4.7 to 17.9 percent, reflecting the increasing benefits of adaptation in more severe climate futures.

To quantify the inefficiency caused by credit constraints, I further compute how much better off a household would be if it could adapt at the optimal (unconstrained) level rather than at the constrained private level. This reflects the utility cost of the underinvestment in adaptation. I define the utility cost of housing lost through the underinvestment in adaptation as the product of the marginal utility of housing and the forgone housing preservation due to the sub-optimal adaptation choice. Panel B of

Table 3: Marginal value of adaptation.

	SSP1–1.9	SSP1–2.6	SSP2–4.5	SSP3–7.0
A. Marginal value of housing *saved* through adaptation				
Consumption equivalent	0.038	0.047	0.083	0.127
Relative to consumption (%)	3.690	4.509	7.724	11.726
Relative to income (%)	3.971	4.909	8.679	13.393
Relative to house value (%)	4.464	5.641	10.731	17.921
B. Utility cost of housing *lost* through the underinvestment				
Consumption equivalent	0.002	0.003	0.010	0.0247
Relative to consumption (%)	0.192	0.295	0.929	2.288
Relative to income (%)	0.207	0.321	1.044	2.613
Relative to house value (%)	0.232	0.369	1.290	3.497

Table 3 reports the utility cost of housing lost through the underinvestment in adaptation under the distinct climate change scenarios. The utility cost of lost housing, relative to consumption, reaches up to 2.3 percent (or 2.6 percent relative to income) under the most severe climate scenario. These costs are borne by constrained households, who underinvest in adaptation. The corresponding loss amounts to up to 3.5 percent of the market value of the home. Taking into account the mean home value in the Miami-area[27] and the model-implied rise in house prices, this implies a welfare loss of approximately $15,700 per household per housing unit. This highlights the long-term implications of constrained adaptation and signals the benefits of improving access to finance or switching to landlord-driven adaptation. Taken together, these results demonstrate the growing value of climate change adaptation as well as the costs of inaction. Importantly, these costs are not evenly distributed: they fall disproportionately on credit-constrained households, who are unable to finance efficient adaptation. As climate risks rise, unequal access to adaptation finance leads to rising welfare inequality.

G. Extension: Insurance Markets

Insurance plays a key role in mitigating the impact of climate change on household wealth, since households can insure against climate related damages, both publicly and privately, through flood - or home insurance. In the context of climate change, a challenge arises as multiple households face similar climate-related risks, leading to the correlation of losses. This complicates the insurance landscape.

*G.*1 Institutional Context

In Florida, homeowners are not legally required to have flood insurance. However, mortgage lenders often require it to protect against the risk of physical damage to the property that serves as collateral, as this could lead to a decline in its value.[28] Government-backed lenders further mandate flood insurance

[27] I use the Zillow Home Value Index (ZHVI), which captures the typical home value across housing types within a region, focusing on homes in the 35th to 65th percentile range. Specifically, I use the smoothed, seasonally adjusted ZHVI for all homes at the county level. In line with the focus of the model simulation on the Miami area, I focus on the Miami-Dade County. To abstract from short-term volatility unrelated to climate change, I compute the average ZHVI over the 2000–2024 period using year-end values. This yields a base home value of 271,423.40 US dollars.

[28] For simplicity, I do not model any relation between the insurance and mortgage contract.

for properties located in areas designated as "Special Flood Hazard Areas" by the Federal Emergency Management Agency (FEMA). Flood damage, caused by storms, heavy rain, or overflowing water bodies, are typically not covered by home insurance policies. Therefore, homeowners who live in a flood zone must obtain separate flood insurance.

Flood insurance is offered through the National Flood Insurance Program (NFIP), a federally-backed initiative administered by the government for homeowners, renters, and businesses. Eligibility for NFIP coverage depends on the property's flood zone and the community's participation in the program. The NFIP covers physical damages directly caused by flooding, up to a limit of 250,000 US dollars for building coverage. In Florida, the average annual cost of NFIP flood insurance is 760 US dollars, and the average claim payout is approximately 29,000 US dollars. Homeowners can also apply for FEMA disaster assistance in addition to an insurance claim. This is available only for properties in areas that have received a Presidential Disaster Declaration.[29] The average FEMA disaster relief payment in Florida is about 5,100 US dollars. Additional flood coverage is available through private insurers. However, private insurance providers are increasingly exiting the Florida market due to the high risks associated with climate change (Sastry et al., 2023; Nicholson et al., 2020). Also Citizens, a state-backed insurer of last resort for those who cannot find affordable coverage through private insurers, potentially brings forward a role for the state in providing coverage as private options fail, does not provide flood insurance.[30]

*G.*2 Climate Risk Insurance

Households may insure damages to their housing capital at the time of purchase. Insurance is provided by insurance intermediaries, which are owned by households. Denote by $\pi_{i,t} \in [0,1]$ the amount of coverage (per unit of housing capital, $L_{i,t}$) chosen by household i, at time t. Thus, $\pi_{i,t} = 1$ indicates that the household purchases full coverage for insured losses, while $\pi_{i,t} < 1$ indicates that the household chooses fractional coverage. Insurance has empirically become increasingly less available, with private insurers exiting the market or limiting the value of losses covered. (Sastry et al., 2023; Boomhower et al., 2024). Since multiple households face similar climate-related risks, and losses thus are correlated, providing coverage will become increasingly challenging as climate risks continue to rise.

The expected payout that insured households receive per unit of housing capital insured equals the future price times the expected losses covered, i.e., $\mathbb{E}\left(\xi_{i,t+1}\right) \cdot p_{t+1}$. Insurers have perfect foresight on the climate risk exposure of the economy, and on future house prices since there is no aggregate uncertainty. However, since it is prohibitively costly to verify individual households' private adaptation choices (see Section V.D.), insurance intermediaries also form expectations on the choice of adaptation of a given household, denoted by $\mathbb{E}\left(\bar{x}_{i,t}\right)$. Denote the insurance premium for full coverage by z_t. Insurance is actuarially priced, that is, the premium reflects the discounted expected payout per unit of insured

[29] Homeowners in flood zones who have previously received federal disaster aid are required to maintain flood insurance to remain eligible for future aid.

[30] Citizens is gradually introducing flood insurance requirements for its home insurance customers. Specifically, in 2023, customers in high-risk flood zones were required to have flood insurance, regardless of mortgage status. By January 2027, all Citizens home insurance customers will need to have flood insurance.

housing capital.[31] [32] Then, the insurance premium is given by

$$z_t = \frac{(1 - \mathbb{E}(\bar{x}_{i,t}))\mu\gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

The rise in climate risk leads to larger expected damages. Simultaneously, the rise in house prices increases the value of the insured asset. This increases the expected payout, raising insurance premia over time.[33]

G.3 Optimal Demand for Adaptation with Insurance

Since households are risk-neutral with respect to their consumption of the non-durable good, there is no demand for insurance, i.e., $\pi^*_{i,t} = 0$. Nevertheless, even without a strictly positive demand for insurance, the implication of insurance on house prices and the private choice of adaptation can be studied – which is the main purpose of this model extension. When households can insure the losses due to flooding, the household maximization problem is given by:

$$\begin{aligned}
\max_{c_{i,t+1}, L_{i,t}, S_{i,t}, x_{i,t}, \pi_{i,t}} \quad & \mathbb{E}_t\left(c_{i,t+1}\right) + v(L_{i,t}) \\
s.t. \quad y_{i,t} &\leq \left(p_t + z_t\pi_{i,t} + \frac{1}{2}x_{i,t}^2\right) L_{i,t} + \ + S_{i,t} \\
c_{i,t+1} &\leq \max\left\{p_{t+1}(1 - (1-\pi_{i,t})\xi_{i,t+1})L_{i,t} + (1+\hat{r})S_{i,t}, 0\right\} \\
c_{i,t+1}, L_{i,t}, x_{i,t}, \pi_{i,t} &\geq 0.
\end{aligned}$$

Lemma VI.1. *When households can insure against losses due to flooding, the optimal private choice of adaptation is given by:*

$$x_{i,t} = \frac{(1 - \pi_{i,t}) \cdot \mu\gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

Climate risk insurance leads to moral hazard in adaptation. Due to the non-verifiability of the private efforts undertaken, insurance allows households to limit the downside from a disaster in a relatively cheaper way than by investing in adaptation. Specifically, the marginal costs of insurance are constant, while the marginal costs of adaptation – which requires an increasingly costly investment to prevent a larger fraction of damages – are rising. Hence, as households do not bear the full consequences of their action any longer, insurance provision reduces households' willingness to undertake adaptation investments. The private adaptation investment falls by a fraction $\pi_{i,t}$ in response. That is, households invest in adaptation to mitigate the *uninsured* damages to their housing only. In the case of full coverage

[31] Since insurance is actuarially fair, premia simply reflect each household's expected losses, thus leaving no net transfer across the system in expectation.

[32] In the U.S., insurance premia are heavily subsidized, preventing full risk pricing. This is also the case in government-provided insurance programs as the NFIP. This provides an implicit subsidy to homeowners living in high risk areas and hinders price signals. While I abstract from mispricing in this framework, this would strengthen the moral hazard effect and further reduce investments in adaptation.

[33] Keys and Mulder (2024) study homeowner insurance and document an increase in the average insurance premium between 2020-2023, which is the result of a stronger relationship between premiums and local disaster risk.

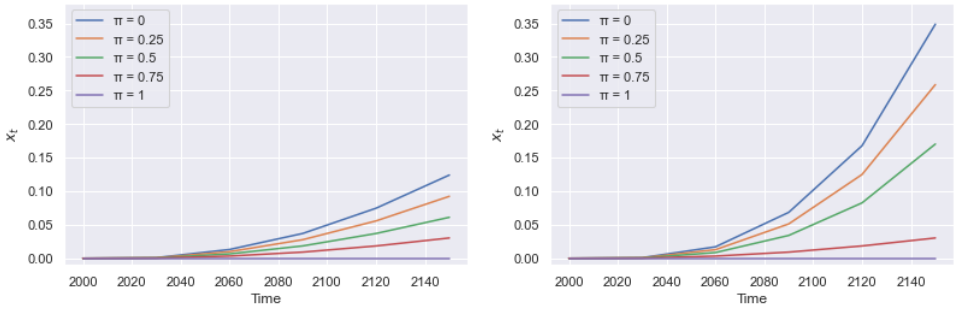


FIGURE 5: THE EVOLUTION OF THE PRIVATE CHOICE OF ADAPTATION, x_t, FOR VARIOUS CHOICES OF INSURANCE COVERAGE, π, UNDER SSP2-4.5 (LEFT) AND SSP3-7.0 (RIGHT).

and without any insurance limit, this means that households do not invest in adaptation at all, and rather rely on insurance to provide compensation for damages after they have occurred. The choice of insurance is not separable from their adaptation decision (Mayers and Smith Jr, 1983), however, since insurance coverage affects the price of the insured good. That is, even though the premium is actuarial, insurance provision affects the price of housing capital in the general equilibrium.

Lemma VI.2. *When households can insure against losses due to flooding, the price of housing capital is given by:*

$$p_{t+1} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-(t+1)} \left[-(1+r)\left(z_j \pi_j + \frac{1}{2}x_j^2\right) + v'(\bar{L}_j)\right] \cdot \prod_{i=t+1}^{j-1} (1-(1-\pi_i)(1-x_i)\mu\gamma_{i+1})$$

where $\pi_t = \int_0^1 \pi_{i,t} di$.

