To Improve Is to Change? The Effects of Risk Rating 2.0 on Flood Insurance Demand

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Abstract

We present a theory of the demand for flood insurance and empirically analyze the effects of the adoption of Risk Rating 2.0, using individual insurance histories for all NFIP policies. The reform increased exit and reduced entry, both in the flood zone and its periphery. The reform had highly heterogeneous effects on insurance costs and triggered adjustments in coverage and deductibles. On average, RR2 increased costs for renewers outside of the flood zone but lowered them for renewers in the flood zone, resulting in an overall average increase. However, the reform reduced revenue and increased financial exposure to flood risk.

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To improve is to change; to be perfect is to change often.

—*Winston Churchill*

1 Introduction

Generally speaking, the *National Flood Insurance Program* (NFIP) seeks three objectives: to reduce current exposure to flood risk by maximizing insurance take-up in flood-prone areas, to provide accurate estimates of flood risk that incentivize adaptation and lower future losses, and to be financially self-sustaining.

With almost 5 million policyholders, the NFIP has succeeded in attaining fairly high take-up rates in many flood-prone areas around the country, partly by offering highly subsidized insurance for most of its existence. However, critics of the program argue that it is also responsible for contributing to excessive agglomeration in high-risk areas due to the subsidies, the reliance on outdated flood risk estimates, and a coarse risk-pricing schedule.

Largely to address these problems, FEMA rolled out a profound overhaul of the NFIP in late 2021, known as *Risk Rating 2.0* (RR2, for short). Essentially, this reform modernizes the estimation of property-level flood risk (based on a wide range of individual property characteristics) and implements a new pricing methodology that tailors premiums to each property's flood risk. The expectation is that by transitioning toward actuarially fair premiums, insurance take-up in flood-prone areas will increase and, at the same time, the program will again become financially self-sustaining. But, unlike car or health insurance, flood insurance remains primarily a voluntary decision.

Besides some recent evidence on the effects of the RR2 reform on average premiums (Mulder and Kousky (2023)), we are unaware of a comprehensive empirical analysis of the effects of the new pricing system on insurance take-up. Our paper presents a new theory of the demand for flood insurance where risk-averse homeowners (who differ by income and flood risk exposure) choose whether to buy insurance, and derive predictions for the effects of the reform.[1] We also build individual insurance histories for the universe of NFIP policies for the period 2019-2023, and estimate the effects of RR2 along the extensive and intensive margins of the demand for insurance, including whether policyholders modified policy parameters (such as coverage and deductibles) in order to mitigate potential premium increases.

According to our theory, the allocations of insurance purchases are symmetric in the 100-year flood zone (FZ) and in its periphery, which essentially coincides with the 500-year flood zone. Under the old pricing function, purchase allocations are characterized by

[1] We also explore extensions of the model with entry-exit dynamics and subjective risk beliefs (Bakkensen and Barrage, 2022).

a threshold level of flood risk in each of the two zones. Homeowners with risk above the threshold buy insurance, provided they can afford the premiums. The resulting allocation entails *implicit* subsidies for some homeowners (paying premiums below the expected annual loss) and *implicit* taxes for others. In the model, when RR2 is adopted, every homeowner can purchase insurance at actuarially fair prices, which eliminates the implicit taxes and subsidies. As a result, the model predicts that homeowners who can afford the premiums will purchase insurance. Because flood risk varies continuously in the model, homeowners experience widely heterogeneous changes in the price of insurance, and this is expected to trigger entry (primarily among homeowners with relatively low flood risk) and exit (largely among relatively high-risk homeowners).

Importantly, our empirical strategy to isolate the effects of RR2 on entry, exit and insurance prices allows for differential effects of the reform in and out of the 100-year flood zone, as well as for policyholders with subsidized rates who had been experiencing higher annual price increases due to previous reforms.[2] We estimate that the reform increased exit by 3 percentage points in the flood zone and by almost 4 percentage point outside of it, over and above the annual exit rate in the year prior to the adoption of RR2. We also document that homeowners choosing to discontinue flood insurance were paying substantially higher premiums (in the previous year) relative to policyholders in the same risk zone who chose to renew their policies. Bearing in mind that risk-averse or risk-neutral homeowners should be willing to purchase insurance at actuarially fair prices, it is plausible that the main driver of the decision to exit the insurance market after the introduction of RR2 is the inability of some policyholders to afford higher premiums.

Naturally, we do not observe the post-reform premiums that led policyholders to exit the insurance market. However, the previously estimated increases in exit strongly suggest that the reform led to premium increases for the majority of policyholders, both in and out of the flood zone. Further insights on the effects of the reform on premiums can be gained by examining the changes in the price distribution among the policies purchased in the years immediately before and after the adoption of RR2. Our second main result is that RR2 had highly heterogeneous effects on insurance prices at the individual level, with many

[2]The subsidies were applied to policies covering houses (in the flood zone) that were built prior to the release of flood maps in a community. Recognizing that subsidized (or pre-FIRM) policies accounted for a disproportionate share of claims (Kousky and Michel-Kerjan, 2017), Congress enacted NFIP reforms in 2012 and 2014. The 2012 Biggert-Waters Act (BWA) introduced an ambitious schedule to eliminate subsidized rates by raising premiums by 20-25% annually until reaching full-risk rates. The resulting increases proved unaffordable for many homeowners and the 2014 Homeowners Flood Insurance Affordability Act (HFIAA) delayed the start of the premium increases (by 4 years) and capped them at 18% for most policies, while also introducing an annual surcharge to all policyholders. At the adoption of RR2, the full convergence of subsidized policies to full-risk rates was not yet completed, resulting in differential trends that can confound the estimation of the effects of RR2 in and out of the flood zone.

policyholders experiencing premium reductions while others witnessed substantial increases. On average, the reform led to larger price increases for policyholders outside of the flood zone, consistent with the larger increase in exit rates estimated for this group of policyholders. Thus, our estimates underscore that renewal-exit decisions are highly responsive to changes in premiums.

Third, when restricting the analysis to homeowners who continuously purchased insurance before *and after* the reform, we find that RR2 increased the average price in the periphery by 12%, surpassing the 9% increase of the previous year. In the flood zone, the average price for renewing policies (pooling full-risk and subsidized policies) actually *fell* by 2.7% when RR2 was adopted, in stark contrast to the 2.7% *increase* in the previous year. As it turns out, the average price increase in the flood zone differed dramatically among policyholders paying full-risk rates and those with subsidized premiums: the former experienced a 4.7% price increase when RR2 was adopted, whereas the average *renewer* with (previously) subsidized premiums experienced a 32% *reduction*.[3] Thus, while some pre-FIRM policyholders were pushed out of the market due to large price increases, the reform was a boon to others that enjoyed large reductions. This finding, based on the universe of policies nationwide, provides confirmation for the survey evidence reported in Sherman and Kousky (2018) for a single city.

Fourth, we also find evidence of adjustments along the intensive margin. Specifically, policyholders experiencing price increases mitigated the impact on their premiums by adjusting coverage and, particularly, building deductibles. Our estimates indicate that RR2 led to a 12% average increase in the deductible chosen by renewing households outside of the flood zone, for whom insurance prices had also increased by 12%. Flood-zone policyholders with full-risk rates, who also saw their premiums increase, also adjusted their deductible upward (by an average of 5%). In contrast, renewers with subsidized rates actually lowered deductibles by 3%, consistent with the average price reduction they received. Pooling the three groups, RR2 led to a 8% increase in the deductible of the average policyholder (and a negligible effect on coverage). As a result, the reform had the unintended consequence of increasing the financial exposure to flood risk of *insured* homeowners.

We also document that RR2 reduced entry into the insurance market, particularly in the periphery, where insurance purchases are largely voluntary and annual premium growth

[3]In 2020 roughly 15% of NFIP policies insured houses built before the release of flood maps, which were almost exclusively located in the 100-year flood zone. These (pre-FIRM) policies were priced favorably, with rates that were, on average, lower than those applied to houses built after the flood maps. However, *high-elevation*, pre-FIRM houses were effectively paying premiums well *above* their expected loss. As we shall show, some pre-FIRM policies experienced large premium increases (and led to exit) while others enjoyed large discounts (and were renewed).

accelerated due to the reform. Combining all the previous effects, we conclude that RR2 lowered the overall NFIP revenue by 3.7%, largely due to reduced entry and the increase in exit. Thus, the reform appears to have reduced the financial sustainability of the NFIP and lowered insurance take-up in the short run, leaving a greater number of homeowners exposed to financial risk and potentially reducing their access to credit (Garmaise and Moskowitz, 2009). However, by providing more accurate assessments of flood risk, and by tying premiums more closely to individual risk, the reform provides stronger incentives for adaptation investments (and location decisions), which could potentially reduce economic and human losses in the future. In this respect, our paper complements the simulation analysis in de Ruig et al. (2022), which shows that RR2 could have important long-term societal benefits if households respond by adopting risk-reduction investments, which would be further magnified if complemented with large-scale infrastructure investments. It is worth emphasizing that their analysis does not use data on actual insurance purchases, relies on strong parametric assumptions on the geographic distribution of income, and assumes that households' choices of coverage and deductibles are fixed. Thus, our empirical findings will also help inform future simulation-based analysis of the long-term effects of the reform.

Our paper builds on the pioneering work by Mulder and Kousky (2023), who provided initial evidence of how the adoption of RR2 led to changes in average premiums. They documented that the new pricing schedule lowered average premiums in the flood zone but increased them elsewhere. However, our paper provides a more complete picture of the effects of RR2 on the flood insurance market by quantifying how the new regime affected policyholders' decisions to renew their policies or exit the market, as well as their choices regarding important policy parameters (such as deductibles and total coverage). Additionally, we also provide estimates of the effects of the reform on entry of new customers, and cast our empirical results through the lens of a theoretical model.

More generally, our paper contributes to the literature describing the various determinants of flood insurance demand, which is almost exclusively based on RR1 pricing. Existing studies indicate that take-up is higher in areas with higher risk (Bradt et al., 2021; Kousky, 2011), for individuals with higher risk aversion (Petrolia et al., 2013), with higher incomes (Atreya et al., 2013; Netusil et al., 2021; Shao et al., 2017), and with more expensive residences (Brody et al., 2018). The impact of the mandatory purchase requirement for mortgaged properties in the floodplain is still subject to debate since some studies find that it increases (Kriesel and Landry, 2004) or does not impact take-up (Kousky, 2011; Landry and Jahan-Parvar, 2011). Compared to this literature, our analysis emphasizes changes in individual insurance histories over time and entry and exit decisions.

Our paper also adds new results related to the intensive margin of flood insurance. The work focusing on the choice of total coverage shows that it increases with policy subsidies (Landry and Jahan-Parvar, 2011) and objective measures of risk (Kousky, 2011). In the case of deductible choice, Dombrowski et al. (2020) argue that deductibles are sticky and are seldom adjusted, while Kousky (2011) compares policies across the flood zone boundary finding that deductibles decrease with risk. Petkov (2022) provides evidence that policyholders choose higher deductibles when they believe that disasters are unlikely. Our results indicate that deductibles are an important margin of adjustment when policyholders experience insurance price increases and imply that *insured* homeowners may end up effectively bearing more flood risk. It is also worth noting that increases in flood insurance costs may crowd out demand for home insurance, perhaps by making policyholders raise their deductibles. Thus, our findings are also relevant for analyses of the effect of climate risk on private insurance companies (Acharya et al., 2023; Jung et al., 2023).

Last, our paper also contributes to the literature that examines how direct disaster experience, or close proximity to losses, affects flood risk beliefs, which in turn affect flood insurance take-up (Gallagher, 2014; Kousky, 2017; Petkov and Ortega, 2023), housing values (Ortega and Taspinar, 2018), business establishment locations (Indaco et al., 2021), human capital investments (Gallagher et al., 2023), and the approval rates of mortgages that can be securitized (Ouazad and Kahn, 2021). This literature complements analyses of the post-disaster distribution of relief aid and its effects on residential choices (Billings et al., 2022; Pang and Sun, 2024).

The structure of our paper is as follows. section 2 presents our theoretical model. section 3 presents our data sources and describes the construction of individual insurance histories. section 4 describes our empirical approach to estimating the effects of RR2 along the extensive and intensive margins. section 5 describes the main features of insurance demand prior to the adoption of RR2. section 6 and section 7 estimate the effects of RR2 on the decision to exit the market and on insurance prices, respectively. section 8 analyzes the effects of the reform on entry and section 9 its effects on overall revenue. section 10 concludes. The appendix contains proofs and extensions to the theoretical analysis.

2 Theory

Next, we build a model for the demand for flood insurance where the schedule mapping flood risk into insurance prices is taken as given, though subject to change at the will of the government. The model focuses on the extensive margin of demand: homeowners either buy full coverage for their potential losses or do not buy any insurance. After characterizing insurance allocations under various pricing schedules using our basic setup, we analyze the effects on overall revenue and social welfare. We also present a dynamic extension of the model and consider situations with subjective flood risk beliefs.

2.1 Setting

Consider a population of heterogeneous homeowners (individuals) where each type is characterized by a pair (r, y), where r is the individual (objective) flood risk and \$$y$ is household income.[4] We assume that there exist independent and continuous probability density functions so that $r \sim h(r)$ and $y \sim g(y)$, and all homeowners live in a house of value \$$V$.

Due to flood risk, homeowner i faces a lottery: with probability r_i, her house will flood and will only deliver $V - L$ units of service. Alternatively, with probability $1 - r_i$, she will enjoy the full value of her house, V. We assume that homeowners maximize expected utility over consumption bundles (c_1, c_2), where c_1 and c_2 denote consumption in the no-flooding and flooding states of the world, respectively. We assume a well-behaved utility function $u(x)$ that is continuous, increasing and concave.[5]

Homeowner i can buy insurance at price $0 < p < 1$ per dollar of coverage, which will be allowed to vary as a function of flood risk, and choose between no insurance at all or paying a premium pL to fully insure against the loss associated to flooding. We also assume that homeowners face the following affordability constraint: $pL \leq y_i$. It is convenient to normalize income, the value of the house, and the price of insurance in loss units (L). As a result, the value of the house when flooding occurs and the premium become $V - 1$ and p, respectively.

Homeowners live inside the 100-year flood zone (denoted by indicator $z = A$) or in its periphery ($z = X$). Both risk zones differ in terms of (objective) flood risk. In particular, we partition flood risk as follows: $X = (0, \overline{r})$ and $A = [\overline{r}, 1)$. The distributional assumptions made earlier imply that the population of homeowners in each of the zones is given by $1 - H(\overline{r})$ in the flood zone and $H(\overline{r})$ in its periphery.

2.2 Utility maximization

Each homeowner compares two consumption bundles: $(V, V - 1)$ if no insurance is purchased and $(V - p, V - p)$ if she chooses to buy insurance. Expected utility maximization implies

[4]For simplicity, we think of income as net of all expenditures in goods and services except for flood insurance.

[5]We allow for linear utility to capture the risk neutrality case. Ocasionally, we specialize to the constant relative risk aversion (CRRA) family of utility functions: $u(c) = c^{1-\rho}/(1 - \rho)$, with $\rho \geq 0$.

that a homeowner with characteristics (r, y) will purchase insurance if and only if

$$u(V-p) \geq (1-r)u(V) + ru(V-1) \tag{1}$$
$$p \leq y. \tag{2}$$

Ignoring for now the affordability constraint, it is helpful to define each individual's certainty equivalent to the no-insurance consumption vector. For a homeowner with flood risk r, the *no-insurance certainty equivalent* x_r is defined by

$$u(x_r) = (1-r)u(V) + ru(V-1) \tag{3}$$
$$x_r = u^{-1}\left((1-r)u(V) + ru(V-1)\right). \tag{4}$$

Note also that under risk neutrality, $x_r = (1-r)V + r(V-1) = V - r$ is simply the expected value.[6] In other words, *risk neutral* homeowners will only purchase insurance at (or below) the actuarially fair price based on their individual flood risk, provided they can afford it. More generally, a homeowner with flood risk r will only be willing to purchase insurance provided that it affords her a higher level of consumption than the no-insurance bundle: $V - p \geq x_r$.

It is well known from standard decision theory that the no-insurance certainty equivalent x_r is a decreasing function of flood risk r, the probability of the low-consumption state of the world. Hence, facing equal premiums, homeowners with higher flood risk are more likely to purchase insurance than homeowners with lower flood risk. It is helpful to collect the following observations into a proposition:

Proposition 1. *When $p \leq 1$,*[7]

1. *The no-insurance certainty equivalent x_r is a continuous and decreasing function in flood risk r with slope $(u(V-1) - u(V))/u'(x_r))$. Furthermore, $x_0 = V$ and $x_1 = V - 1$.*

2. *For a given value of r, x_r is lower under risk aversion than under risk neutrality.*

3. *Given price p, there exists a threshold risk $r_p < 1$ such that the allocation of insurance*

[6] For CRRA, the no-insurance certainty equivalent simplifies to $x_r = \left((1-r)V^{1-\rho} + r(V-1)^{1-\rho}\right)^{1/(1-\rho)}$, where $\rho \geq 0$ is the coefficient of relative risk aversion.

[7] If $p > 1$, neither risk-neutral nor risk-averse individuals would be willing to purchase insurance.

purchases is given by indicator function

$$b(r,y) = \begin{cases} 0 & \text{if } r < r_p \text{ or } y < p \\ 1 & \text{if } r \geq r_p \text{ and } p \leq y, \end{cases} \tag{5}$$

where

$$r_p = \frac{u(V) - u(V-p)}{u(V) - u(V-1)}. \tag{6}$$

4. *Under risk neutrality, (i) the no-insurance certainty equivalent becomes the expected value of consumption $x_r = r(V-1) + (1-r)V$, and (ii) threshold $r_p = p$.*

Proof. See Appendix A. ■

Claim 3 in the proposition illustrates what Bradt et al. (2021) refer to as *adverse selection* in the insurance market: faced with similar premiums, the buyers of insurance are more likely to have higher flood risk than the non-buyers.

2.3 Insurance demand prior to RR2

For convenience, we will refer to the old insurance pricing system as RR1, for the first risk rating system. Under this system, flood insurance premiums were substantially higher inside the 100-year flood zone than outside of it. Within each risk zone, premiums were somewhat tied to each property's individual risk (e.g. because of differences in elevation), but with a relatively low price-risk elasticity.

A simple functional form that captures the essence of the RR1 pricing schedule is the following linear spline function:

$$p_1(r) = \begin{cases} \alpha_X + \beta r & \text{if } r \in X = (0, \overline{r}) \\ \alpha_A + \beta r & \text{if } r \in A = [\overline{r}, 1), \end{cases} \tag{7}$$

where, for simplicity, the slope of the two linear parts is assumed to be the same. Furthermore, we assume $0 < \alpha_X \leq \alpha_A$ and $0 \leq \beta < 1$, where the latter assumption implies that premiums increase marginally less rapidly than flood risk.[8]

Figure 1 illustrates the price schedule and the relevant purchasing thresholds. To characterize the purchase allocations, it is helpful to first find the fixed points of the pricing

[8] In practice, prices within a given risk zone are a function of some structural characteristics of the house, such as whether it has a basement, and whether the first floor lies above or below the risk zone's base flood elevation (BFE), defined as the estimated height of waters in a 100-year flooding event (Kousky and Shabman, 2014). We will often interpret variation in flood risk r as reflecting differences in elevation (relative to BFE).

function ($p_1(r) = r$) in each risk zone, denoted by (r^A, r^X), which provide the indifference thresholds for purchasing insurance for *risk-neutral* homeowners. As stated in *Proposition 2* below, under risk aversion, the indifference thresholds become (r_p^A, r_p^X) and it is easy to show that $r_p^Z < r^Z$ for $z = A, X$.

It is straightforward to prove the observations collected in the following proposition:

Proposition 2. *Assume premiums are given by the pricing schedule in Equation 7. Then*

1. *If $\alpha_X < (1-\beta)\overline{r}$ then there exists threshold r_p^X such that $0 < r_p^X < r^X < \overline{r}$ (where r^X is the threshold under risk neutrality) and insurance purchases in zone X are given by indicator function*

$$b_1(r, y) = \begin{cases} 0 & \text{if } r < r_p^X \text{ or } y < p_1(r) \\ 1 & \text{if } r \geq r_p^X \text{ and } y \geq p_1(r). \end{cases} \tag{8}$$

2. *Similarly, if $(1-\beta)\overline{r} < \alpha_A < 1-\beta$ then there exists threshold r_p^A such that $\overline{r} \leq r_p^A < r^A < 1$ (where r^A is the threshold under risk neutrality) and insurance purchases in zone A are given by indicator function*

$$b_1(r, y) = \begin{cases} 0 & \text{if } \overline{r} < r < r_p^A \text{ or } y < p_1(r) \\ 1 & \text{if } r \geq r_p^A \text{ and } y \geq p_1(r). \end{cases} \tag{9}$$

3. *The risk-neutral threshold, $r^z = p_1(r^z) = \alpha_z/(1-\beta)$, for $z = A, X$. Under risk neutrality, no homeowner voluntarily purchases insurance with a premium above her expected loss ($p_1(r) > r$).*

4. *The average premium paid by buyers in zone A will be larger than the average premium paid in zone X. Moreover, in each risk zone $z = A, X$, insurance buyers with $r_p^z \leq r < r^z$ pay a premium above their expected loss: $r < p_1(r)$. Conversely, buyers with $r > r^z$ pay a premium below their expected loss: $r > p_1(r)$.*

5. *The mass of the set of buyers under the RR1 pricing schedule is*

$$\begin{aligned} Prob(B_1) &= \int_{r=r_p^X}^{r=\overline{r}} h(r)\left[1 - G(p_1(r))\right] dr + \int_{r=r_p^A}^{r=1} h(r)\left[1 - G(p_1(r))\right] dr && (10) \\ &= \left[H(\overline{r}) - H(r_p^X)\right] + \left[1 - H(r_p^A)\right], && (11) \end{aligned}$$

where the later expression applies when all homeowners can afford insurance.