The provision of insurance reduces incentives for households to invest in adaptation, leading to a faster reduction in the housing supply. This accelerates the rise in house prices. As households' adaptation choices depend on house prices — which reflect the value at risk – this "home equity effect" provides a countervailing force against the moral hazard effect. However, as there is moral hazard in the first place, the home equity effect never dominates in equilibrium. More specifically, this is because the elasticity of future house prices with respect to the choice of insurance remains less than unity. Therefore, climate risk insurance provision crowds out private adaptation. Figure 5 illustrates this over time.

Proposition 6. *The provision of climate risk insurance crowds out private adaptation.*

Proof: See Appendix A.6

While encouraging partial coverage (i.e., altering quantities) alleviates moral hazard (Stiglitz and Weiss, 1981), a trade-off emerges between reducing inequality across generations and reducing inequality within generations. While a higher insurance coverage would reduce the redistributive effects of climate change *within* a generation due to the monetary compensation provided for damages, a too high coverage discourages investments in resilience against climate risks, which increases wealth inequality *across*

generations. This has implication for the optimal design of climate risk insurance, which should account for its distributional consequences - both across and within generations. Policymakers must carefully balance this trade-off in designing effective insurance schemes.

VII. Conclusion

This paper explores the broader macro-financial implications of climate change and adaptation, by embedding climate risk in a general equilibrium framework. Households are exposed to physical climate risks, which damage the housing and degrades land. While the exposure to climate risk weakens demand for housing, I show that the materialization of climate change raises house prices, as habitable land becomes increasingly scarcer. This leads to an rise in household debt and a reallocation of credit in the economy towards households.

I analyze the changing incentives of households to invest in climate change adaptation against the backdrop of rising climate risk. Although in frictionless markets price signals lead to efficient adaptation, credit-constrained households have weaker incentives to adapt to climate change, indicating that pricing alone may be insufficient. This reinforces wealth inequality and further weakens the incentives of future credit constrained households to invest in resilience, leading to a widening of the private adaptation gap over time. Credit constraints present a significant challenge to effective climate adaptation necessitating policy action to address the differential impacts of climate change. One such policy is to encourage credit constraint households to rent rather than buy housing. I demonstrate that such a counterfactual shift from constrained homeownership to a rental model with unconstrained owners could lead to more efficient adaptation.

The results in this paper indicate that low-income households do not need to live in a riskier area to be more exposed to climatic impacts. A potential limitation of the analysis is that migration is not explicitly considered. Cruz and Rossi-Hansberg (2024); Bilal and Rossi-Hansberg (2023); Desmet and Rossi-Hansberg (2015); Muis et al. (2015). Bilal and Rossi-Hansberg (2023) show that migration is a key adaptation mechanism, as it reduces substantially the welfare impact of climate change. However, migration is also very costly (Aron-Dine, 2024; Desmet and Rossi-Hansberg, 2015). Therefore, migrating only offers an alternative to investing in self-protective measures to those who are able to afford it. While not considered explicitly, the model provides insights on how the possibility of migrating affects equilibrium outcomes. Suppose that, instead of investing in adaptation, households could choose their home's distance from the coast. If relocating further inland entails a convex adjustment cost, the migration decision would resemble the adaptation decision, leading to under-migration by credit-constrained households. Unlike adaptation, migration would only reduce households' expected property damages without affecting the overall rate of land degradation. This distinction underscores the significant role of adaptation in slowing the loss of habitable land, whereas migration "merely" reallocates exposure to risk.

Finally, this paper focused on analyzing household incentives to adapt to climate change, while abstracting from mitigation strategies. Given the non-linear nature of climate change, it is important to

recognize that adaptation alone cannot completely prevent potentially large economic losses (see also Bilal and Rossi-Hansberg, 2023). Indeed, the extent to which we succeed in mitigating climate change directly affects the necessity for adaptation measures. Adaptation and mitigation strategies both involve substantial costs. Thus, a trade-off between these may emerge, especially when decisions are made when financial resources are scarce. The interplay between adaptation and mitigation strategies is left as avenue for future research.

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Appendix A: Proof of Propositions

A.1 Proof of Proposition 1

Suppose climate risk rises in all future periods by some factor $\sigma > 1$, i.e. $\{\sigma\gamma_{t+1}, ..., \sigma\gamma_{\infty}\}$. Then, the price of house capital is given by

$$p_t^* = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} (1 - \mu\sigma\gamma_{\iota+1})$$

Then, the FOC of p_t with respect to σ is given by

$$\frac{\partial p_t}{\partial \sigma} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \frac{\partial \bar{L}_j}{\partial \sigma} \cdot \prod_{\iota=t}^{j-1}(1 - \mu\sigma\gamma_{\iota+1}) + v'\left(\bar{L}_j\right) \cdot \frac{\partial}{\partial \sigma}\left(\prod_{\iota'=t}^{j-1}(1 - \mu\sigma\gamma_{\iota'+1})\right)\right]$$

Remark that

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} (1 - \mu\sigma\gamma_{\iota+1})$$

and

$$\frac{\partial \bar{L}_j}{\partial \sigma} = -\mu \bar{L}_t \sum_{\iota=t}^{j-1} \gamma_{\iota+1} \prod_{\iota'=t,\iota'\neq\iota}^{j-1} (1 - \mu\sigma\gamma_{\iota'+1})$$

then

$$\frac{\partial p_t}{\partial \sigma} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[-\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j - v'\left(\bar{L}_j\right)\right] \cdot \mu \sum_{\iota=t}^{j-1} \gamma_{\iota+1} \prod_{\iota'=t,\iota'\neq\iota}^{j-1} (1 - \mu\sigma\gamma_{\iota'+1})$$

This is positive if

$$-\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j - v'\left(\bar{L}_j\right) \geq 0$$

or, equivalently if

$$-\frac{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j}{v'\left(\bar{L}_j\right)} \geq 1$$

A.2 Proof of Proposition 2

The unconstrained social planner maximizes utilitarian welfare, i.e.

$$\max_{x_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^{t} \left[-\frac{1}{2}(1+r)\bar{L}_t \cdot x_t^2 + v(\bar{L}_t)\right]$$

subject to

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} (1 - (1 - x_\iota)\mu\gamma_{\iota+1})$$

The first order condition for x_t is

$$\left(\frac{1}{1+r}\right)^{t} \cdot (1+r)x_t \cdot \bar{L}_t = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j} \left[-(1+r)\frac{1}{2}x_j^2 + v'(\bar{L}_j)\right] \frac{\partial \bar{L}_j}{\partial x_t}$$

Using that

$$\frac{\partial \bar{L}_j}{\partial x_t} = \mu\gamma_{t+1} \cdot \bar{L}_t \prod_{\iota=t+1}^{j-1} (1 - (1 - x_\iota)\mu\gamma_{\iota+1})$$

this becomes

$$(1+r)x_t = \mu\gamma_{t+1} \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-(1+r_{j+1})\frac{1}{2}x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1 - (1 - x_\iota)\mu\gamma_{\iota+1})$$

The first-order condition of the unconstrained household is

$$(1+r)x_t = \mu\gamma_{t+1} \cdot p_{t+1}$$

and the first-order condition of the unconstrained social planner is

$$(1+r)x_t = \mu\gamma_{t+1} \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r)x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1-(1-x_\iota)\mu\gamma_{\iota+1})$$

A necessary and sufficient condition for the privately optimal level of investment to be efficient is

$$p_{t+1} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r)x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1-(1-x_\iota)\mu\gamma_{\iota+1})$$

which holds. Therefore, under the condition that the social planner discounts the welfare of future generations using the market-implied discount rate, the first-order condition of the unconstrained social planner is equivalent to the first-order condition of the unconstrained household. This implies that the market outcome is efficient.

A.3 Proof of Proposition 3

The first-order condition for L_l^* is derived from the constrained household problem as

$$-(1+r)(1+\lambda)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda) + p_t\right) + (1+\lambda)\left(1-\left(1-x_{l,t}^*\right)\mu\gamma_{t+1}\right)p_{t+1} + v'\left(L_{l,t}^*\right) = 0$$

This condition defines an implicit expression for λ_t, i.e.

$$\lambda_t = \frac{\left(1-\left(1-x_{l,t}^*(\lambda_t)\right)\mu\gamma_{t+1}\right)p_{t+1} + v'\left(L_{l,t}^*\right) - (1+r)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda_t) + p_t\right)}{(1+r)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda_t) + p_t\right) - p_{t+1}\left(1-\left(1-x_{l,t}^*(\lambda_t)\right)\mu\gamma_{t+1}\right)}$$

Since λ_t denotes the change in the optimal level of utility for loosening the constraint by one unit, it holds by construction that $\lambda_t \geq 0$. What remains to be determined, is under which condition $\lambda_t = 0$.

As the denominator is strictly positive, the following condition must hold:

$$p_t = \frac{\left(1-\left(1-x_{l,t}^*(0)\right)\mu\gamma_{t+1}\right)p_{t+1} + v'\left(L_{l,t}^*\right)}{1+r} - \frac{1}{2}x_{l,t}^{*,2}(0)$$

In this case, $\lambda_t = 0 \implies x^*_{l,t} = x^*_{h,t}$. Recall that the price of housing capital is defined as

$$p_t = \frac{\left(1 - (1 - x^*_{h,t})\mu\gamma_{t+1}\right) p_{t+1} + v'\left(L^*_{h,t}\right)}{1+r} - \frac{1}{2}x^{*,2}_{h,t}$$

Then, a necessary and sufficient condition for the above condition to hold is that $v'\left(L^*_{l,t}\right) = v'\left(L^*_{h,t}\right)$. This implies that $L^*_{l,t} = L^*_{h,t}$, which can only hold if the constraint doesn't bind. However, in the presence of binding credit constraints, $L^*_{l,t} < L^*_{h,t} \implies v'\left(L^*_{l,t}\right) > v'\left(L^*_{h,t}\right)$. By contradiction, it must then be the case that $\lambda_t > 0$.