Proof. See Appendix A. ■

2.4 Partial reform: elimination of implicit subsidies

As noted above, under RR1, some policyholders enjoyed implicit subsidies (i.e. were paying premiums below the annual expected loss) while others were implicitly taxed. Clearly, both situations are departures from actuarially fair pricing. Before examining the effects of RR2, it is helpful to consider a partial reform of the pricing schedule where implicit subsidies are eliminated, but implicit taxes remain.

Specifically, let us assume that premiums increase for policyholders with premiums below the annual expected loss ($p_1(r) < r$) while keeping premiums unchanged for all other policyholders ($p_1(r) \geq r$). The reformed price schedule can be described as

$$\widehat{p}_1(r) = \begin{cases} \alpha_X + \beta r & \text{if } r \in (0, r^X) \\ \widehat{\alpha}_X + \widehat{\beta} r & \text{if } r \in (r^X, \overline{r}) \\ \alpha_A + \beta r & \text{if } r \in [\overline{r}, r^A) \\ \widehat{\alpha}_A + \widehat{\beta} r & \text{if } r \in [r^A, 1), \end{cases} \tag{12}$$

where $0 < \beta < \widehat{\beta} \leq 1$ and $\widehat{\alpha}^z = \alpha^z - (\widehat{\beta} - \beta) r^z$.

Clearly, if $\widehat{p}_1(r) = r$ then the new premium equals the expected loss. The resulting utility maximizing purchase decisions are depicted in Figure 2 and described more formally below:

Proposition 3: *Under pricing function Equation 12, in each zone $z = X, A$,*

1. *The utility-maximizing choices are given by*

$$\widehat{b}_1(r, y) = \begin{cases} b_1(r) & \text{if } r < r^z \\ 0 & \text{if } r \geq r^z \text{ and } y < \widehat{p}_1(r) \\ 1 & \text{if } r \geq r^z \text{ and } y \geq \widehat{p}_1(r). \end{cases} \tag{13}$$

2. *The switch from pricing function $p_1(r)$ to $\widehat{p}_1(r)$ triggers exit:*

$$Exit \;\; = \;\; \int_{r=r^X}^{r=\overline{r}} h(r)[G((\widehat{p}_1(r)) + G(p_1(r))]dr - \int_{r=r^A}^{r=1} h(r)[G((\widehat{p}_1(r)) - G(p_1(r))]dr > 0.$$

Proof. See Appendix A. ■

In words, below the risk-neutral threshold (where the premium equals the expected loss) in each zone, optimal choices are identical to those made under RR1 ($\widehat{b}_1(r, y) = b_1(r, y)$). However, homeowners with flood risk above the threshold experience a premium increase, resulting in exit from the insurance market by policyholders who can no longer afford insurance. Thus, the reform triggers selective exit and lowers overall take-up: low-income policyholders with high risk levels (relative to their zone) exit the market.

Clearly, social welfare falls because the reform leaves prices unchanged for some homeowners but raises them for others, forcing some of them to stop purchasing insurance because they can no longer afford it. However, the change in overall revenue is ambiguous since renewers (above the risk neutral threshold) pay higher premiums but take-up is now lower.

2.5 Risk Rating 2.0

The main tenets of RR2 are that premiums become individualized and actuarially fair, which entails the elimination of the implicit subsidies and taxes discussed above. Thus, as in Equation 12, policyholders with premiums below their individual expected loss should see premium increases, whereas the converse should occur for policyholders with premiums above expected loss. The resulting price function can be described as

$$p_2(r) = r. \tag{14}$$

It is straightforward to show that every homeowner with enough income will buy (full) insurance.[9]

Proposition 4: *Under pricing function Equation 14,*

1. *Regardless of risk, everyone who can afford the premiums buys insurance:*

$$b_2(r, y) = 1 \iff r \leq y.$$

2. *The mass of the set of buyers under the RR2 price schedule is*

$$Prob(B_2) \;=\; \int_{r=0}^{r=\overline{r}} h(r)\,[1 - G(r)]\,dr + \int_{r=\overline{r}}^{r=1} h(r)\,[1 - G(r)]\,dr, \tag{15}$$

which equals to one if all homeowners can afford insurance.

Proof. See Appendix A. ■

Let us now turn to the entry and exit generated by the switch from RR1 to RR2. As described in the following proposition (and illustrated in Figure 3), the qualitative pattern

[9] Observe that the price-risk gradient in $p_2(r)$ has a slope of 1, which is steeper than the price-risk gradient under RR1, the spline pricing function in Equation 7.

of entry and exit triggered by the new pricing system is the same in and out of the flood zone:

Proposition 5: *Assume* $0 < \alpha_X < (1-\beta)\bar{r} < \alpha_A < (1-\beta)$. *Switching from RR1 to RR2, in each zone* $z = A, X$, *there are 6 classes of homeowners:*

1. *There is new entry (*$b_1 = 0$ *and* $b_2 = 1$*) for all homeowners with relatively low flood risk* $r \leq r_p^z$ *that can afford the premiums* $y \geq r$. *These entrants pay lower premiums than renewers.*

2. *There is also new entry (*$b_1 = 0$ *and* $b_2 = 1$*) for homeowners with flood risk* $r_p^z < r < r^z$ *that were willing, but could not afford, to buy insurance under RR1 who now can afford it because* $p_2(r) = r < p_1(r)$.

3. *There is exit for high-risk homeowners* $r > r^z$ *who cannot afford the new premiums* $y < p_2(r) = r$. *The probability of exit increases in the individual flood risk and RR1 premium (*$p_1(r)$*) paid by each policyholder.*

4. *High-risk renewers* $r \geq r^z$ *experience an increase in premiums.*

5. *Low-risk renewers* $r_p^z < r < r^z$ *experience a reduction in premiums. Under risk neutrality, this set is empty (since* $r_p^z = r_z$*).*

6. *Last, there are homeowners that did not purchase insurance under either price system (*$b_1(r,y) = b_2(r,y) = 0$*) because they cannot afford it:* $y < min\{p_1(r), p_2(r)\}$.

Proof. See Appendix A. ■

Our analysis so far has focused on voluntary purchases of flood insurance. However, it is well known that homeowners in the 100-year flood zone ($z = A$) with a (publicly backed) mortgage are required to purchase insurance, regardless of their income. Moreover, there is recent evidence that lenders are increasingly requiring flood insurance as a condition for approval of mortgage requests, or some other adjustments in loan requirements, such as higher loan-to-value ratios (Sastry, 2023) or rationing (Blickle and Santos, 2022). Thus, involuntary buyers (due to the mandate) will increase take-up (primarily in zone A) relative to the scenario where all insurance purchases are voluntary, and some of these buyers may have risk below threshold r_p^z.

2.6 Revenue and Social Welfare

As we have seen above, the set of homeowners who purchase insurance (and the premiums they pay) differs under RR1 and RR2. An important outcome to gauge if the switch to

RR2 has improved the financial solvency of the NFIP is the change in the overall revenue collected through premiums, which reflects the convolution of entry, exit, and the composition of homeowners purchasing insurance.

Let us index the pricing functions for RR1 and RR2 by $j = 1, 2$, respectively. Overall revenue under pricing function j is given by

$$R_j = \int_{r=0}^{r=1} \int_{y=0}^{y=\infty} b_j(r, y)p_j(r)h(r)g(y)drdy, \tag{16}$$

where $b_j(r, y) = 1$ identifies the homeowners that choose to purchase insurance.[10] Specializing this expression to each pricing schedule delivers:

$$R_1 = \int_{r\in(0,r_p^X)\cup(r_p^A,1)} p_1(r)[1 - G(p_1(r))]h(r)dr \tag{17}$$

$$R_2 = \int_{r=0}^{r=1} p_2(r)[1 - G(p_2(r))]h(r)dr, \tag{18}$$

where the last expression makes clear that there is full take-up under RR2 among homeowners that can afford the premiums. The following proposition describes the change in **revenue** as we switch from RR1 to RR2:

Proposition 6. *The change in overall revenue (in units of the income numeraire) as we switch from RR1 to RR2 is given by*

$$\Delta R = Prob(Renew)E[p_2 - p_1|Renew] \tag{19}$$

$$+ \; Prob(Entry) \times E[p_2|Entry] \tag{20}$$

$$- \; Prob(Exit)E[p_1|Exit]. \tag{21}$$

Proof. See Appendix A. ■

The proposition makes clear that the effects of the reform on overall revenue and, hence, the financial sustainability of the NFIP depend importantly on the entry and exit triggered by the new pricing schedule, which in turn depend on the parameters of the reform and the underlying risk and income distributions. Thus, whether the adoption of RR2 increased overall revenue is an empirical question. Importantly, our data allow us to estimate each of

[10]It is worth noting that, in our model, the population of the floodplain has been normalized to one and, therefore, R_j measures per-capita revenue. To obtain the aggregate dollar amount, we need to multiply R_j by the number of homeowners in the floodplain.

the terms in the equation above, which provides a decomposition of the changes in revenue due to changes in entry, exit and renewal decisions.

It is also interesting to analyze the changes in **social welfare** arising from changes in the pricing schedule, which can be found in Appendix B.[11] The main insights of the analysis are easy to convey. First of all, changes in the pricing schedule generically produce winners and losers. The winners are homeowners receiving *lower* premium quotes for flood insurance (i.e. for which the implicit tax is removed), which expands their budget sets and therefore leads to gains in expected utility (with a strict sign if they purchase insurance after the reform). Conversely, homeowners experiencing increases in premiums (due to the loss of implicit subsidies) will suffer a loss in expected utility (with a strict sign if they purchased insurance prior to the reform). In either case, the reform can lead to extensive margin effects (entry or exit) and to intensive margin effects in the form of changes in premiums (for homeowners who purchase insurance both before and after the reform). As was the case with revenue, whether a particular reform delivers a net increase or decrease in social welfare depends on the parameters of the reform and the underlying risk and income distributions.

Secondly, it is easy to see that entry and premium reductions increase social welfare, whereas exit and premium increases lower it. Additionally, our analysis shows that exit and entry may not have symmetric effects on social welfare. To the extent that the (consumer) surplus from purchasing insurance ($V - p(r) - x_r$) increases in flood risk r, the volume of exit will have a larger weight than that of entry for reforms that disproportionately trigger exit of high-risk policyholders, as is the case with the reforms analyzed in subsection 2.4 and subsection 2.5.

2.7 Extensions

We extend the model along three dimensions. First, we show how a simple dynamic extension produces a baseline level of churning with entry and exit in every period. Second, we discuss how subsidized policies can be incorporated into the framework. Last, we consider insurance purchases when homeowners have subjective beliefs that differ from objective flood risk.

2.7.1 Dynamics

So far our model is purely static. As a result, provided that the pricing schedule remains unchanged, the model implies zero entry and exit, and all policyholders always renew their

[11] Our analysis assumes a utilitarian social welfare function where all homeowners are assigned equal weights. We do not account for the dynamic incentives in terms of risk-mitigation investments.

policies. Appendix C presents a simple overlapping generations extension of our current model that produces churning in the insurance market, perhaps driven by changes in property ownership due to home sales. More specifically, over periods of time when the pricing schedule remains unchanged, there is non-zero entry and exit in each period (and both offset each other) and, in addition, the renewal rate is strictly between zero and one.

More importantly, when the pricing schedule changes as in subsection 2.4 or subsection 2.5, entry, exit and renewal experience changes relative to their baseline values, and these changes correspond to the situations depicted in Figure 1-Figure 3. In particular, in our dynamic setting, the partial reform analyzed in subsection 2.4, where implicit subsidies are eliminated, leads to a reduction in *both* renewals and entry. More specifically, each shift of the pricing schedule in this direction leads to a one-time reduction in renewals among affected homeowners who cannot afford the higher premiums and a persistent reduction in entry affecting new homeowners who cannot afford the higher premiums. These groups are depicted in the pink triangles in Figure 2 and are characterized by high flood-risk levels (relative to their zone) and low household income.

Similarly, the adoption of RR2 (taking RR1 as the baseline) triggers exit and reduces entry for relatively high-risk homeowners, corresponding to the pink triangles in Figure 3. However, the reform is also predicted to incentivize entry among relatively low-risk homeowners who are now able to purchase low-premium policies aligned with their low levels of flood risk. As a result, RR2 may increase entry or lower it, relative to pre-reform levels.

2.7.2 Subsidized policies

Before the adoption of RR2, premiums for some properties built prior to the creation of flood maps were priced according to a more favorable pricing schedule. Insurance policies covering these properties are referred to as *pre-FIRM* or subsidized.

Essentially all *pre-FIRM* properties are located in the 100-year flood zone and their premiums did not depend on elevation because this information was not easy to establish in the absence of official flood maps. A simple way to think about the pricing schedule for these type of policies prior to RR2 is $p(r) = \alpha_A$ for $\overline{r} \leq r < 1$. Indeed, as one can deduce from Figure 1, some of the so-called 'subsidized' policies were receiving an implicit subsidy ($p(r) < \alpha_A$) whereas others were bearing an implicit tax ($p(r) > \alpha_A$). According to the figure, the former would have relatively high flood risk whereas the latter would have relatively low flood risk.

When RR2 was adopted, subsidized policies became subject to the same (full-risk) pricing schedule as all other properties. Hence, those enjoying an implicit subsidy (tax) are expected to experience a premium increase (reduction).

2.7.3 Subjective risk beliefs

Our analysis so far has assumed that homeowners flood risk beliefs reflect objective flood risk. However, several studies have empirically documented departures from this assumption. Bakkensen and Barrage (2022) document underestimation of flood risk beliefs in the 100-year flood zone arising from sorting of homeowners with downward biased subjective flood risk beliefs. Likewise, Weill (2022) argues that homeowners residing in the periphery of the floodplain underestimate their exposure to flood risk. A simple modification of our setting allows us to analyze the effect of these behavioral traits on flood insurance take-up. In particular, we allow for subjective flood risk by assuming that homeowners choose whether to buy insurance on the basis of a subjective probability of flooding given by $\pi(r) = \lambda r$ where $0 < \lambda \leq 1$, where lower values of λ entail a larger degree of underestimation of the objective risk. For the sake of brevity, we refer interested readers to Appendix D for the formal analysis. The gist of this extension of the model is that there is a clash between flood risk skepticism (inversely related to λ) and risk aversion: for a given degree of risk aversion, insurance take-up falls in the discount placed on objective flood risk probabilities.

3 Data: Sources and panel construction

3.1 NFIP policies

Our main data source is the *OpenFEMA Dataset* retrieved in January 2024.[12] The data contains the universe of flood insurance policies sold through the *National Flood Insurance Program* since 2014, even though our main focus is the period since 2019.

These data contain a rich set of attributes, as illustrated by Table 1. The table focuses on the approximately 17 million policies purchased in calendar years 2019-2023 for residential buildings with up to 4 residential units. Among these, 44% were in the 100-year flood zone (defined as properties with flood zone designations A or V) and 97% pertained to single-family houses. In addition, 82% of the policies covered primary residences, 7.4% of the policies were subsidized (due to pre-FIRM construction), and 15.2% of the policies were reported to be mandatorily purchased (mostly due to federally backed mortgages for buildings located in the 100-year flood zone). We also note that Florida and Texas account for a 46.5% market share.

The average building replacement cost was around $308,000, which is often used as a

[12] As required by FEMA, we acknowledge that this data product uses the FEMA OpenFEMA API, but is not endorsed by FEMA. The Federal Government or FEMA cannot vouch for the data or analyses derived from these data after the data have been retrieved from the Agency's website(s).

proxy for household wealth. The average total coverage was around $280,000, with 76% of this amount insuring the building (and the rest providing coverage for contents). On average, the annual cost of flood insurance policies was $941, consisting of a $711 premium and $230 fees. It will be helpful to define the *insurance price* for $1,000 of coverage, which on average was $4.5. Another important parameter affecting the price of insurance is the building deductible, which on average was $2,049.

Importantly, these data have two important limitations for our purposes. First, FEMA does not release a policyholder identifier. In addition, due to privacy concerns, the data do not include detailed building coordinates (such as an address or precise latitude-longitude coordinates).

3.2 Individual Insurance Histories

Analyzing individual insurance histories longitudinally requires a method to link individual policies pertaining to a specific policyholder over time. To do so we build on Mulder and Kousky (2023) and extend it in several ways. Their goal was to provide a descriptive analysis of the effect of RR2 on annual premiums, based on NFIP policies (restricted to single-family homes) purchased in the month of April in years 2021 and 2022. Their main contribution is the use of the rich set of policy attributes in the data to link individual policies purchased by the *same policyholder* over time. Essentially, the authors identified a set of attributes that could plausibly be considered time-invariant and grouped policies with identical values for said vector. Using these data, they concluded that the adoption of RR2 led to a reduction in the average premium in the 100-year flood zone but an increase in the average premium paid by homeowners located in its periphery. Importantly, their estimates provide only a partial view of the effects of RR2 on the NFIP revenue. A more comprehensive analysis requires estimating the effects of the reform on entry and exit.

We will rely heavily on their algorithm to group policies, but extend it in several ways. Thus, we first describe the vector of attributes used by Mulder and Kousky (2023) and we will also evaluate the validity of their time-invariance assumptions. It is worth noting that our analysis will require linking policies over a longer (5-year) period of time (2019-2023), which requires adapting the algorithm used by Mulder and Kousky (2023) to link policies over a 2-year period.[13]

[13]Note that the unit of analysis is a homeowner. Analogous to a business establishment, it is a combination of a fixed physical location and the people who inhabit it.

3.2.1 Algorithm performance metrics

The linking algorithm proposed by Mulder and Kousky (2023) (MK for short) is based on the following 7 policy attributes: census tract, original construction date, original new business date, flood zone location, base flood elevation, lowest floor elevation, lowest adjacent grade, and (implicitly) month the policy becomes effective.[14]

Because of the high dimensionality of this vector, provided these attributes remain *invariant over time for a given policyholder*, it is extremely likely that policies with identical values for the vector of attributes were purchased by the same policyholder. However, if either attribute happens to vary over time, the MK algorithm will introduce an excessive fragmentation of individual insurance histories by creating two different identifiers when, in reality, all those policies belong to a single policyholder.

In order to examine the plausibility of the time-invariance assumptions and to gauge the relative contribution of each attribute, we will reconstruct the MK algorithm by adding attributes one at a time and examine the performance of the corresponding groupings (policyholder identifiers) along 6 metrics.[15] At each step, we evaluate the metrics on the basis of the groupings of policies resulting from the use of the attributes introduced up to that point:

1. Duplicates. This metric is based on the number of policies in the same group in a given year (minus one), normalized by the overall number of in-force policies in that year. The NFIP only allows a policyholder to have a single policy in-force for a specific residence at any point in time. Thus, observing multiple policies for a single ID-year points to an excessively coarse partition where some groups agglomerate policies that, in reality, belong to different policyholders.[16] Clearly, provided that all attributes used to define a group are indeed time-invariant, a more successful algorithm will exhibit fewer duplicates. We also note that, erroneously including a time-varying attribute in the attributes vector will *also* lower the number of duplicates, but result in an excessive fragmentation of individual insurance

[14] The original new business date records the first time (day, month and year) that a policyholder purchased insurance for a specific building. By restricting their sample to the month of April for 2021 and 2022, the MK algorithm effectively only links policies that came into effect in the same month (April). For exact variable definitions, see `https://www.fema.gov/openfema-data-page/fima-nfip-redacted-policies-v2`.

[15] Obviously, the contribution of each attribute depends on the specific ordering of the attributes. We introduce first the attributes that are more plausibly time-invariant.

[16] For instance, the first attribute we will use to create groups that partition the set of policies is the census tract (CT) reported in the policy. We will then compute the number of policies (referred to as copies) that belong to the same group and year. The number of duplicates is the number of copies minus one. Clearly, because most census tracts contain more than one policyholder, a partition based solely on census tract will exhibit many duplicates. Next, we will create a new partition where the groups are defined using two attributes: census tract (CT) and original construction date (OCD) and then recompute the number of duplicates, that is, the number of policies with the same values for census tract, OCD and year, minus one.

histories. As shown in the top panel of Table 2 (last row), the MK algorithm results in a duplicates rate of 1.26%.

2. Average length of insurance spells. For each group (ID), we compute the number of years between the first and last insurance policies and then average across all groups. To fix ideas, an 5-year insurance history $(b_1, b_2, b_3, b_4, b_5) = (1, 0, 0, 0, 1)$ has a spell of length 4, which is the maximum length in our 5-year dataset. Analogously, homeowners that only purchased one policy have a spell of zero length. Unfortunately, we do not know the actual average length of the individual insurance histories in our dataset, but it is well known that there is new entry every year and purchases are highly persistent. Hence, the true average length is likely to range between 2 and 4 years (for a 5-year data span). As noted earlier, erroneously relying on time-varying attributes will shorten insurance spells. Thus, this metric helps assess the validity of the time-invariance assumptions. The average length of the insurance histories obtained with the MK algorithm is 2.46 years.

3. Coverage lapses Typically, policyholders renew their policies on the same exact day (month-day) every year. However, unexpected (income or health) shocks can make a policyholder be late on a payment, creating a lapse in coverage. Our metric counts the number of groups (IDs) displaying a lapse in coverage, defined as a period of more than 12 months between two consecutive insurance purchases, normalized by the number of groups. Clearly, income and health shocks are a fact of life, so policy lapses surely take place, but are probably a rare occurrence. Thus, the true number of lapses is expected to be positive, but small.[17] The MK algorithm entails a minuscule frequency of policy lapses (0.08%).