A.4 Proof of Proposition 4

To evaluate the effect of a rise in γ_{t+1} on λ_t, the expression for λ_t is first rewritten as:

$$(1+\lambda_t) = \frac{v'\left(L^*_{l,t}\right)}{v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r)\cdot x^{*2}_{l,t}(\lambda_t)\cdot\lambda_t^2}$$

Then, the FOC becomes

$$\frac{\partial\lambda_t}{\partial\gamma_{t+1}} = \frac{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}\cdot\frac{\partial L^*_{l,t}}{\partial\gamma_{t+1}}\cdot\left[v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r)\cdot x^{*2}_{l,t}\cdot\lambda_t^2\right]}{\left(v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r)\cdot x^{*2}_{l,t}(\lambda_t)\cdot\lambda_t^2\right)^2}$$
$$- \frac{v'\left(L^*_{l,t}\right)\cdot\left[\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}}\cdot\frac{\partial L^*_{h,t}}{\partial\gamma_{t+1}} + (1+r)\cdot\left(\frac{\partial x^*_{l,t}}{\partial\lambda_t}\cdot\frac{\partial\lambda_t}{\partial\gamma_{t+1}}\cdot x^*_{l,t}\lambda_t^2 + x^{*2}_{l,t}\lambda_t\cdot\frac{\partial\lambda_t}{\partial\gamma_{t+1}}\right)\right]}{\left(v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r)\cdot x^{*2}_{l,t}(\lambda_t)\cdot\lambda_t^2\right)^2}$$

This FOC is positive if

$$\frac{\partial\lambda_t}{\partial\gamma_{t+1}}\left[1 + v'\left(L^*_{l,t}\right)\cdot(1+r)\cdot\left(\frac{\partial x^*_{l,t}}{\partial\lambda_t}\cdot x^*_l\cdot\lambda_t^2 + x^{*2}_{l,t}\cdot\lambda_t\right)\right] \geq$$
$$\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}\cdot\frac{\partial L^*_{l,t}}{\partial\gamma_{t+1}}\cdot\left[v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r)x^{*2}_{l,t}\cdot\lambda_t^2\right] - v'\left(L^*_{l,t}\right)\cdot\left[\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}}\cdot\frac{\partial L^*_{h,t}}{\partial\gamma_{t+1}}\right]$$

Using that

$$\frac{\partial x^*_{l,t}}{\partial\lambda_t} = -\frac{x^*_{l,t}}{(1+\lambda_t)}$$

the LHS is rewritten

$$\frac{\partial\lambda_t}{\partial\gamma_{t+1}}\underbrace{\left[1 + \lambda_t\cdot v'\left(L^*_{l,t}\right)\cdot(1+r)\cdot x^2_{l,t}\cdot\left(1 - \frac{\lambda_t}{(1+\lambda_t)}\right)\right]}_{\geq 0}$$

which is positive. Hence, the RHS remains to be evaluated. The RHS is rewritten as

$$\underbrace{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}}_{\leq 0}\cdot\underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0}\cdot\underbrace{\frac{1}{v'\left(L^*_{l,t}\right)}}_{\geq 0}-\underbrace{\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}}}_{\leq 0}\cdot\underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0}\cdot\underbrace{\frac{1}{v'\left(L^*_{h,t}\right)}}_{\geq 0}+\underbrace{\frac{\left(\frac{1}{2}(1+r_{t+1})x^{*2}_{l,t}\lambda^2_t\right)}{v'\left(L^*_{h,t}\right)}}_{\geq 0}\cdot\underbrace{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}}_{\leq 0}\cdot\underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0}\cdot\underbrace{\frac{1}{v'\left(L^*_{l,t}\right)}}_{\geq 0}$$

Then, in order for $\partial\lambda_t/\partial\gamma_{t+1}$ to be positive, it must hold that

$$\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}\cdot\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}\cdot\frac{1}{v'\left(L^*_{l,t}\right)}-\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}}\cdot\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}\cdot\frac{1}{v'\left(L^*_{h,t}\right)}\geq 0$$

Suppose the utility function is characterized by CRRA with relative risk aversion coefficient ς. Then, the expression becomes

$$-\varsigma\left(\underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0}\cdot\frac{1}{L^*_{l,t}}-\underbrace{\frac{\partial L^*_{h,t}}{\partial \gamma_{t+1}}}_{\leq 0}\cdot\frac{1}{L^*_{h,t}}\right)\geq 0$$

which holds as the elasticity of the demand for housing of credit constrained, low-income households is larger than the elasticity for housing of unconstrained households in the presence of binding financial constraints. In conclusion, λ_t rises in γ_{t+1} if the utility function for housing is characterized by CRRA with RRA coefficient ς.

A.5 Proof of Proposition 5

If the rental market is perfectly competitive, it must be that (unconstrained) households are indifferent between renting and buying, i.e.

$$\mathbb{E}(U(\text{buy}))=-\left(p_t+\frac{1}{2}{x_{i,t}}^2\right)\cdot L_{i,t}+\frac{\left(1-(1-x_{i,t})\mu\gamma_{t+1}\right)p_{t+1}\cdot L_{i,t}}{(1+r)}+v(L_{i,t})=$$
$$\mathbb{E}(U(\text{rent}))=v\left(L_{i,t}\right)-\Upsilon_t\cdot L_{i,t}$$

with Υ_t the rental price price per unit of housing capital. This gives:

$$\Upsilon_t=\left(p_t+\frac{1}{2}{x_{i,t}}^2\right)-\frac{\left(1-(1-x_{i,t})\mu\gamma_{t+1}\right)p_{t+1}}{(1+r)}$$

Recall that with adaptation, the house price is given by

$$p_t+\frac{1}{2}{x_t}^2=\frac{\left(1-(1-x_t)\mu\gamma_{t+1}\right)p_{t+1}+v'(\bar{L}_t)}{(1+r)}$$

where $\bar{L}_t = \int_0^1 L^*_{i,t} di$ and $x_t = \int_0^1 x^*_{i,t} di$. Hence, the rental price per unit of housing capital is given by:

$$\Upsilon_t = v'(\bar{L}_t)$$

The investment in adaptation is purely driven by financial motives. Hence, landlords have the incentive to invest optimally in adaptation, i.e.

$$x^*_{i,t} = \frac{\mu\gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

Consequently, if credit constrained households rent, the optimal investment in adaptation is made for all houses in the economy, not just those owned by unconstrained household.
Since the probability of being hit by the flood is i.i.d. across households, unconstrained households remain equally well-off in expectation when they become landlords, i.e.

$$\mathbb{E}(U_h(\text{landlord})) = \mathbb{E}(U_h(\text{no landlord}))$$

where

$$\mathbb{E}(U_h(\text{landlord})) = 2\left[-\left(p_t + \frac{1}{2}{x_{i,t}}^{*2}\right) \cdot L^*_t + \frac{\left(1-(1-x^*_{i,t})\mu\gamma_{t+1}\right) p_{t+1} \cdot L^*_t}{(1+r)}\right] + v(L^*_t) + \text{Rent} \cdot L^*_t$$

$$\mathbb{E}(U_h(\text{no landlord})) = -\left(p_t + \frac{1}{2}{x_{i,t}}^{*2}\right) \cdot L^*_t + \frac{\left(1-(1-x^*_{i,t})\mu\gamma_{t+1}\right) p_{t+1} \cdot L^*_t}{(1+r)} + v(L^*_t)$$

Finally, constrained households are better off if they rent, as this allows them to consume the optimal level of housing capital:

$$\mathbb{E}(U_l(\text{rent})) = -\left(p_t + \frac{1}{2}{x_{i,t}}^{2*}\right) \cdot L^*_t + \frac{\left(1-(1-x^*_{i,t})\mu\gamma_{t+1}\right) p_{t+1} \cdot L^*_t}{(1+r)} + v(L^*_t)$$

This gives them a higher than in the case in which they buy housing (see Proof of Proposition 3):

$$\mathbb{E}(U_l(\text{buy})) = -\left(p_t + \frac{1}{2}{x_{l,t}}^{2}\right) \cdot L_{l,t} + \frac{\left(1-(1-x_{l,t})\mu\gamma_{t+1}\right) p_{t+1} \cdot L_{l,t}}{(1+r)} + v(L_{l,t})$$

A. A.6 Proof of Proposition 9

Future house price rises in choice of insurance if and only if insurance accelerates the rate at which the housing stock falls:

$$\frac{\partial p_{t+1}}{\partial \pi_t} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-(t+1)} \left[\underbrace{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j}}_{<0} \cdot \frac{\partial \bar{L}_j}{\partial \pi_t}\right] \cdot \prod_{i=t+1}^{j-1} \underbrace{\left(1-(1-\pi_i)(1-x_i)\mu\gamma_{i+1}\right)}_{>0}$$

which requires that

$$\frac{\partial \bar{L}_j}{\partial \pi_t} = \bar{L}_t \cdot \sum_{i=t}^{j-1} \mu\gamma_{i+1} \left(\frac{\partial x_i}{\partial \pi_t}\right) \prod_{i'=t, i' \neq i}^{j-1} \underbrace{(1-(1-x_{i'})\mu\gamma_{i'+1})}_{>0} < 0$$

where

$$\frac{\partial x_t}{\partial \pi_t} = -\frac{\mu\gamma_{t+1}p_{t+1}}{(1+r)} + \frac{(1-\pi_t)\mu\gamma_{t+1}}{(1+r)} \cdot \frac{\partial p_{t+1}}{\partial \pi_t}$$

For this derivative to be negative, it must be that the elasticity of future house prices, p_{t+1} with respect to the choice of insurance, π_t is less than unity, i.e.

$$\frac{\partial p_{t+1}}{\partial \pi_t} \cdot \frac{1}{p_{t+1}} < 1$$

Suppose this condition does *not* hold. Then, insurance fosters private adaptation, i.e., $\frac{\partial x_t}{\partial \pi_t} > 0$, which implies that insurance reduces the rate at which the housing supply falls, i.e., $\frac{\partial \bar{L}_j}{\partial \pi_t} > 0$. Then, since the supply of housing falls at a slower rate, it must be that $\frac{\partial p_{t+1}}{\partial \pi_t} < 0$.
However, this implies that the home equity effect is negative. Consequently, the choice of adaptation must fall in the choice of insurance, i.e., $\frac{\partial x_t}{\partial \pi_t} < 0$. This implies that the supply of housing falls at a faster rate, i.e., $\frac{\partial \bar{L}_j}{\partial \pi_t} < 0$, which is a contradiction. Hence, demand for insurance crowds out private adaptation.

A.7 Proof of Proposition 7

Wage inequality increases with climate-related damages when

$$\frac{\partial \left(q_t/w_t\right)}{\partial \gamma_t} = \frac{\eta}{(1-\eta)} \cdot \left(\frac{(1-\phi)\tilde{l})}{\phi\tilde{h}}\right)^{1-(1-\alpha)\rho} \cdot \frac{\partial}{\partial \gamma_t}\left(\frac{H_t}{(1-\mu_K\gamma_t)\,K_t}\right)^{\alpha\rho} \geq 0$$

For this to hold, it must be that

$$\frac{\mu_K}{(1-\mu_K\gamma_t)} + \frac{\partial H_t/\partial\gamma_t}{H_t} - \frac{\partial K_t/\partial\gamma_t}{K_t} \geq 0$$

or equivalently

$$\frac{\mu_K}{(1-\mu_K\gamma_t)} \geq \frac{\partial}{\partial\gamma_t} ln\left(\frac{K_t}{H_t}\right)$$

Hence, the losses of tangible capital (*i.e. the direct effect*) must be larger than the change in the investment in tangible capital relative to the investment in intangible capital in response to climate-related damages *(i.e. the indirect effect)*. To proof this, it suffices to show that

$$\frac{\partial}{\partial\gamma_t} ln\left(\frac{K_t}{H_t}\right) \leq 0$$

Note first that

$$H_t = I^*_{t-1} = \omega \cdot A^{\rho} \alpha\eta \cdot \frac{{Y_t}^{(1-\rho)}}{H_t^{1-\alpha\rho}} \cdot h_t^{(1-\alpha)\rho}$$

Using logarithmic differentiation, the derivative of H_t to γ_t becomes

$$(2-\alpha\rho)\frac{\partial}{\partial\gamma_t} ln(H_t) = (1-\rho)\frac{\partial}{\partial\gamma_t} ln(Y_t)$$