4. Changes in elevation variables. Policyholders that provide an elevation certificate benefit from lower premiums. The elevation certificate reports information on the base flood elevation, elevation of the lowest floor, and lowest adjacent grade that is incorporated into the insurance policy. Prior to RR2, obtaining such a certificate was costly and a very infrequent event, but could be an endogenous response to a premium increase.[18] Specifically, our metric reports the number of groups exhibiting within-group variation in either of the three elevation variables, divided by the overall number of groups. We expect this value to be positive, but small. Because the MK algorithm uses the levels of the elevation variables as attributes to define groups, it mechanically implies a value of zero for this metric, which very likely underestimates the actual number of changes in elevation variables.

[17] The average forbearance rate for mortgages, defined by the share of consumers with mortgage balances who are more than 30 days late on their payments, was 2.2% in the period 2018-2023. It is likely that policyholders in forbearance who are due for renewal of their flood insurance policy will also let their coverage lapse. Among policyholders who do not have an outstanding mortgage, the probability of an insurance policy lapse is likely to be much lower.

[18] The new flood risk estimates used to price policies under RR2 incorporate property-level estimates for all buildings and adjust premiums accordingly (Mulder and Kousky, 2023).

5. House sales with policy endorsement. When a house is sold, the buyer often keeps the existing insurance policy (to benefit from the lower old rate). In this case, the insurance history continues and the purchase date is recorded as a policy attribute. Obviously, houses are sold every year, but this is an infrequent event for a given property.[19] We compute the rate of sales with a policy endorsement and then normalize by the number of groups. We expect this rate to be around 1.7%, under the assumption that flood insurance policies are always endorsed by the buyer of the house. The MK algorithm implies that 0.8% of policies were endorsed at the time a house was sold.

6. Changes in flood zone status. FEMA gradually updates flood maps and, as a result, some houses are moved into or out of the 100-year flood zone. This has been used in the literature to identify the effects of flood zone status on housing prices (Ortega and Taspinar, 2018; Indaco et al., 2019) and flood insurance take-up (Weill, 2022). We report the number of groups exhibiting a change in flood zone status within our period of analysis, normalized by the number of groups. The MK algorithm assumes that flood zone status is a time-invariant attribute and, hence, mechanically implies zero status changes.

3.2.2 The MK algorithm

Let us now examine the evolution of the performance metrics as we gradually add policy attributes to the MK algorithm. As shown in the top panel of Table 2, relying on census tract as the single attribute to identify policyholders is clearly not enough as it produces 71,156 groups (homeowner IDs) with an average insurance spell of 3.75 years (out of a maximum of 4 years) and 98% duplicates. In other words, it clearly generates too few groups with unrealistically long insurance spells and too many duplicates.

Adding the original construction date (OCD) as an attribute helps a lot: the number of groups increases to 2.44 million, but the rate of duplicates remains too high (45%). Further adding the original new business date (ONBD) as an attribute practically doubles the number of groups (4.74 million) and brings down the rate of duplicates to 2.15% and the average spell to 2.52 years. Including the remaining 3 attributes (flood zone status, elevation variables, and month the policies become effective) has relatively small effects on the number of groups, rate of duplicates, and average spell, but let us examine the metrics in columns 5-7 in Table 2. The MK algorithm implies a very low frequency of policy lapses (0.08%) and assumes away the possibility of changes in elevation variables and flood zone status, both of which are known to happen occasionally. As a result, the rate of duplicates and the average insurance

[19] In the United States, 6.12 million homes were sold in 2021 out of a stock of 143.13 million housing units (*Statista.com*). Hence, a 0.43% annual rate of sales. Since we focus on a 5-year period, each house could conceivably be sold 4 times. Hence, the 4-year probability of sale is $4 \times 0.43\% = 1.72\%$.

spell produced by the MK algorithm may be excessively low. It is also worth noting that the analysis in Mulder and Kousky (2023) entails only one year of data and, therefore, flood map revisions entailing changes in flood zone status and updates to elevation variables will affect very few policyholders. However, in other analyses (like ours) that require linking together policies for more years, these time-invariance assumptions will be less tenable.

3.2.3 The OP algorithm

On the basis of the previous discussion, we propose a new algorithm (named after ourselves) that (i) does not rely on some of the attributes that potentially vary over time for a given property (such as flood zone status, elevation variables and constant effective month), and (ii) introduces several new attributes that help refine the partition of policies (and are likely to be time-invariant). More specifically, our algorithm uses census block groups (rather than the broader census tract), latitude and longitude (only available with one decimal), flood map number, original construction date, number of floors, and new business date. Last, we also make use of a policy attribute indicating when a house was sold and the flood insurance policy endorsed by the new buyer. While this is not an intrinsically time-invariant attribute, it is convenient to break up insurance spells when this event happens because relevant characteristics of the policyholder may change, such as income, or whether the house is used as collateral for a mortgage, which could require mandatory purchases of flood insurance.

The performance of our algorithm is assessed in the bottom panel of Table 2. The first row creates groups using the most plausible time-invariant features of the house (census block group, latitude-longitude, flood map, original construction date and number of floors). These attributes lead to 3.56 million policies and a duplicates rate of 24.65%. When we add the original new business date, the number of groups grows to 4.82 million, the rate of duplicates falls to 1.49% and the average spell becomes 2.49 years. When we also require that insurance histories not contain a house sale, the number of groups (policyholder IDs) grows to 4.85 million groups, and the duplicates rate and average spell fall to 1.27% and 2.48 years, respectively. These values are very similar to those attained by the MK algorithm. However, the insurance histories in our dataset allow for more policy lapses (1.14% vs. 0.08%), updates in elevation variables (0.38% versus 0%), and changes in flood zone status (0.29% versus 0%) than the MK algorithm. At the end of the day, over short time periods, these discrepancies are unlikely to matter much, but our enhanced algorithm is more versatile and can be reliable applied to long periods of time.

4 Empirical Approach

Our longitudinal dataset contains the universe of policies for the period 2019-2023, which allows us to reconstruct the longitudinal insurance histories of all individuals that purchased insurance at least one during our period of study. Specifically, let $b_{i,t}$ be an indicator for whether policyholder i purchased insurance in year $t = 2019, ..., 2023$. Our original longitudinal dataset does *not* contain homeowners that never bought insurance over our period of study, but we can expand our dataset by entering zero values ($b_{i,t} = 0$) in the years in which a homeowner did *not* purchase insurance (provided she had purchased at least one time in our period of study). As a result, we obtain a balanced panel $\{(i, t) : b_{it} = 0, 1\}$ for $t = 2019, ..., 2023$. Next, we discuss the empirical models we shall employ to estimate the effects of the reform on insurance demand and prices, which allow for differential effects in and out of the flood zone and for policyholders with formerly subsidized rates.

4.1 Extensive Margin: the Renewal-Exit Decision

Our analysis of the effects of RR2 along the extensive margin of insurance demand focuses on the changes in the probability of renewal or, conversely, the probability of exiting the market for individuals who had purchased insurance in the previous period. Considering individuals who purchased insurance one period ago ($b_{i,t-1} = 1$), we define *renewal* if $b_{i,t} = 1$ and *exit* if $b_{i,t} = 0$.

One of our main goals will be to estimate the effect of the adoption of RR2 on individual renewal (exit) probability, taking as baseline the probability of renewal (exit) under the previous pricing function. More specifically, we will focus on 3-year insurance histories $\{(b_{i,t-2}, b_{i,t-1}, b_{i,t})\}$ where policies in periods $t - 2$ and $t - 1$ were priced under RR1 and policies in t were priced under RR2. Importantly, the empirical model allows the reform to differentially affect renewal (exit) decisions by risk zone and subsidized status:

$$Prob(b_{i,t-1} = 1 | b_{i,t-2} = 1) = \Phi(\alpha_1 + \alpha_2 FZ_i + \alpha_3 FZ_i \times Subsidized_i) \tag{22}$$

$$Prob(b_{i,t} = 1 | b_{i,t-1} = 1) = \Phi(\beta_1 + \beta_2 FZ_i + \beta_3 FZ_i \times Subsidized_i). \tag{23}$$

Naturally, it is possible to estimate linear versions of these equations (i.e. linear probability models) with a single-equation model by including interactions with an indicator function $RR2_t$ taking a value of one for the period when RR2 was introduced.

Generally speaking, a complete analysis of the effects of RR2 along the extensive margin of insurance demand should also include entry decisions by homeowners who had not purchased insurance in the past. Unfortunately, our data is not suitable to analyze the entry decision at the individual level because we do not see homeowners that never purchase insurance.[20] As a result, our analysis of entry will be more limited as we will need to limit ourselves to estimating models at a higher level of aggregation, such as census tracts.

4.2 Intensive Margin: prices and policy adjustments

Estimation of the effects of the reform on (segments of) the pricing function while neutralizing the confounding effects of potentially selective entry and exit can be achieved by restricting the analysis to renewals. Specifically, our intensive margin analysis of the effects of RR2 is based on the subsample of individuals who purchased insurance in the last two rounds of RR1 *and* in the first one of RR2. That is, we consider a sample composed exclusively of always-buyers: $\{(i,t) : b_{i,t} = b_{i,t-1} = b_{i,t-2} = 1\}$. Obviously, for these individuals we observe all the policy attributes (including premiums) for the three periods and we are able to identify the changes in the outcome of interest both prior to the introduction of RR2 *and* in the first period after its adoption.

We are particularly interested in *within-individual* changes (for always-buyers) in the following policy attributes: insurance price, total coverage, and building deductible. We define *insurance price* by $p = 1,000 \times PolCost/InsTot$, which provides the price per \$1,000 of coverage. Denoting by $X_{i,t}$ our policy attribute of interest, we model its changes over time using the following linear regression model, which allows for different parameter values before and after RR2 was introduced and variation inside and outside of the flood zone:

$$\Delta X_{i,t} = (\alpha_1 + \alpha_2 FZ_i + \alpha_3 FZ_i \times Subs_i) + RR2_t(\beta_1 + \beta_2 FZ_i + \beta_3 FZ_i \times Subs_i) + u_i, \quad (24)$$

where $\Delta X_{i,t} = X_{i,t} - X_{i,t-1}$ is the change in the attribute between the last two rounds of policies priced under RR1, FZ_i is an indicator for location in the 100-year flood zone, $Subs_i$ indicates a subsidized (pre-FIRM) policyholder, and $RR2_t$ takes a value of one from the onset of the reform (and zero otherwise).

5 Demand for Flood Insurance Prior to RR2

Let us summarize the key attributes of the policies purchased in the last year during which RR1 was in effect, namely, between 2021Q2 and 2022Q1 (both included), which we refer to as

[20] This is most clearly seen in the context of 2-year insurance histories. For any two pair of years $(t-1, t)$, our data contain purchase histories $(b_{i,t-1}, b_{i,t}) \in \{(1,0), (1,1), (0,1)\}$ but individuals with $(0,0)$ histories are missing. As a result, conditional on $b_{i,t-1} = 1$, our data implies that $b_{i,t} = 1$, which results in a degenerate likelihood function.

fiscal year 2021 (fy21). Specifically, Table 3 restricts the sample to 2-year insurance histories for policyholders who purchased insurance in fy20 and are up for renewal in fy21, which contains almost 3.57 million policyholders. The first row shows that 86% of the homeowners renewed insurance in fy21 (3.07 million). Almost all policies (97.3%) were for single-family homes, and slightly less than half of all policies (48.1%) were purchased by homeowners in the 100-year flood zone. The average total cost of the policies was $955, which can be broken down into a premium of $724 and $231 in fees. The average total insurance coverage was approximately $282,000 (with 76% corresponding to building coverage and the rest to contents). In turn, the average policy had a building deductible of $1,972. Last, 16.1% of the policies were subject to mandatory purchase and 10.7% benefitted from subsidized rates.

It is also instructive to compare the mean attributes of the policies purchased in the flood zone and the periphery. As shown in Table 4, the renewal rate was 4 percentage points higher in the flood zone than in the periphery (88.1% versus 84.1%). Put otherwise, the annual probability of exit was 11.9% in the flood zone and 15.9% in the periphery, partly reflecting the insurance purchase mandate affecting properties with mortgages in the flood zone. In addition, houses in the flood zone are on average about 7 years newer.[21] Not surprisingly, the annual insurance cost (including premiums and fees) is substantially higher in the flood zone by an average of $696 ($612 in the periphery vs. $1,308 in the flood zone). In turn, policyholders in the flood zone choose larger building deductibles ($2,693 versus $1,269 in the periphery) and lower coverage ($250,960 versus $312,604 in the periphery) in order to lower their annual premiums. There's also a large discrepancy in the prevalence of subsidized rates (mainly linked to pre-FIRM construction) and purchase mandates, both of which are heavily concentrated in the flood zone. In the flood zone, 21.7% of the policies enjoy discounts (compared to only 0.5% in the periphery) and 29% are bought *involuntarily* (compared to only 4% in the periphery).[22]

It is also interesting to compare the characteristics of renewers and quitters prior to RR2, conditional on both having purchased insurance in the previous year. We do this by restricting the sample to homeowners who purchased insurance in the second-to-last round of RR1 (fy20, 2020Q2-2021Q1) and estimate linear regression models for various lagged outcomes (such as log insurance price and log of the building replacement cost) where we

[21] Rather than a feature of the stock of housing, we suspect that the house age difference is due to the insurance mandate. Newer houses are more likely to be collateral for a mortgage and thus subject to mandatory insurance purchase.

[22] The purchase mandate linked to publicly backed mortgages only applies to properties located in the 100-year flood zone. The policies in the periphery reported to be subject to a mandate may reflect changes in the boundary of the flood zone. However, these policies could also be requirements imposed by lenders who increasingly require mortgage applicants in flood-prone areas to purchase flood insurance in order to approve their loan applications.

include an *exit* indicator as a regressor, which takes a value of one for homeowners who did *not* purchase insurance in the last round of RR1, and zero if they did. As shown in Table 5 (columns 1-2), on average, homeowners who exited the insurance market were paying annually between 0.11 log points (in the periphery) and 0.31 log points (in the flood zone) more than renewers. Keeping in mind that RR2 offers actuarially fair premiums, which in our theoretical model implies that all homeowners are willing to purchase insurance, this finding suggests that affordability may have been the key factor in the decision to discontinue insurance coverage (Figure 2). Column 2 provides additional support for this interpretation: quitters lived in properties that had lower value (measured by replacement costs) by about 0.015 log points (similarly in the flood zone and its periphery). In addition, policies attached to a primary residence were significantly less likely to be discontinued.

6 The Effects of NFIP Reforms on Renewal and Exit

Our main outcome for the analysis of the effects of RR2 along the extensive margin of insurance demand is the exit (renewal) decision, conditional on having purchased insurance in the previous period. Because exit was already happening prior to the adoption of RR2, it is important to investigate whether the reform led to an *increase* in exit, as predicted by our model (Figure 3). To do this, we focus on data for 3 years: the last two rounds of purchases under RR1 (fy20 and fy21) and the first round under RR2 (fy22).[23] We shall return later to the (more limited) analysis of entry in the next section.

We estimate a linear version of the model in Equation 22-Equation 23. The estimates are collected in Table 6, where renewal rates are allowed to vary by risk zone and after RR2 was adopted. As shown in column 1, under RR1, the renewal rate in the periphery was 84.1% and 4 percentage points higher in the flood zone, possibly due to the much higher prevalence of the insurance purchase mandate. When RR2 was adopted (in 2022Q2), annual renewal rates fell substantially: by about 3 percentage points in the flood zone and 4 percentage points in the periphery. Thus, the implementation of RR2 lowered renewal rates in both risk zones and, in addition, widened the gap between both zones by roughly one additional percentage point.

Column 2 allows for heterogeneous effects of RR2 for policyholders with subsidized rates (prior to the reform), practically all of which are residents of the 100-year flood zone. The estimates show that the effects of RR2 on exit (renewal) varied very significantly along this

[23] RR2 was phased in gradually. Starting in October 2021, there was an interim period during which new policies (for entrants) were already priced under RR2 but renewals were priced under old system. The full implementation of RR2 began in April 2022. From that moment onward, all policies were priced under RR2.

dimension. While the the exit probability for the average policyholder paying full-risk rates increased by 2.6 percentage points when RR2 was adopted, the corresponding increase in exit was more than *twice* as large (6 percentage points) for policyholders with subsidized rates. This implies that more policyholders with subsidized rates experienced premium increases when the reform was enacted compared to policyholders paying full-risk rates.[24]

Next, we test an implication of our theoretical model. As illustrated by the pink triangles in Figure 3, the adoption of RR2 is expected to trigger exit among policyholders with high risk levels (and thus high insurance prices) relative to others in their same zone. In the model, the policyholders who exit would like to continue purchasing insurance but cannot afford the increase in premiums. To test this prediction, we include in the empirical model controls for lagged insurance prices (in logs) both before and after RR2, restricting the sample to full-risk rate policies (89% of the sample). As reported in column 3, the estimates are negative in both cases, implying that exit is systematically higher among policyholders paying relatively high premiums (vis-a-vis others in the same risk zone), which is consistent with the theoretical predictions (Figure 3).

Table 6 also includes separate estimates for Florida, Texas and New York, which account for about half of the flood insurance market and could differ from each other by having very different distributions of income and flood risk over their respective floodplains. In all of these states, prior to RR2, the renewal rates were higher in the flood zone than in the periphery (by a margin ranging between 5 and 6 percentage points). As was the case nationwide, the introduction of RR2 lowered renewal rates (i.e. increased exit) in all 3 states, with higher intensity in the periphery than in the flood zones and for policyholders with subsidized rates. Hence, the effects of RR2 on exit were qualitatively similar in the main regional markets.

To sum up, the analysis in this section has clearly shown that the adoption of RR2 led to an increase in exit from the insurance market, with higher intensity in the periphery than in the flood zone and for policyholders with subsidized rates. Moreover, (full-risk-rate) homeowners that chose to exit the market had been paying substantially more than those (in the same risk zone) that chose to stay, and the reform may have raised premiums to levels they could not afford.

[24] As reported in Table 4, about 22% of the policies in the flood zone (A) were subsidized (mostly because of pre-FIRM construction) whereas the corresponding number for the periphery (X) was 0.5%. It is also worth noting that not all properties with pre-FIRM construction experienced a rate increase when RR2 was adopted. As we shall show below, many experienced large reductions.

7 Effect of RR2 on Insurance Prices

When FEMA announced the introduction of RR2, it highlighted that while some policyholders would experience premium increases, others would benefit from lower premiums. The pioneer study by Mulder and Kousky (2023) provided early evidence on the heterogeneous effects of RR2 on the premiums paid by policyholders (who purchased insurance both immediately before and after RR2 was adopted). In particular, they found that RR2 lowered average premiums in the flood zone but increased them elsewhere.

We extend their analysis in two important ways. First, we focus on coverage-adjusted insurance prices, rather than premiums. In addition, we estimate the post-RR2 price increases over and above the increases in the previous period. The latter are driven by the earlier NFIP reforms and the steady-state churning due to property ownership changes, which confounds the identification of the effects of RR2. In addition, we also allow for differential effects of the reform on policyholders with subsidized rates and examine whether policyholders made adjustments to policy parameters, such as coverage and deductibles in response to the RR2 price changes.

7.1 Overall changes in the distribution of prices

Let us begin by examining the cross-sectional distribution of insurance prices in the last round of purchases under RR1 (fy21) and in the first round after RR2 (fy22), considering all in-effect policies (renewals and new entry). Clearly, these distributions will be affected both by entry and exit, as well as by within-individual changes in insurance prices.

We conduct the analysis separately for the flood zone and its periphery.[25] As seen in Figure 4, the adoption of RR2 significantly affected the distribution of insurance prices in the *flood zone* (zone A). Specifically, the price density for fy22 (orange line) has a lower probability mass of high-price policyholders (in the range of \$10-20 per \$1,000 of coverage) than the density for fy21 (blue line). Thus, either the reform led them to exit the insurance market, or they experienced premium reductions.

It is also interesting to examine the price distribution in the flood zone excluding homeowners with subsidized policies (about 20% of the flood zone). As seen in Figure 5, the

[25] Before turning to the estimation of the effects of RR2 on insurance prices, we note that our estimation sample will also include homeowners subject to the mandatory purchase requirement. While excluding these individuals would more clearly connect the predictions of the model with the data, there are practical difficulties in identifying these homeowners. In particular, we observe a sudden increase in missing values for the mandatory purchase indicator in the NFIP dataset at the adoption of RR2. At any rate, to the extent that distribution of individuals (within the 100-year flood zone) subject to the requirement is independent from flood risk, our estimates of the price changes will not be biased by not excluding them from the sample. Obviously, keeping mandatory purchases in the sample will increase take-up in the 100-year flood zone.

pre-reform and post-reform price densities in the flood zone are now much more similar. In particular, the discrepancy between the right-tails of the price densities in Figure 4 has vanished, implying that those high-price policies belong to 'subsidized' policyholders. Put differently, the largest price effects of RR2 among policyholders in the flood zone were borne by pre-FIRM policyholders, resulting both in exit and (as we shall show below) in substantial price reductions.

Let us now turn to the effects of the adoption of RR2 on insurance prices in the *periphery* of the flood zone (zone X). As seen clearly in Figure 6, the new pricing schedule essentially shifted the price density rightward. Under RR1, the bulk of the policyholders paid insurance prices ranging from \$1.5-2 per \$1,000 of coverage. When RR2 was adopted, the price for the majority of policies shifted up to \$1.8-2.3 per \$1,000 of coverage. It is also worth noting that RR2 led to an increase in the density of homeowners in the periphery paying very low insurance prices (in the range of \$1-1.4 per \$1,000 of coverage), illustrating that some residents of the periphery also experienced premium reductions when RR2 was adopted.

7.2 Intensive-margin changes in prices

The changes in the price densities just discussed do not disentangle the changes in prices due to selective entry-exit from those purely due to changes in the pricing function conditional on renewal. To focus on the price changes along the intensive margin, we now examine the within-individual price changes experienced by homeowners who purchased insurance continuously both before and after RR2 was introduced.