The derivative of Y_t to γ_t is given by

$$\begin{aligned}\frac{\partial}{\partial\gamma_t} Y_t &= \frac{\partial Y_t}{\partial H_t} \cdot \frac{\partial H_t}{\partial\gamma_t} + \frac{\partial Y_t}{\partial K_t} \cdot \frac{\partial K_t}{\partial\gamma_t} \\ &= R_t \cdot \frac{\partial H_t}{\partial\gamma_t} + (1+r_t) \cdot \frac{\partial K_t}{\partial\gamma_t}\end{aligned}$$

This equation provides a relation between the partial derivatives of capital to climate-related damages:

$$\frac{\partial K_t}{\partial\gamma_t} = \frac{\frac{(2-\alpha\rho)\cdot Y_t}{H_t\cdot(1-\rho)} - R_t}{(1+r_t)} \cdot \frac{\partial H_t}{\partial\gamma_t}$$

It remains to be verified that:

$$\frac{\partial}{\partial\gamma_t} ln\left(\frac{K_t}{H_t}\right) \leq 0 \Leftrightarrow \frac{1}{H_t} \cdot \frac{\partial H_t}{\partial\gamma_t} \geq \frac{1}{K_t} \cdot \frac{\partial K_t}{\partial\gamma_t}$$

There are two cases:

1. $\partial H_t/\partial\gamma_t \leq 0$. The relation between the partial derivatives of capital to climate-related damages gives:

   $$R_t H_t + (1+r_t)K_t \leq \frac{(2-\alpha\rho)Y_t}{(1-\rho)}$$

   Recall that:

   $$\alpha Y_t = R_t H_t + (1+r_t)K_t$$

   Then, rewriting gives:

   $$\alpha \leq 2$$

   which is always satisfied. Therefore,

   Lemma A1. *The elasticity of tangible capital to climate-related damages is higher than the elasticity*

of intangible capital, i.e.

$$\frac{1}{K_t} \cdot \left| \frac{\partial K_t}{\partial \gamma_t} \right| \geq \frac{1}{H_t} \cdot \left| \frac{\partial H_t}{\partial \gamma_t} \right|$$

Consequently, wage inequality increases in climate-related damages if $\partial H_t / \partial \gamma_t \leq 0$.

2. $\partial H_t / \partial \gamma_t \geq 0$. Lemma A1 ensures that:

Corollary A1. *The partial derivatives of H_t, K_t and Y_t to γ_t have the same sign, i.e.*

$$\frac{\partial H_t}{\partial \gamma_t} \geq 0 \implies \frac{\partial K_t}{\partial \gamma_t} \geq 0 \implies \frac{\partial Y_t}{\partial \gamma_t} \geq 0$$

Then, $\partial H_t / \partial \gamma_t \geq 0 \implies \partial Y_t / \partial \gamma_t \geq 0$. This is a contradiction, since $\mathcal{F}_\gamma \leq 0$. Therefore, Case 2 is ruled out and wage inequality increases in climate-related damages.

A.8 Proof of Proposition 8

The return to tangible capital is given by

$$(1 + r_t^*) = A^\rho \alpha (1 - \eta) \frac{\tilde{Y}_t^{1-\rho}}{\left((1 - \mu_K \gamma_t) K_t \right)^{1-\alpha\rho}} l_t^{(1-\alpha)\rho}$$

Using logarithmic differentiation, the derivative of r_t^* to γ_t becomes

$$\frac{\partial r_t^*}{\partial \gamma_t} = \frac{(1-\rho)}{Y_t} \cdot \frac{\partial Y_t^{net}}{\partial \gamma_t} - (1 - \alpha\rho) \left[\frac{1}{K_t} \cdot \frac{\partial K_t}{\partial \gamma_t} - \frac{\mu_K}{(1 - \mu_K \gamma_{t+1})} \right]$$

For $\rho = 0$, this derivative becomes

$$\left. \frac{\partial r_t^*}{\partial \gamma_t} \right|_{\rho=0} = \frac{1}{Y_t^{net}} \cdot \frac{\partial Y_t}{\partial \gamma_t} - \frac{1}{K_t} \cdot \frac{\partial K_t}{\partial \gamma_t} + \frac{\mu_K}{(1 - \mu_K \gamma_{t+1})}$$

Recall that

$$\begin{aligned} \frac{\partial}{\partial \gamma_t} \tilde{Y}_t &= \frac{\partial \tilde{Y}_t}{\partial H_t} \cdot \frac{\partial H_t}{\partial \gamma_t} + \frac{\partial \tilde{Y}_t}{\partial K_t} \cdot \frac{\partial K_t}{\partial \gamma_t} \\ &= R_t \cdot \frac{\partial H_t}{\partial \gamma_t} + (1 + r_t) \cdot \frac{\partial K_t}{\partial \gamma_t} \end{aligned}$$

and that

$$\left. \frac{\partial K_t}{\partial \gamma_t} \right|_{\rho=0} = \frac{\frac{2 \cdot \tilde{Y}_t}{H_t} - R_t}{(1 + r_t)} \cdot \frac{\partial H_t}{\partial \gamma_t} \Leftrightarrow \left. \frac{\partial H_t}{\partial \gamma_t} \right|_{\rho=0} = (1 + r_t) \cdot \frac{\partial K_t}{\partial \gamma_t} \cdot \frac{H_t}{2\tilde{Y}_t - R_t H_t}$$

then

$$\begin{aligned}\left.\frac{\partial r_t^*}{\partial \gamma_t}\right|_{\rho=0} &= \frac{\partial K_t}{\partial \gamma_t}\cdot\left[(1+r_t)\cdot\left(\frac{2}{2\tilde{Y}_t - R_tH_t}\right) - \frac{1}{K_t}\right] + \frac{\mu_K}{(1-\mu_K\gamma_{t+1})} \\ &= \frac{\partial K_t}{\partial \gamma_t}\cdot\frac{2}{K_t\cdot(2\tilde{Y}_t - R_tH_t)}\cdot\left((1+r_t)K_t + R_tH_t - \tilde{Y}_t - 1/2R_tH_t\right) + \frac{\mu_K}{(1-\mu_K\gamma_{t+1})}\end{aligned}$$

Recall that

$$\alpha\tilde{Y}_t = R_tH_t + (1+r_t)K_t$$

Then

$$\left.\frac{\partial r_t^*}{\partial \gamma_t}\right|_{\rho=0} = \underbrace{\frac{\partial K_t}{\partial \gamma_t}}_{\leq 0}\cdot\underbrace{\frac{2}{K_t\cdot(2\tilde{Y}_t - R_tH_t)}}_{\geq 0}\cdot\underbrace{\left((\alpha-1)\tilde{Y}_t - 1/2R_tH_t\right)}_{\leq 0} + \underbrace{\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}}_{\geq 0} \geq 0$$

Note that $\frac{\partial r_t^*}{\partial \gamma_t}$ falls in ρ:

$$\begin{aligned}\frac{\partial r_t^*/\partial\gamma_t}{\partial\rho} &= -\frac{1}{Y_t}\cdot\frac{\partial Y_t}{\partial\gamma_t} + \frac{\alpha}{K_t}\cdot\frac{\partial K_t}{\partial\gamma_t} - \frac{\alpha\mu_K}{(1-\mu_K\gamma_t)} \\ &= \frac{\partial K_t}{\partial\gamma_t}\cdot\left[\frac{\alpha}{K_t} - \frac{2(1+r_t)}{2Y_t - R_tH_t}\right] - \frac{\alpha\mu_K}{(1-\mu_K\gamma_t)} \\ &= \underbrace{\frac{\partial K_t}{\partial\gamma_t}}_{\leq 0}\cdot\underbrace{\left[\frac{2}{K_t(2Y_t - R_tH_t)}\right]}_{\geq 0}\cdot\underbrace{[\alpha Y_t - (1+r_t)K_t - \alpha R_tH_t + \alpha/2\cdot R_tH_t)]}_{\geq 0} - \underbrace{\frac{\alpha\mu_K}{(1-\mu_K\gamma_t)}}_{\geq 0} \leq 0\end{aligned}$$

Nevertheless, for $\rho = 1$, the derivative remains positive, i.e.

$$\left.\frac{\partial r_t^*}{\partial \gamma_t}\right|_{\rho=1} = (1-\alpha)\left[-\frac{1}{K_t}\cdot\underbrace{\frac{\partial K_t}{\partial\gamma_t}}_{\leq 0} + \underbrace{\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}}_{\geq 0}\right] \geq 0$$

Since $\rho \in [0,1)$, it holds that the cost of capital *rises* is climate-related damages.

A.9 Proof of Proposition 9

Share prices are given by

$$e_t^* = \frac{(1-\omega)R_{t+1}H_{t+1}}{1+r_{t+1}}$$

i.e.

$$e_t^* = (1-\omega)\cdot\frac{\eta}{(1-\eta)}\cdot\left(\frac{\tilde{h}}{\tilde{l}}\right)^{(1-\alpha)\rho}\cdot H_{t+1}^{\alpha\rho}\cdot\left(\left(1-\mu_K\gamma_{t+1}\right)K_{t+1}\right)^{(1-\alpha\rho)}$$

Using logarithmic differentiation, the derivative of e_t^* to γ_{t+1} becomes

$$\frac{\partial e_t^*}{\partial \gamma_{t+1}} = \frac{\alpha\rho}{H_{t+1}} \cdot \frac{\partial H_{t+1}}{\partial \gamma_{t+1}} + (1-\alpha\rho)\left[\frac{1}{K_{t+1}} \cdot \frac{\partial K_{t+1}}{\partial \gamma_{t+1}} - \frac{\mu_K}{(1-\mu_K\gamma_{t+1})}\right]$$

For $\rho = 0$, this derivative becomes

$$\left.\frac{\partial e_t^*}{\partial \gamma_{t+1}}\right|_{\rho=0} = \frac{1}{K_{t+1}} \cdot \underbrace{\frac{\partial K_{t+1}}{\partial \gamma_{t+1}}}_{\leq 0} - \underbrace{\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}}_{\geq 0} \leq 0$$

Note that $\frac{\partial e_t^*}{\partial \gamma_{t+1}}$ increases in ρ, as

$$\frac{\partial e_t^*/\partial \gamma_{t+1}}{\partial \rho} = \alpha\left[\frac{\mu_K}{(1-\mu_K\gamma_{t+1})} + \frac{1}{H_{t+1}} \cdot \frac{\partial H_{t+1}}{\partial \gamma_{t+1}} - \frac{1}{K_{t+1}} \cdot \frac{\partial K_{t+1}}{\partial \gamma_{t+1}}\right]$$

Following Proof of Proposition 5, this derivative is positive and increases monotonically in climate risk.

Since the derivative remains negative for $\rho = 1$, i.e.

$$\left.\frac{\partial e_t^*}{\partial \gamma_{t+1}}\right|_{\rho=1} = \frac{\alpha}{H_{t+1}} \cdot \underbrace{\frac{\partial H_{t+1}}{\partial \gamma_{t+1}}}_{\leq 0} + (1-\alpha)\left[\frac{1}{K_{t+1}} \cdot \underbrace{\frac{\partial K_{t+1}}{\partial \gamma_{t+1}}}_{\leq 0} - \underbrace{\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}}_{\geq 0}\right] \leq 0$$

and $\rho \in [0,1)$, it holds that share prices *decline* is climate risk.

Appendix B: Model Extensions

B.1 High vs Low Risk Regions

The two opposing effects on house prices can be intuitively understood through geographical variation in climate risk exposure. Consider a region with two distinct types of housing stocks. That is, a fraction $f(\gamma_t)$ of all houses are located on high elevation (e.g., on a hill) and the expected loss conditional on being hit for these houses is given by $\underline{\mu}$. The remaining houses are located on low elevation (e.g., at the waterfront) and the expected loss conditional on being hit for these houses is given by $\bar{\mu}$, with $1 > \bar{\mu} > \underline{\mu} > 0$.

If the risk exposure is common across houses in the region and housing markets are unsegmented, house prices adjust in equilibrium to ensure that households are indifferent between purchasing housing in the region with a high or low risk exposure. Then, house prices in each respective region are given by

$$p_t^{low} = \frac{\left(1 - \underline{\mu}_L \gamma_{t+1}\right) p_{t+1} + v'(\bar{L}_t)}{(1+r)}$$
$$p_t^{high} = \frac{\left(1 - \bar{\mu}_L \gamma_{t+1}\right) p_{t+1} + v'(\bar{L}_t)}{(1+r)}$$

The differences in risk exposure results in implicit price segmentation, since houses with a higher risk exposure trade at lower prices than houses with a lower risk exposure. Intuitively, this implies that houses on higher elevation are a hedge against houses on lower elevation. In aggregate, house prices are given by

$$p_t = f(\gamma_t) \cdot p_t^{low} + (1 - f(\gamma_t)) \cdot p_t^{high}$$

The supply of housing with a high climate risk exposure decreases faster. Over time, the composition of the housing stock in the region changes, as houses with a lower risk exposure have a higher likelihood to remain. As houses with high risk becomes increasingly scarce, this shifts demand to low-risk housing, pushing up prices.

Corollary A2. *Within a region, houses on higher elevation trade at higher prices than those on lower elevation. Over time, aggregate house prices rise.*

B.2 Land vs Housing Structures

The baseline model implicitly assumes that housing equals land, where land is in fixed supply but degrades with climate risk. This implies a perfectly inelastic housing supply in both the short and long run, such that climate damages increase housing prices through land scarcity. This raises the question whether households could partially offset land loss by using surviving land more intensively (e.g., by building taller or denser structures).

To address this, consider a setting that distinguishes between land L_t and effective housing services H_t. Households consume and trade housing services, where the total amount of housing services, $\bar{H}_t$, depends on land availability, $\bar{L}_t$, and structure intensity, K_t. Specifically, effective housing services are given by the Cobb–Douglas aggregator (Combes et al., 2021):

$$H_t = K_t^{\alpha} L_t^{1-\alpha}$$

where the structure intensity captures building height or density on surviving land. Physical climate risk reduces the effective supply of land, as in the baseline model. Structure intensity is adjusted to its static optimum given remaining land. Then, housing services evolve as follows:

$$H_{t+1} = (1 - \mu\gamma_{t+1})^{1-\alpha} \left(\frac{K_{t+1}}{K_t}\right)^{\alpha} H_t$$

Adjusting structure intensity is costly, with a per unit per period user cost of maintaining a given intensity level of q.[34]. Housing services are delivered competitively, with developers choosing structure intensity to maximize the value of housing services net of intensity costs:

$$\max_{K_t} p_t \cdot H_t$$
$$s.t. \quad H_t = K_t^{\alpha} L_t^{1-\alpha}$$

Lemma A2. *The optimal structure intensity is given by*

$$K_t^* = \left(\frac{\alpha p_t}{q}\right)^{\frac{1}{1-\alpha}} \cdot L_t$$

Given land market clearing (i.e., $L_t = \bar{L}_t$), effective housing services are therefore:

$$H_t = \left(\frac{\alpha p_t}{q}\right)^{\frac{\alpha}{1-\alpha}} \cdot \bar{L}_t$$

Corollary A3. *Effective housing services decline with land loss if and only if the elasticity of housing prices with respect to land supply, $\epsilon_{p,\bar{L}}$, satisfies*

$$\epsilon_{p,\bar{L}} \equiv \frac{\partial log(p_t)}{\partial log(\bar{L}_t)} > -\frac{(1-\alpha)}{\alpha}.$$

This corollary highlights two forces. First, effective housing services are proportional to land supply. Therefore, land loss directly reduces housing services. Second, if households are sufficiently risk-averse with respect to their housing consumption, the marginal value of housing rises to reflect increased scarcity,

[34] Endogenizing the marginal cost of structure intensity through a general-equilibrium construction sector would further limit substitution toward structures when land becomes scarce, reinforcing the paper's core mechanism.

in line with Proposition 1.[35] This induces greater structure intensity on remaining land. When the price response is positive but moderate, the increase in structure intensity dampens – but does not overturn – the scarcity effect. Only if housing prices respond sufficiently elastically can higher structure intensity fully offset physical land loss.[36]

B.2.1 Proof of Proposition A1 (housing vs structures)

Suppose climate risk rises in all future periods by some factor $\sigma > 1$, i.e. $\{\sigma\gamma_{t+1}, ..., \sigma\gamma_{\infty}\}$. Then, the price of house capital is given by

$$p_t^* = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{H}_j\right)\right] \prod_{\iota=t}^{j-1} \left(1-\mu\sigma\gamma_{\iota+1}\right)^{1-\alpha}$$

Then, the FOC of p_t with respect to σ is given by

$$\frac{\partial p_t}{\partial \sigma} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[\frac{\partial v'(\bar{H}_j)}{\partial \bar{H}_j} \cdot \frac{\partial \bar{H}_j}{\partial \sigma} \cdot \prod_{\iota=t}^{j-1} (1-\mu\sigma\gamma_{\iota+1})^{1-\alpha} + v'\left(\bar{H}_j\right) \cdot \frac{\partial}{\partial \sigma}\left(\prod_{\iota'=t}^{j-1} \left(1-\mu\sigma\gamma_{\iota'+1}\right)^{1-\alpha}\right)\right]$$

Remark that

$$\frac{\partial \bar{H}_j}{\partial \sigma} = \frac{\partial \bar{H}_j}{\partial \bar{L}_j} \cdot \frac{\partial \bar{L}_j}{\partial \sigma} = (1-\alpha)\frac{\bar{H}_j}{\bar{L}_j} \cdot \frac{\partial \bar{L}_j}{\partial \sigma}$$

and

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} \left(1-\mu\sigma\gamma_{\iota+1}\right)$$

where

$$\begin{aligned}\frac{\partial \bar{L}_j}{\partial \sigma} &= -\mu\bar{L}_t \sum_{\iota=t}^{j-1} \gamma_{\iota+1} \prod_{\iota'=t,\iota'\neq\iota}^{j-1} \left(1-\mu\sigma\gamma_{\iota'+1}\right) \\ &= -\mu \sum_{\iota=t}^{j-1} \gamma_{\iota+1} \frac{\bar{L}_j}{\left(1-\mu\sigma\gamma_{\iota+1}\right)}\end{aligned}$$

[35] Note that under the new formulation, the house price becomes given by

$$p_t = \frac{(1-\mu\gamma_{t+1})^{(1-\alpha)} p_{t+1} + v'\left(H_t^*\right)}{(1+r)}$$

with $(1-\mu\gamma_{t+1})^{(1-\alpha)}$ the survival rate of housing services. In this case, the relevant condition for house prices, p_t, to rise as land supply, $\bar{L}_t$, falls remains that $RRA > 1$ (see Proof of Proposition A1, Appendix A.1.1.

[36] Empirically, Combes et al. (2021) estimate a structure elasticity (i.e., α) of 0.65, implying a threshold of $\epsilon_{p,\bar{L}} > -0.54$.

then

$$\frac{\partial p_t}{\partial \sigma} = \mu(1-\alpha) \cdot \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left(-\frac{\partial v'(\bar{H}_j)}{\partial \bar{H}_j} \cdot \bar{H}_j \cdot \sum_{\iota=t}^{j-1} \frac{\gamma_{\iota+1}}{(1-\mu\sigma\gamma_{\iota+1})} \cdot \prod_{\iota=t}^{j-1} (1-\mu\sigma\gamma_{\iota+1})^{1-\alpha} \right.$$
$$\left. -v'\left(\bar{H}_j\right) \cdot \sum_{\iota=t}^{j-1} \frac{\gamma_{\iota+1}}{(1-\mu\sigma\gamma_{\iota+1})^{\alpha}} \prod_{\iota'=t,\iota'\neq\iota}^{j-1} (1-\mu\sigma\gamma_{\iota'+1})^{1-\alpha} \right)$$

which can be rewritten as

$$\frac{\partial p_t}{\partial \sigma} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[-\frac{\partial v'(\bar{H}_j)}{\partial \bar{H}_j} \cdot \bar{H}_j - v'\left(\bar{H}_j\right) \right] \cdot \mu(1-\alpha) \sum_{\iota=t}^{j-1} \frac{\gamma_{\iota+1}}{(1-\mu\sigma\gamma_{\iota+1})^{\alpha}} \prod_{\iota'=t,\iota'\neq\iota}^{j-1} (1-\mu\sigma\gamma_{\iota'+1})^{1-\alpha}$$

This is positive if

$$-\frac{\partial v'(\bar{H}_j)}{\partial \bar{H}_j} \cdot \bar{H}_j - v'\left(\bar{H}_j\right) \geq 0$$

or, equivalently if

$$-\frac{\frac{\partial v'(\bar{H}_j)}{\partial \bar{H}_j} \cdot \bar{H}_j}{v'\left(\bar{H}_j\right)} \geq 1$$

B.3 Alternative Preference Specifications

In the main framework, I assume quasi-linear preferences. With quasi-linearity, income does not affect the housing choice of unconstrained households, as housing is the concave part of utility. Once financial constraints bind, constrained households consume less housing and therefore optimally underinvest in adaptation. In this Appendix, I show that this result is robust to the specification of household preferences. First, to isolate the role of utility curvature, I evaluate the CRRA household problem. Then, to explore the robustness to non-seperability of the utility function, I evaluate the CES household problem. I evaluate both versions along the equilibrium price and climate-risk paths implied by the baseline model. Holding the general-equilibrium environment fixed ensures that any differences in behavior arise solely from the change in preferences.

A.1 B.3.1 CRRA-Household Optimization Problem

To stay as close as possible to the quasi-linear structure, I use separable CRRA utility in consumption with relative risk aversion parameter $\zeta > 0$, combined with concave housing utility, $v(\cdot)$, with $v'(\cdot) > 0, v''(\cdot) < 0$. Then, the household maximization problem is given by:

$$\max_{c_{i,t+1},L_{i,t},S_{i,t},x_{i,t},} \mathbb{E}\left(U(c_{i,t+1},L_{i,t})\right) = \frac{c_{i,t+1}^{1-\zeta}}{1-\zeta} + v\left(L_{i,t}\right)$$

$$s.t. \quad y_i \leq \left(p_t + \frac{1}{2}x_{i,t}^2\right) L_{i,t} + S_{i,t}$$

$$c_{i,t+1}(\xi_{i,t+1}) \leq \max\left\{p_{t+1}\left(1-\xi_{i,t+1}\right)L_{i,t} + \left(1+\hat{r}_{t+1}\right)S_{i,t}, 0\right\}$$

$$-(1+\hat{r}_{t+1})S_{i,t} \leq \left(1-\left(1-\mathbb{E}\left(\bar{x}_{i,t}\right)\right)\mu\gamma_{t+1}\right)p_{t+1}L_{i,t}$$

$$c_{i,t+1}, x_{i,t}, L_{i,t} \geq 0$$

Given the default cutoff, $\hat{\xi}_{i,t+1}$, which solves:

$$p_{t+1}\left(1-\hat{\xi}_{i,t+1}\right)L_{i,t} + \left(1+\hat{r}_{t+1}\right)S_{i,t} = 0$$

the household is solvent for $\xi_{i,t+1} < \hat{\xi}_{i,t+1}$, and defaults otherwise. Expected utility can therefore be written as:

$$\mathbb{E}\left(U(c_{i,t+1},L_{i,t})\right) = \frac{1}{1-\zeta}\int_0^{\hat{\xi}_{i,t+1}} \left[p_{t+1}\left(1-\xi_{i,t+1}\right)L_{i,t} + \left(1+\hat{r}_{t+1}\right)S_{i,t}\right]^{1-\zeta} dF\left(\xi_{i,t+1}\right) + v\left(L_{i,t}\right)$$

Because the introduction of stochastic climate losses and default eliminates the closed-form solution for $x_{i,t}^*$, I solve the household problem numerically. The implementation follows standard methods used in numerical macroeconomics for models with occasionally binding constraints.