Specifically, we restrict the analysis to policyholders who continuously purchased flood insurance in fiscal years 2020, 2021 and 2022, and estimate models analogous to Equation 24, focusing on the change in the log insurance price as our outcome of interest. In addition, we complement the analysis by plotting the cumulative distribution functions (CDFs) for the corresponding (intensive-margin) price changes, by period and risk zone.

The estimates in Table 7 (column 1) show that, prior to RR2, insurance prices for renewers in the *periphery* increased by about 9.2 percent (0.088 log points) in 2021, compared to an average annual increase of only 2.7% in the flood zone. The adoption of RR2 *increased* the average price in the periphery by 12% (0.113 log points) but, in stark contrast, RR2 *lowered* the average price in the flood zone by 2.7%. Thus, RR2 reinforced the rapid pre-existing price growth in the periphery but reversed the upward price trend in the flood zone, confirming the pattern found in Mulder and Kousky (2023). Column 2 extends the model to allow for differential effects of the reform within the flood zone, distinguishing between policyholders paying full-risk rates and those with subsidized rates. The estimates reveal that the reform had vastly different effects on the premiums of renewers in the flood zone. As was the case in the periphery, the average renewer previously paying full-risk rates experienced a 3 percentage-point price increase. In contrast, the average subsidized *renewer* saw the price of her insurance fall by 35.8% (0.410 log points). Thus, RR2 had vastly heterogeneous effects on the premiums of subsidized policyholders, largely reflecting individual differences in elevation: some policyholders experienced increases that made them exit the market (Table 6) whereas others enjoyed very large price reductions and, naturally, renewed their policies.[26] Last, the estimates in columns 4-6 reveal similar patterns in Florida, Texas and New York. The main departure is found in Texas, which displays a larger increase in premiums for policyholders in the periphery (5% versus less than 2% in the other states).

Plotting the CDFs for the (within-individual) nationwide changes in log prices provides additional detail. Figure 7 plots the CDFs for the price changes in the last round of RR1 (blue line) and when RR2 was adopted (orange line) for the *flood zone* (zone A). The most striking finding is the large increase in the mass of policyholders receiving large price reductions: almost 20% of policyholders enjoyed reductions upward of 0.10 log points. In comparison, fewer than 5% of policyholders saw such price reductions prior to the adoption of RR2. Additionally, the figure also shows that the share of policyholders experiencing large price increases (above 0.10 log points) also increased substantially (from about fewer than 10% of policyholders to approximately 60%). Excluding subsidized (pre-FIRM) policyholders substantially reduces the mass of policyholders receiving large discounts (Figure 8), implying that many of the beneficiaries were overpaying (relative to their actual flood risk) despite receiving 'subsidized' rates.

Turning now to the *periphery* (zone X), Figure 9 also displays an increase in the share of policyholders experiencing a price reduction when RR2 was introduced, similar to what we found for policyholders paying full-risk (post-FIRM) rates. As was the case in the flood zone, the figure also displays a large increase in the fraction of policyholders experiencing large annual price increases: the share with increases above 10% went from about 10% to roughly 75%). In fact, the price increases for many of these policies appear to have been capped at the statutory 18% limit, suggesting that these policies will experience further price increases in the years to come.

Summing up, the empirical estimates presented in this section show that RR2 increased

[26] Premiums under RR1 for pre-FIRM houses were computed using rates that did not take into account elevation because it was unknown for most of these houses. One of the innovations introduced with RR2 was the use of individual elevation information for all properties (Sherman and Kousky, 2018). As a result, even though all pre-FIRM properties are subject to the regular (full-risk) pricing schedule under RR2, those with high elevation (i.e. above the base flood elevation, BFE) may end up paying lower premiums than under RR1. In contrast, pre-FIRM properties with below-BFE elevation will be doubly penalized by the switch to RR2.

average insurance prices by about 12% in the periphery of the flood zone, surpassing by almost 3 percentage points the increase in the previous year. The reform also increased prices for policyholders paying full-risk rates in the flood zone by almost 5% on average, also surpassing the previous year increase (by 3 percentage points). However, RR2 entailed a large *reduction* (of almost 30%) in the average premium paid by *pre-FIRM* policyholders (in the flood zone), conditional on *renewal*. These premium reductions resulted from the introduction of more accurate flood risk estimates, which account for elevation.

7.3 Intensive margin changes in policy attributes

Policyholders confronted with rising insurance prices might have sought to counteract those hikes by adjusting policy attributes, such as coverage and deductibles. Conversely, those enjoying premium reductions may have responded by upgrading their policies. It is worth noting that these adjustments could have important implications regarding the flood risk exposure of *insured* homeowners since reductions in coverage and increases in deductibles effectively increase the financial exposure of policyholders to flood risk.

To examine whether policyholders adjusted their policies, we slightly modify the empirical specification just used to investigate the intensive-margin changes on insurance prices. As before, we restrict the analysis to policyholders who continuously purchased insurance in the last two rounds of RR1 (fy20 and fy21) and in the first round of RR2 (fy22).

Column 1 of Table 8 analyzes the changes in total coverage, including both contents and building. Prior to RR2, renewers in the periphery increased their coverage by about 1.1 percent year-on-year on average, compared to a slightly lower average increase in the flood zone (0.7 percent for full-risk policies and 0.5% for subsidized policies, respectively). The estimates show that RR2 had statistically significant but quantitatively small effects on coverage. When the reform was adopted, the average renewer in the periphery increased coverage by about 0.5%, that is, 0.6 percentage points lower than in the previous year. In contrast, renewers in the flood zone increased coverage at higher annual rates than in the previous year. The total increase was 1.6% among renewers with full-risk policies and 3.1% among those with subsidized policies. The reduction in annual coverage growth for periphery renewers and the significant increase in coverage among flood-zone residents with subsidized policies are in line with the intensive-margin changes in insurance prices discussed above, whereas the increase in coverage annual growth for policyholders paying full-risk rates is a bit unexpected. At any rate, columns 2-4 reveal very similar patterns in Florida, Texas and New York. All in all, RR2 seems to have affected decisions regarding the amount of coverage, but the effects are quantitatively small.

The picture is dramatically different when we turn to deductibles (column 5). Prior to RR2, deductibles were practically constant between fy20 and fy21 in both risk zones (with 0.1% to 0.6% year-on-year increases). However, our estimates indicate that the adoption of RR2 led to a 12.2% average increase in deductibles in the periphery (0.115 log points) and a 5.4% increase for the average flood-zone renewer paying full-risk rates. Such upward adjustments in deductibles are novel (i.e. were not happening prior to the reform) and are quantitatively large, and were fundamentally driven by policyholders' efforts to mitigate the increase in their annual premiums. Further evidence of this motive, but in reverse, emerges from the average 2.3% *reduction* in deductibles among flood-zone *renewers* with subsidized rates who experienced large insurance price reductions when RR2 was adopted. Once again, the estimates show very similar patterns in Florida, Texas and New York, although it is worth noting that the changes in deductibles among policyholders in New York were much larger: approximately 27% in the periphery, 11% among full-risk policyholders in the flood zone and practically zero for flood-zone policyholders with subsidized rates.

In sum, our estimates show that premium-relevant policy parameters are price-elastic. In particular, we found that the adoption of RR2 led to average increases in deductibles. These increases were particularly large in the periphery of the flood zone, increasing the financial exposure to flood risk of *insured* homeowners.

8 RR2 and Entry Decisions

As discussed earlier, it is infeasible to estimate an individual decision model of entry that is analogous to the exit-renewal model of the previous section because our data does not contain the homeowners that could potentially purchase insurance but did not over our sample period. Our analysis of entry decisions has two parts. First, we analyze entry into the insurance market in the aggregate, by simply tallying up the number of policies purchased in each quarter and netting out those purchased by homeowners that had also purchased insurance in the previous year. Then we shall turn to the estimation of a census-tract entry model. Importantly, we need to keep in mind that RR2 applied to new entrants from 2021Q4 onward, whereas it only affected renewals from 2022Q2.

8.1 Aggregate trends

We begin by aggregating insurance purchases nationwide at the quarterly level, separating purchases in the flood zone from those in the periphery. The blue lines in Figure 10 and Figure 11 report the evolution of insurance purchases between 2020Q1 and 2023Q4 in the periphery and flood zone, respectively. The figures make clear that, in both risk zones, flood insurance purchases display strong seasonal patterns: purchases peak in the third quarter of each year, which typically precedes the hurricane season in the United States. Additionally, there's a noticeable downward trend in total purchases in both zones that pre-dates the adoption of RR2. The third quarter (Q3) total purchases in the periphery were nearly 700,000 policies in 2020 and 2021 but fell to roughly 500,000 in 2023. Likewise, the Q3 purchases in the flood zone were upward of 400,000 in 2020 and 2021 but fell to approximately 350,000 in 2023.

Using our panel of individual insurance histories, we decompose annual purchases into renewals ($b_{i,t-1} = b_{i,t} = 1$) and new entry ($b_{i,t-1} = 0, b_{i,t} = 1$), which clearly shows that new entry is only a small fraction of overall purchases (about 15%) in both zones. Focussing first on the flood zone, Figure 10 illustrates a downward trend in quarterly entry that pre-dated the adoption of RR2. This trend continued and, perhaps even accelerated, after 2021Q4 when RR2 was first applied to the pricing of new policies. We shall return to this question shortly in our census-tract analysis. Turning now to purchases in the flood zone, Figure 11 more clearly suggests a negative effect of RR2 on entry. Prior to 2021Q4, entry in the flood zone was fairly constant (with very low seasonal variation). With the adoption of RR2, entry began to fall, particularly during fiscal year 2023.

8.2 Census-tract analysis

To make further progress, we estimate entry models at the census tract level. Most census tracts on the floodplain are neither completely contained within the flood zone nor in its periphery but, rather, extend across both zones. Following Bradt et al. (2021), we split census tracts into their flood zone and periphery segments, which we refer to as CT-Z units. We then aggregate individual policies to the CT-Z level (at a quarterly frequency) and estimate models for entry separately for the samples of units in the flood zone (CT-A) and outside of it (CT-X).

Our main estimation sample covers 10 quarters: $q = 2020Q4, ..., 2023Q1$, where 2020Q4-2021Q3 pre-dates the reform, 2021Q4-2022Q1 is the interim period of adoption of RR2 (when it only applied to new policies), and 2022Q2-2023Q1 is the period of full implementation of RR2. Using these data, we estimate two models (separately for the flood zone and its periphery):

$$Entry_{c,q} = \alpha + \beta_1 Interim_q + \beta_2 Full_q + u_{c,q} \quad (25)$$

$$\Delta Entry_{c,q} = \beta_1 Interim_q + \beta_2 Full_q + v_{c,q}, . \quad (26)$$

The dependent variable in Equation 25 is the count of new-entry purchases in census tract c (within the corresponding zone $z = A, X$) and quarter q, but this model fails to account for seasonal effects. To address this problem, Equation 26 employs as dependent variable the changes in entry between the current quarter-year and a baseline period in a previous year for the *same* quarter.[27] It is also worth noting that the within-tract differences in entry also net out the variation arising from time-invariant characteristics of the census-tract segments.