1. **Smoothing the consumption floor**: Since default introduces a kink in consumption (through $c = \max\{z, 0\}$)), direct evaluation of expected utility leads to non-differentiabilities that make gradient-based optimization unstable. To ensure smoothness of the objective function, I replace the consumption floor with a standard smooth approximation (softplus).

   $$\text{softplus}(z) = log(1+\exp\left(z\right))$$

   This modification affects utility only in an infinitesimal neighborhood of the zero-consumption boundary and preserves economic implications. This smoothing approach is widely adopted in the computational macroeconomic literature (CITE).

2. **Enforcing the collateral constraint**: I impose the collateral constraint:

   $$-\left(1+\hat{r}\right)S_{i,t} <= \left(1-\left(1-\bar{x}_{i,t}\right)\mu\gamma_{t+1}\right)p_{t+1}L_{i,t}$$

using a smooth quadratic penalty:

$$P(L,S,x) = \eta \cdot \max\left\{0, (1+\hat{r}_{t+1})\, S_{i,t} - (1-(1-\bar{x}_{i,t})\mu\gamma_{t+1})\, p_{t+1} L_{i,t}\right\}^2$$

with the penalty weight η sufficiently large. When the constraint is satisfied the penalty is zero; when violated, the penalty increases rapidly in the size of the violation. For sufficiently large penalty weight, this method enforces the inequality constraint while preserving differentiability of the objective function.

3. **Discretizing the loss distribution**: Idiosyncratic climate losses $\xi_{i,t+1}$ follow a $Beta(a,b)$ distribution on $[0,1]$, where the scale parameters (a,b) are set to match the baseline model-implied mean, i.e. $\mathbb{E}(\xi_{i,t+1}) = \frac{a}{a+b} = \mu\gamma_{t+1}$, and $b > a$ (i.e., small losses are likely, while very large losses are possible but uncommon). Expected utility is then computed by numerically integrating over a fine grid of loss realizations.

4. **Solution method**: For each income level on the grid $y_i \in [0.1, 0.9]$, I solve the household problem using the equilibrium prices and climate-risk parameters implied by the baseline model. I use a relative risk aversion of $\zeta = 10$, consistent with the long-run risk literature (Bansal and Yaron 2004). The optimal adaptation choice $x^*_{i,t}$ is then solved for each income level.

The results are plotted for the SSP2-4.5 (left panel) and SSP3-7.0 (right panel) scenario in Figure 6. Adaptation is measured relative to the value for the lowest-income household in each scenario, to highlight both the level differences based on income, as well as the income gradient across the scenarios. Under both scenarios, the optimal adaptation choice is strictly increasing in income. That is, richer households invest more in resilience. Moreover, the slope of $x^*_{i,t}(y_i)$ is steeper in the more severe climate scenario, indicating that the adaptation gap between low- and high-income households widens as climate risk rises. This confirms the key distributional insights of Propositions 3 and 4, and shows how these are driven by financial frictions and climate-induced collateral risk, rather than by the quasi-linear preference specification in the baseline model.

B.3.2 CES-Household Optimization Problem

I use non-separable CES utility in consumption and housing, with $\varrho = (\varsigma - 1)/\varsigma$ the inverse of the elasticity of substitution between housing and non-durable consumption. Then, the household maximization problem is given by.

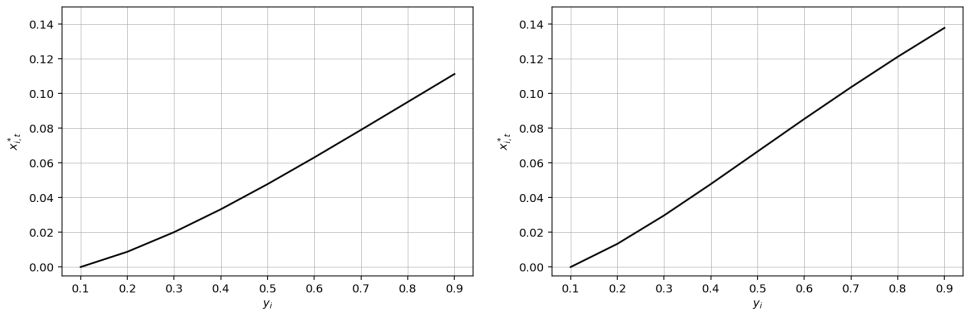


FIGURE 6: THE OPTIMAL CHOICE OF ADAPTATION, $x^*_{i,t}$, FOR DIFFERENT INCOME LEVELS, y_i, DERIVED UNDER CRRA UTILITY. THE LEFT PANEL SHOWS THE RESULTS FOR THE SSP2-4.5 SCENARIO AND THE RIGHT PANEL SHOW THE RESULTS FOR THE SSP3-7.0 SCENARIO. ADAPTATION IS MEASURED RELATIVE TO THE VALUE FOR THE LOWEST-INCOME HOUSEHOLD IN EACH SCENARIO.

$$\begin{aligned}
\max_{c_{i,t+1},L_{i,t},S_{i,t},x_{i,t},} \mathbb{E}\left(U(c_{i,t+1},L_{i,t})\right) &= \left(c^{\varrho}_{i,t+1}+L^{\varrho}_{i,t}\right)^{1/\varrho} \\
s.t. \quad y_i &\leq \left(p_t+\frac{1}{2}x^2_{i,t}\right)L_{i,t}+S_{i,t} \\
c_{i,t+1}(\xi_{i,t+1}) &\leq \max\left\{p_{t+1}\left(1-\xi_{i,t+1}\right)L_{i,t}+\left(1+\hat{r}_{t+1}\right)S_{i,t},0\right\} \\
-(1+\hat{r}_{t+1})S_{i,t} &\leq \left(1-(1-\mathbb{E}\left(\bar{x}_{i,t}\right))\mu\gamma_{t+1}\right)p_{t+1}L_{i,t} \\
c_{i,t+1},x_{i,t},L_{i,t} &\geq 0
\end{aligned}$$

Expected utility can in this case be written as:

$$\mathbb{E}\left(U(c_{i,t+1},L_{i,t})\right)=\left(\int_0^{\hat{\xi}_{i,t+1}}\left[p_{t+1}\left(1-\xi_{i,t+1}\right)L_{i,t}+\left(1+\hat{r}_{t+1}\right)S_{i,t}\right]^{\rho}dF\left(\xi_{i,t+1}\right)+L^{\varrho}_{i,t}\right)^{1/\varrho}$$

I use a similar numerical implementation as specified in Section B.2, and use a elasticity of substitution between housing and non-durable consumption of 1.25, consistent with the macro-housing literature (Guren et al., 2021; Piazzesi et al., 2007). The results are visualized for the SSP2-4.5 (left panel) and SSP3-7.0 (right panel) scenario in Figure 7. Adaptation is again measured relative to the value for the lowest-income household in each scenario. In line with the baseline model, and the version with CRRA-utility, the optimal adaptation choice is strictly increasing in income and the slope of $x^*_{i,t}(y_i)$ is steeper in the more severe climate scenario.

Appendix C: General Equilibrium with Firms

I introduce a general equilibrium framework that incorporates firms. Firms operate for a single period and produce the non-durable consumption good, using physical and intangible capital, alongside labour supplied by households. A flood occurs in each period and damages the firms' physical capital, hindering

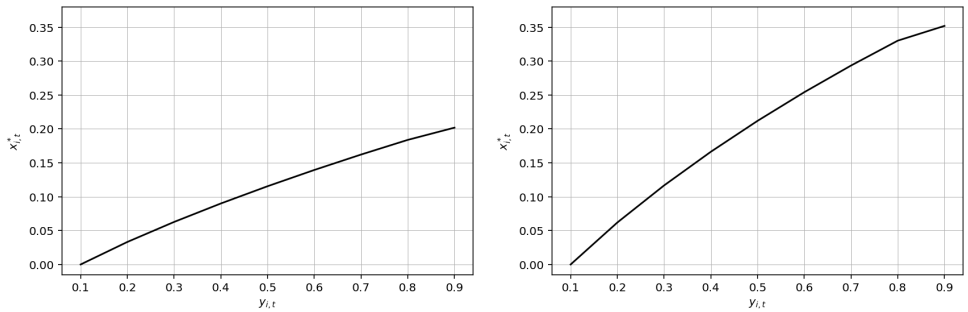


FIGURE 7: THE OPTIMAL CHOICE OF ADAPTATION, $x^*_{i,t}$, FOR DIFFERENT INCOME LEVELS, y_i, DERIVED UNDER CES UTILITY. THE LEFT PANEL SHOWS THE RESULTS FOR THE SSP2-4.5 SCENARIO AND THE RIGHT PANEL SHOW THE RESULTS FOR THE SSP3-7.0 SCENARIO. ADAPTATION IS MEASURED RELATIVE TO THE VALUE FOR THE LOWEST-INCOME HOUSEHOLD IN EACH SCENARIO.

its production.[37] Besides endogenizing wages, the interest rate, and the production of the non-durable consumption good, the purpose of introducing firms is to study the effects of climate risk on relative prices and credit allocation.

C.1 Households

The characterization of household preferences is equivalent to the one provided in the simple model (see Section III.A.1). Floods destroy the housing capital of households (following Section III.B) and households adapt to climate change (following Section V.A). In the general equilibrium framework, wages are endogenous and are equal to the marginal productivity of the respective labour type. Skill levels remain exogenously given. However, the general equilibrium framework features a third type of household, high-skilled workers who have some entrepreneurial talent.

A.2 C.1.1 Innovators

A fraction $\varepsilon \in (0, 1)$ of high-skilled workers has some entrepreneurial talent. These 'innovators' create intangible capital when they are young (Döttling and Perotti, 2017). Intangible capital lacks any physical presence and rather represents information (cf. Corrado et al., 2009; Corrado and Hulten, 2010; Crouzet et al., 2022a). Intangibles can thus be regarded as knowledge capital and are created through investments like research and development or human capital and skill accumulation (Crouzet et al., 2022a). The investment is given by $I_{H,t}$, where $I_{H,t} = H_{t+1}$, and requires an effort cost:

$$C\left(I_{H,t}\right) = \frac{1}{2} I_{H,t}^2$$

I assume that intangible capital is non-rival in use (Crouzet et al., 2022a,b). That is, innovators invest in intangible capital once, and may deploy the intangible capital within multiple firms.

[37] Adaptation by firms is covered in a model extension, in Appendix C.6

B. C.2 Firms

There is a unit mass of firms in the economy, which operate a single period and maximize profits.

B.1 C.2.1 Production Technology

Firm produce the non-durable consumption good, using physical capital and intangible capital in the production process. Physical capital (K) is complementary to low-skilled labour (l; see e.g., Krusell et al. (2000), Goldin and Katz (2009), Eisfeldt et al. (2023)), while intangible capital (H) is complementary to high-skilled labour (h). Output, Y_t, is produced according to the following constant elasticity of substitution production technology:

$$\begin{aligned} Y_t &= A\mathcal{F}(H_t, h_t, K_t, l_t) \\ &= A\left[\eta\left(H_t^{\alpha} h_t^{1-\alpha}\right)^{\rho} + (1-\eta)\left(K_t^{\alpha} l_t^{1-\alpha}\right)^{\rho}\right]^{\frac{1}{\rho}} \end{aligned}$$

with A a technology parameter, $\rho \in [0, 1)$ the substitution parameter, and η a distribution parameter reflecting the relative productivity of intangible capital and high-skilled labour.[38]

B.2 C.2.2 Capital Investments

While intangible capital is created through the effort of innovators, physical capital is created upon (monetary) investment, with $I_{f,K,t} = K_{f,t+1}$. Tangible, as well as intangible capital, depreciate fully after the production period (i.e. $\delta_K = \delta_H = 1$). Firms operating in $t = 0$ are endowed with an initial stock of physical capital, K_0, and the old innovators at $t = 0$ are endowed with an initial stock of intangible capital, H_0.

B.3 C.2.3 Appropriation of Intangibles

The value of intangible capital may be captured and privately appropriated (Crouzet et al., 2022a,b). Specifically, innovators can hold up the firm, by threatening to withdraw their human capital (Hart and Moore, 1994). This hinders the firm's production and enables the innovators to appropriate part of the value generated by its intangible capital (Eisfeldt and Papanikolaou, 2014; Eisfeldt et al., 2023). Let $\omega \in (0, 1]$ represent the innovator's bargaining power over the returns generated by intangible capital (Döttling and Perotti, 2017). Accordingly, innovator capture a fraction ω of the value of intangible capital, while the firm's shareholders receives the remaining fraction.

[38] To ensure that wages of high-skilled workers are higher than those of low-skilled workers, I assume that high-skilled labour is relatively scarce (see Döttling and Perotti, 2017), i.e.,

$$\frac{\phi}{1-\phi} \leq \frac{\eta}{1-\eta}$$

B.4 C.2.4 Climate Risk and Firm Capital

Firms are exposed to climate change, as floods destroy its physical capital (Bilal and Känzig, 2024; Acharya et al., 2022).[39] Let $\gamma_{t+1} \in [0,1]$ capture the probability that a given firm experiences losses due to flooding in period, $t+1$. This probability is common among firms and, by the law of large numbers, corresponds to the fraction of firms that experience climate-related damages in any period $t+1$. Denote by $\xi_{f,t+1} \in [0,1]$ the losses of a given firm, f, in period, $t+1$. These losses follow some distribution, $G(\xi_{f,t})$, which is i.i.d. across firms. The losses are idiosyncratic, reflecting that flooding events may hit certain firms harder than others. However, as idiosyncratic risk can be diversified, it is the expected losses that matter to investors. Denote by $\mu_K \in [0,1]$ the expected losses, as a fraction of physical capital, conditional on experiencing losses due to flooding. The expected idiosyncratic losses are given by:

$$\begin{aligned}\mathbb{E}(\xi_{f,t+1}) &= \mathbb{E}\left(\xi_{f,t+1}\middle|\text{Hit by the flood}\right)\cdot\mathbb{P}(\text{Hit by the flood})\\ &= \mu_K\gamma_{t+1}\end{aligned}$$

Climate-damages reduce the amount of physical capital which has productive value:

$$\tilde{K}_t = (1-\xi_{f,t})\,K_t$$

Climate-related damages thus hinder production[40]:

$$\tilde{Y}_t = A\mathcal{F}(H_t, h_t, \tilde{K}_t, l_t), \qquad \mathcal{F}'_\gamma(H_t, h_t, \tilde{K}_t, l_t) \leq 0$$

and reduce the firm's output. In contrast to damages to the housing stock, climate-related damages to the physical capital stock affect a firm's output only within the given period, as the firms' capital stock depreciates fully after each production period. Consequently, climate-related damages affect firms on a *flow* basis. In contrast, in the housing market, the supply of habitable houses experiences a permanent decline over time, indicating that climate-related damages have a *stock* effect.

[39] While intangible capital, which may represent system-wide infrastructure can also be affected by physical climate risk, I take physically localized view and abstract from damages to intangible capital. This is in accordance with Acharya et al. (2022), who show that tangible industries (e.g., construction, mining, oil & gas, utilities, manufacturing and forestry & fishery) are more exposed to physical climate risk than service industries.

[40] In the environmental economics literature climate-related damages to production are modeled using a damage function (see e.g., Golosov et al., 2014; Nordhaus, 1992). Specifically, a damage function, which rises in temperatures, reduces TFP. While I model climate-related damages to production as a physical capital loss of fraction $\xi_{f,t}$, the production function can be rewritten as

$$\tilde{Y}_t = A\left[\eta\left(H_t^\alpha h_t^{1-\alpha}\right)^\rho + (1-\eta)\left(1-\xi_{f,t}\right)^{\alpha\rho}\left(K_t^\alpha l_t^{1-\alpha}\right)^\rho\right]^{\frac{1}{\rho}}$$

This function reflects that climate-related damages reduce firm's overall productivity of physical inputs (i.e. low-skilled labour and physical capital). This specification also captures a decline in the productivity of manual labour due to, e.g., heat-stress (Acharya et al., 2022).

C. C.3 Firm Financing and Financial Markets

Each firm, f, issues corporate debt to finance the investment in physical capital. Corporate debt, which has a face value of $D_{f,t}$, is funded by households with positive savings. The corporate debt held by household i in firm f in period t is denoted by $D_{i,f,t}$ and the total holdings of corporate debt of a given household are denoted by $D_{i,t} = \int_0^1 D_{i,f,t} df$. Lending to firms occurs against collateral, and the firm's physical capital backs its corporate debt. Corporate debt earns a risk-free rate of return, r_t, and is repaid each period.[41]

Innovators also issues equity, which is backed by the value of the share of intangible capital appropriated by equity holders. I denote the equity held by shareholder i in firm f in period t by $s_{i,f,t}$ and the total equity holdings of a given household are denoted by $s_{i,t} = \int_0^1 s_{i,f,t} df$. I normalize the quantity of shares of each firm to 1. The price of a share of firm f is denoted by $e_{f,t}$, and shares receive a dividend payment, $d_{f,t}$, at the end of the period.

D. C.4 General Equilibrium

D.1 C.4.1 Household Optimization Problem

Households maximize utility subject to the budget constraint and limited liability constraint:

$$\begin{aligned}
\max_{c_{i,t+1}, L_{i,t}, s_{i,t}, S_{i,t}, x_{i,t}} \mathbb{E}\left(U(c_{i,t+1}, L_{i,t})\right) &= \mathbb{E}_t\left(c_{i,t+1}\right) + v\left(L_{i,t}\right) \\
s.t. \quad y_{i,t} &\leq \left(p_t + \frac{1}{2}x_{i,t}^2\right) L_{i,t} + s_{i,t} e_t + S_{i,t} \\
c_{i,t+1} &\leq \max\{y_{i,t+1} + p_{t+1}(1-\xi_{i,t+1}) L_{i,t} + d_{t+1} s_{i,t} + (1+\hat{r}_{t+1}) S_{i,t}, 0\} \\
c_{i,t+1}, L_{i,t}, x_{i,t} &\geq 0,
\end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.

Within the general equilibrium framework, the optimal demand for housing and adaptation matches that of the simple framework, as outlined in Section V.B.2. In the general equilibrium framework, the risk-free rate is time-variant.

The share price follows from households' demand for share holdings, $s_{i,t}$ and is equal to the discounted value of the dividend payment, d_{t+1}

$$e_t = \frac{d_{t+1}}{(1 + r_{t+1})}$$

Investments in corporate and household debt follow as residual. Households with net savings lend to others households and firms, while households with negative savings take out a mortgage.

[41] While physical capital is also exposed to climate-related risks, I abstract from corporate default in the model. This simplify the analysis and maintains the focus on the allocation of resources and the economic consequences of climate risks, while avoiding the complexities of modeling default.

D.2 C.4.2 Firm Optimization problem

Firms maximize the value to its equity holders. Since firms only operate for one period, and pay out all profits, the maximization problem is given by:

$$\max_{H_t,h_t,K_t,l_t} \pi_{f,t} = \tilde{Y}_t(A, H_t, h_t, \tilde{K}_t), l_t) - \omega R_t H_t - q_t h_t - (1 + r_t) D_{t-1} - w_t l_t$$

Labour markets are perfectly competitive, which implies that high-skilled and low-skilled workers earn their marginal productivity.

Lemma A3. *Wages of high- and low-skilled workers, q_t respectively w_t are equal to*

$$q_t^* = A^\rho (1-\alpha)\eta \cdot \frac{\tilde{Y}_t^{1-\rho}}{h_t^{1-(1-\alpha)\rho}} \cdot H_t^{\alpha\rho}$$
$$w_t^* = A^\rho (1-\alpha)(1-\eta) \cdot \frac{\tilde{Y}_t^{1-\rho}}{l_t^{1-(1-\alpha)\rho}} \left(1 - \mu_K \gamma_t\right)^{\alpha\rho} \cdot K_t^{\alpha\rho}$$

The wage ratio is defined as $\frac{q_t^*}{w_t^*}$ and is given by:

$$\frac{q_t^*}{w_t^*} = \frac{\eta}{1-\eta} \cdot \left(\frac{H_t}{\left(1 - \mu_K \gamma_t\right) K_t}\right)^{\alpha\rho} \cdot \left(\frac{l_t}{h_t}\right)^{1-(1-\alpha)\rho}$$

Climate-related damages lead to a decline in income, reducing wages of high- and low-skilled workers. However, the damages to physical capital have a direct, negative impact on the productivity of low-skilled workers. As a result, the skill premium rises, leading to a rise in wage inequality. The skill premium also depends on the balance of intangible and physical capital used in production. Firms (and innovators) scale back their investments as income declines. However, as tangible capital is more vulnerable to climate risks, firms scale back their investments in physical capital to a greater extent. This further reduces the productivity of low-skilled workers relative to high-skilled workers over time.[42]

Proposition 7. *Wage inequality rises in climate-related damages.*

Proof: See Appendix A.7

Firms are financially unconstrained and borrow up to the point where the marginal cost of capital is equal to its marginal productivity

Lemma A4. *The return to physical capital is given by*

$$(1 + r_t^*) = A^\rho \alpha (1-\eta) \cdot \frac{\tilde{Y}_t^{1-\rho}}{\left(\left(1 - \mu_K \gamma_t\right) K_t\right)^{1-\alpha\rho}} \cdot l_t^{(1-\alpha)\rho}$$

and firms fully finance the investment in physical capital by debt in each period, $I_{K,t}^* = D_t$.

[42] This result also holds if intangible capital were exposed to climate risk, as long as the elasticity of tangible capital to climate-related damages is larger than the elasticity of intangible capital to climate-related damages.

The return on physical capital determines the cost of capital and is affect by climate change along two channels.[43] First, climate-related damages reduce the firm's income, $\tilde{Y}$. In response, firms cut back their investments, reducing capital demand and lowering the return on physical capital. However, and second, the return to physical capital also depends directly on the amount of physical capital, K, used in production. Since physical capital is vulnerable to climate risks, physical capital becomes riskier and, in response, firms scale back their investments in physical capital to a greater extent - thus reducing the firms' relative reliance on physical capital. In equilibrium, the risk-channel dominates, and the cost of capital rise in climate-related damages.

Proposition 8. *The cost of capital rises in climate-related damages.*

Proof: See Appendix A.8

The rise in the cost of capital has redistributive implications. Specifically, as the cost of capital rises, households with positive savings accumulate wealth at a faster rate. In contrast, households that finance the purchase of housing capital by issuing household debt face an increase in the costs of servicing their mortgage contract. Hence, through the costs of capital channel, savings act as an *unequalizing* force, increasing wealth inequality.

Shareholders capture a fraction $(1-\omega)$ of the return to intangibles capital. In equilibrium, dividends are given by:

$$\begin{aligned} d_t^* &= \tilde{Y}_t(H_t, \tilde{K}_t, h_t, l_t) - (\omega R_t^* H_t + q_t^* h_t + (1+r_t^*)K_{t-1} + w_t^* l_t) \\ &= (1-\omega)R_t^* \cdot H_t \end{aligned}$$

where the return on intangible capital is given by[44]

$$R_t^* = A^\rho \alpha \eta \cdot \frac{\tilde{Y}_t^{1-\rho}}{H_t^{1-\alpha\rho}} \cdot h_t^{(1-\alpha)\rho}$$

Share prices are given by the discounted value of the dividend payment:

$$e_t^* = \frac{(1-\omega)R_{t+1} \cdot H_{t+1}}{1+r_{t+1}}$$

Lemma A5. *Climate-related damages reduce dividends.*

Since climate-related damages hinder the firm's production, the firm experiences a decline in its output and therefore its profitability. This reduces the dividend payment *(cashflow effect)*. Simultaneous, the cost of capital rises *(discount rate effect)*. Through both channels, firm's equity prices are suppressed.

[43] Redistributive technological change (reflected by a rise in η) produces a decline in interest rates due to excess savings (Döttling and Perotti, 2017). Excess savings arise as technological change increases the reliance of the economy on intangible capital, reducing demand for physical capital and corporate debt.

[44] Competitive firms pay a return on intangible capital equal to its marginal productivity. Given the return, innovators create an amount of intangible capital equal to:

$$I_t^* = \frac{\omega}{\phi\varepsilon} R_{t+1}^* = \tilde{\omega} R_{t+1}^*$$

where $I_t^* = H_{t+1}^*$ (Döttling and Perotti, 2017).

Proposition 9. *Share prices decline in climate risk.*

Proof: See Appendix A.9

The decline in equity prices reduces the financial wealth of shareholders. Therefore, financial asset price changes act as an *equalizing* force for the wealth distribution.[45]

D.3 C.4.3 Equilibrium and Market Clearing

A competitive equilibrium is defined as an allocation $\{c_t^l, c_t^h, L_t^l, L_t^h, s_t^l, s_t^h, D_t^l, D_t^h, K_t, H_t, l_t, h_t\}_{t=0}^T$ and prices $\{p_t, e_t, r_t, R_t, w_t, h_t\}_{t=0}^T$ such that in each period, t, given prices

1. Households maximize lifetime utility;
2. Firms maximize profits;
3. Innovators optimally choose intangible investment;

and all markets clear.

Within the general equilibrium framework, the housing market clearing condition and the expression for the price of housing capital, p_t, are similar to those of the simple framework, as outlined in Sections V.C. In the general equilibrium framework, the risk-free rate becomes time-variant.

Total labour demand equals total labour supply, so that

$$\int_0^1 \left[h_{f,t}^d, l_{f,t}^d\right] df = [h^s, l^s]$$

Households supply their entire labour endowment since the marginal product of labour is strictly positive. Therefore, $[h^s, l^s] = \{\phi\bar{h}, (1-\phi)\bar{l}\}$ and the labour market equilibrium requires:

$$\int_0^1 \left[h_{f,t}^d, l_{f,t}^d\right] df = \{\phi\bar{h}, (1-\phi)\bar{l}\}$$

Aggregate income of young households must equal the value of assets that carry savings over time. This consists of the aggregate investment in housing, corporate debt and shares:

$$(1-\alpha)\tilde{Y}_t - p_t\bar{L}_t = e_t + D_t$$

where $(1-\alpha)\tilde{Y}_t = q_t\phi\bar{h} + w_t(1-\phi)\bar{l}$. For equity markets to clear, the total share holdings must equal the total supply of shares:

$$\int_0^1 s_{i,t}^* di = 1$$

[45] Bauluz et al. (2022) study the rise of global saving and wealth between 1980-2018. One of the authors' finding is that saving were an unequalizing force for the wealth distribution, while capital gains were an equalizing force.

Recall that the investment in physical capital is fully financed by corporate debt, i.e. $D_t = K_t$. Hence, the financial market clearing condition provides an expression for the supply of physical capital:

$$K_t = (1-\alpha)\tilde{Y}_t - p_t\bar{L}_t - e_t$$

C.5 Endogenous Supply of Adaptation Capital

Households invest in adaptation by channeling part of their resources to adaptation capital. Thus far, the supply of adaptation capital was considered exogenous. The supply can be endogenized by requiring households to sacrifice part of their labour endowment. Specifically, households must use some of their time to take preventive measures that protect their housing capital. Denote the amount of high-skilled respectively low-skilled labour that a household must sacrifice, for a given choice of adaptation $x_{i,t}$ and housing consumption $L_{i,t}$, by h_x respectively l_x, where

$$l_x, h_x = f(x_{i,t}, L_{i,t}), \quad f'_x > 0, f''_{xx} > 0, \quad f'_L > 0, f''_{LL} = 0$$

When adaptation is labour-based, the income of high- respectively low-skilled households is given by:

$$y_l = w \cdot \left(\tilde{l} - l_x\right) \qquad y_h = q \cdot \left(\tilde{h} - h_x\right)$$

For simplicity, assume that

$$l_x = \frac{1}{2} \cdot \frac{x_l^2 L_l}{w} \qquad h_x = \frac{1}{2} \cdot \frac{x_h^2 L_h}{q}$$

Labour-based adaptation reduces the income of households by an amount equal to what they would have spent on adaptation in monetary terms. Hence, the private choice of adaptation is equivalent to the solution derived in Section V.B.2. However, less labour can be used in production, this strengthens the negative effect of climate change on output, the more so if climate risk rises.

C.6 Adaptation by Firms

The general equilibrium framework abstracted from adaptation by firms. In this extension, I study the effect of adaptation by firms on output and the costs of capital.[46] Suppose firms invest in climate change adaptation at the same time they invest in physical capital. Denote by $x_{f,t} \in [0,1)$ the choice of adaptation of firm f in period t. This investment comes at a cost. Specifically, the investment costs are given by $\psi(x_{f,t}, K_{f,t}) = \frac{1}{2}K_{f,t}(x_{f,t})^2$. Similarly as to the household-setting, the costs increase linearly in

[46] Acharya et al. (2023) document that firms in the United States respond to heat stress by reducing employment in the affected locations and increasing it in unaffected locations, preventing heat-related decline in labour productivity. Balboni et al. (2023) find that flood-affected firms in Pakistan are more likely to relocate to safer areas, and shift purchases towards suppliers in less flood- prone regions. Bilal and Rossi-Hansberg (2023) model adaptation through migration and capital investment decisions in a spatial macroeconomic model, finding that anticipation of future climate damages amplifies climate-induced worker and investment mobility.

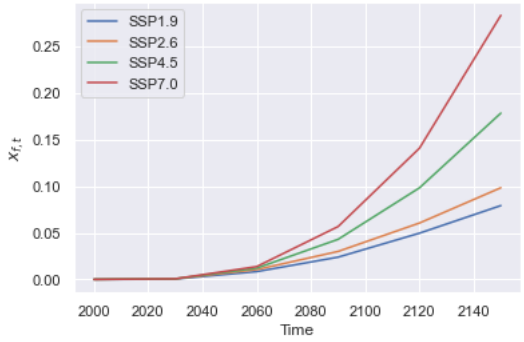


FIGURE 8: THE EVOLUTION OF THE FIRM'S CHOICE OF ADAPTATION, $x_{f,t}$, UNDER THE SSP1-1.9, SSP1-2.6, SSP2-4.5 AND SSP3-7.0 SCENARIO.

the amount of physical capital protected, and the investment costs rise at an accelerating rate in the choice of adaptation.

By adapting to climate change, firms reduce protect themselves against climate-related damages in the next period. Specifically, for a given choice of adaptation, $x_{f,t}$, the firm prevents a fraction $x_{f,t}$, of the idiosyncratic losses. Hence, adaptation leads to a leftward shift in the distribution of losses by $x_{f,t} \cdot \mu_K \gamma_{t+1}$. In expectation, the losses experienced by a given firm, $\xi_{f,t+1}$, are:

$$\mathbb{E}\left(\xi_{f,t+1}\right) = \left(1 - x_{f,t}\right) \mu_K \gamma_{t+1}$$

By reducing damages to physical capital used in production, adaptation reduces the decline in output:

$$Y_{t+1} = A\left[\eta\left(H_{t+1}^{\alpha} h_{t+1}^{(1-\alpha)}\right)^{\rho} + (1-\eta)\left(\left[\left(1-(1-x_{f,t})\mu_K\gamma_{t+1}\right)K_{t+1}\right]^{\alpha} l_{t+1}^{(1-\alpha)}\right)^{\rho}\right]^{\frac{1}{\rho}}$$

I assume that firms can pledge the adaptation capital as collateral. Then, firms borrow to finance the investment in adaptation capital.

Lemma A6. *The optimal choice of adaptation by firms is implicitly defined as:*

$$x_{f,t}^{*} = A^{\rho}\alpha(1-\eta) \cdot \frac{\tilde{Y}_{t+1}^{1-\rho}}{\left(\left(1-(1-x_f)\mu_K\gamma_{t+1}\right)K_{t+1}\right)^{1-\alpha\rho}} \cdot l_{t+1}^{(1-\alpha)\rho} \cdot \frac{\mu_K\gamma_{t+1}}{(1+r_{t+1})}$$

Figure 8 plots the evolution of the firm's choice of adaptation over time, showing that the firm's choice of adaptation rises as climate change worsens. Under the most severe climate change scenario, firms invest to reduce more than 25 percent of idiosyncratic losses by the end of the century. This reduces the fall in output. Adaptation by firms is neutral on the cost of capital. By adapting to climate change, firms reduce the decline in aggregate income. This increases the supply of capital in the economy compared to the case in which firms do not adapt, thus reducing the cost of capital. However, firms finance their investment in adaptation by issuing corporate debt. This raises demand for capital, thus increasing the cost of capital. In equilibrium, these two effects fully offset one another.