Our estimates are collected in Table 9. Column 1 estimates Equation 25 for the segments of census tracts that belong to the 100-year flood zone. The estimates indicate that the average quarterly entry in CT-A segments prior to RR2 was about 16 policyholders on average.[28] The coefficients for the interim and full implementation of RR2 are both negative, suggesting a reduction in entry in the FZ after RR2 was adopted. It is worth noting that the interim period only lasts for 2 quarters, whereas the full-implementation period lasts for 4 quarters. Thus, annualizing the effects on entry requires multiplying the interim coefficient by two, suggesting that entry might have fallen by a similar amount in both periods (roughly 3-4 policies per year in the average CT-A unit). Column 2 reports the estimates of the model in differences (Equation 26) for the flood zone. The estimates also indicate a reduction in entry in the flood zone. However, it appears that the reduction started with the full implementation of RR2 (in 2022Q2) and affected nearly 4 policies per year in the average CT-A unit.

Turning to the periphery, the estimates in column 3 strongly suggest a much larger reduction in entry, already during the interim period, than we found in the flood zone. Specifically, the differenced model in column 4 implies an annualized reduction of approximately 11 policyholders for the average CT-X unit during the interim period and a similar annual reduction in entry in the first year of full implementation of RR2.

In sum, our analysis of the effects of RR2 on entry into the insurance market points to a substantial reduction, particularly in the periphery of the flood zone, where insurance purchases are largely voluntary and premiums increased substantially with the adoption of RR2. At first sight, the reduction in entry seems at odds with the predictions of our theoretical model (*Proposition 5*). However, a simple dynamic extension easily accounts for the decline in entry (as discussed in subsubsection 2.7.1), which would disproportionately affect low-income, high-risk homeowners (relative to their risk zone) that cannot afford the high RR2 premiums.

[27] The baseline periods used to compute $\Delta Entry_{c,q}$ are the (pre-sample) entry levels in 2020Q4 through 2021Q3.

[28] Roughly speaking, the average census tract contains 1,600 households. Thus, entry of 16 policyholders would amount to 2% of households in a census tract equally divided between the flood zone and its periphery.

9 Adoption of RR2 and Revenue

As we have shown in the previous sections, the adoption of RR2 had important effects both along the intensive and extensive margins of insurance demand. These changes impact overall revenue and, hence, the financial sustainability of the system, but their net effect is theoretically ambiguous. The goal of this section is to evaluate the various effects of RR2 on insurance demand on the basis of the estimates presented in the previous sections. It is also worth noting that the revenue effects of the reform along the extensive and intensive margins (i.e. conditional on renewal) are likely to have opposite signs. Simply put, raising premiums clearly increases revenue conditional on renewal but, at the same time, is likely to drive homeowners out of the insurance market.

As we discussed in subsection 2.6, the change in revenue associated with the adoption of RR2 can be decomposed into:[29]

$$\Delta R = Entry \times E\left[p_2|Entry\right] - Exit \times E\left[p_1|Exit\right] + Renew \times E\left[p_2 - p_1|Renew\right], \quad (27)$$

where *Entry* (*Exit*) should be interpreted as the additional entry (exit) induced by RR2, over and above the pre-existing annual flows. In turn, p_1 and p_2 denote the before-reform and after-reform premiums, respectively, and *Renew* is the set of homeowners who purchased insurance prior to RR1 and continue to do so when the reform is implemented.

Let us now turn to the evaluation of the terms in Equation 27. For ease of exposition, Table 10 collects all the relevant figures. As just discussed in section 8, the adoption of RR2 led to a reduction in annual *entry* into the flood insurance market, particularly in the periphery of the flood zone. We estimate that the annual entry in the first year after RR2 was adopted was nearly 109,000 policies lower nationwide than in the year prior to its adoption, with about 73% of the decline taking place in the periphery (top panel of Table 10). Naturally, the reduced entry entails the full loss of the revenue that would have been generated by those policies.[30]

Let us now turn to the estimated effects of RR2 on *exit*. As shown in Table 6 (column 1), RR2 increased the probability of exit (i.e. lowered the probability of renewal) in both zones. To inflate the estimates into actual exit counts nationwide requires multiplying the

[29] To discuss the effects of the reform on overall revenue, one needs to multiply the terms in Equation 27 by the number of *policyholders* at the time the reform was adopted.

[30] It is worth noting that we are likely underestimating the effects of RR2 on exit, but overestimating the effects on entry. If the insurance market had been in steady state in the year prior to RR2, netting out the previous flows identifies the effects of RR2. However, it is clear that in fy21 many policyholders were experiencing high premium increases due to the 2012-2014 NFIP reforms, which triggered exit and depressed entry relative to steady-state values.

estimated exit rates by the number of policyholders at the time of the reform.[31] This results in an overall *increase* in exit (relative to the exit in the last year of RR1) of approximately 122,000 homeowners, 43% of which were located in the flood zone and 37% lived in pre-FIRM houses . Hence, the combination of increased exit and reduced entry is estimated to have led to an increase in *net exit* of about 231,000 policyholders nationwide. Combining this estimate with the average annual premiums (inclusive of fees) paid by those that exited the market (in their last policy) and by those that entered the market (in their first policy) entails a reduction in revenue of about \$269 Mn annually, as reported in the bottom panel of the table.

To obtain the overall effect of the reform on overall revenue, we need to incorporate the effects of the reform on the average premiums paid by homeowners who renewed their policies. Our estimates imply that 2.87 Mn homeowners (in 1-to-4 unit houses) purchased flood insurance both in the year before RR2 was adopted and immediately after, practically divided equally between those located in the flood zone and those in the periphery. Approximately 26% of the renewers experienced a price reduction, but the vast majority saw a price increase. As we discussed at length in section 7, a substantial share of policyholders in the flood zone experienced significant premium reductions, which lowered their average annual cost by 16.5%. In contrast, premium reductions were less prevalent and smaller in amount in the periphery.[32] For policyholders experiencing price increases due to RR2, the resulting average increase in the annual cost of insurance was similar in the flood zone and its periphery (11-12%). Pooling both zones, our estimates indicate that RR2 led to an average 5% *increase* in annual insurance costs, resulting in an aggregate increase in revenue (from renewers) of approximately \$137 Mn annually.

Summing up, the changes ushered in by RR2 led to an increase in the overall amount collected from renewers. However, accounting for the effects of the reform along the extensive margin of demand led to a reduction in revenue (due to an increase in exit and a reduction in entry), largely because the new pricing system has failed to generate enough additional entry into the market. We estimate that the overall effect of RR2 on revenue has been a \$132 Mn annual revenue loss (or about 3.7% of NFIP's overall revenue from premiums).

It is interesting to compare our estimate of the loss in revenue to the NFIP's own statement of operations (FIMA, 2022). According to their figures, revenue from premiums fell by

[31] The effect of RR2 on exit counts in zones X and A, respectively, is given by $0.0394n_{t-1}^X$ and $(0.0394 - 0.0082)n_{t-1}^X$, where n_{t-1}^z is the number of policyholders in zone z in the year prior to the adoption of RR2.

[32] It is important to keep in mind that policyholders reacted to the price changes (per dollar of coverage) by adjusting policy parameters (mainly, deductibles), which affects the overall annual cost of the policy. As it turns out, periphery policyholders that experienced a price reduction (per dollar of coverage), lowered their deductibles and this led to a small (2.9%) increase in the overall annual cost of insurance for these policyholders.

$276 Mn (or nearly 8%) between fiscal years 2021 and 2022. Our analysis (for 1-to-4 unit residential buildings) suggests that roughly half of the reduction is due to the adoption of RR2, while the lion's share of the remainder should probably be chalked up to the earlier reforms of the NFIP (and the resulting net exit from the insurance market).

10 Conclusions

We have developed a simple theory of the demand for flood insurance in a setting where risk-averse homeowners differ by household income and flood risk, and used this framework to analyze the effects of the adoption of *Risk Rating 2.0* (RR2) and the 2012-2014 reforms to the NFIP program.

The theoretical model provides a useful guide to the empirical analysis and makes clear that the overall effects of the reform are theoretically ambiguous and crucially depend on how the reform affects entry and exit into the insurance market. The theoretical analysis also highlights that income (or borrowing) constraints play an important in modeling insurance demand and its effects on overall revenue and social welfare. In particular, the theory predicts that the adoption of RR2 will lead to exit and reduced entry among relatively high-risk homeowners but induce entry among relatively low-risk homeowners, both in the flood zone and its periphery. The model also predicts heterogeneous effects on the premiums paid by policyholders who were purchasing insurance prior to the reform and continue doing so after its adoption, both within the 100-year flood zone and outside of it. However, the overall effect of RR2 on revenue is theoretically ambiguous, as it depends on distributional assumptions and (unknown) parameter values.

To conduct our empirical analysis we extend the approach introduced by Mulder and Kousky (2023) to construct individual insurance histories for the whole United States for the period 2019-2023. We then proceed to estimate the effects of RR2 along the extensive and intensive margins of the demand for flood insurance, isolating them from the pre-existing trends triggered by earlier reforms of the NFIP.

Our empirical findings provide support for most of the predictions derived from our theoretical analysis. Most notably, we show that RR2 generated substantial exit from the insurance market, both in the 100-year flood zone and its periphery, and that policyholders that did not renew their policies were paying, on average, substantially higher premiums than policyholders located in the same zone that chose to continue purchasing flood insurance.

Furthermore, we also find that RR2 had highly heterogeneous effects on individual insurance costs, both within the flood zone and outside of it. However, on average, the reform lowered the price of insurance in the flood zone, offsetting the pre-existing price growth due to the previous NFIP reforms, but increased it outside of the flood zone, reinforcing the price growth inertia due to the previous NFIP reforms.

We also provide evidence showing that policyholders adjusted the deductibles in their insurance policies in response to the changes in insurance prices to either mitigate the effect of price increases on annual premiums, or take advantage of price reductions. In particular, the large average increase in insurance prices in the periphery of the flood zone has led to a substantial increase in deductibles, increasing the financial exposure of *insured* homeowners in this area. Lastly, we combine all the intensive and extensive margin effects to asses the overall effect of the reform on the program's revenue. We conclude that RR2 lowered the NFIP's revenue by 3.7%, increasing the program's fiscal imbalance in the short run. Importantly, ignoring the negative effects of RR2 along the extensive margin of demand would have led to the opposite conclusion.

It is worth noting that the long-run effects of RR2 could potentially overturn its short-term negative effects, as pointed out in de Ruig et al. (2022). Specifically, the improved granularity of the flood risk estimates and its tighter link to annual premiums may provide stronger incentives for homeowners in high-risk areas to undertake adaptation investments (or consider relocation), which could lower the human and economic losses of future flooding events.

We close by highlighting that the NFIP, and any other insurance market where insurance purchases are mostly voluntary, faces the dilemma of how to raise enough revenue while attaining high participation. Future reforms of the NFIP may need to consider means-tested premiums, expanding the purchase mandate, or other actions (Horn (2023)).

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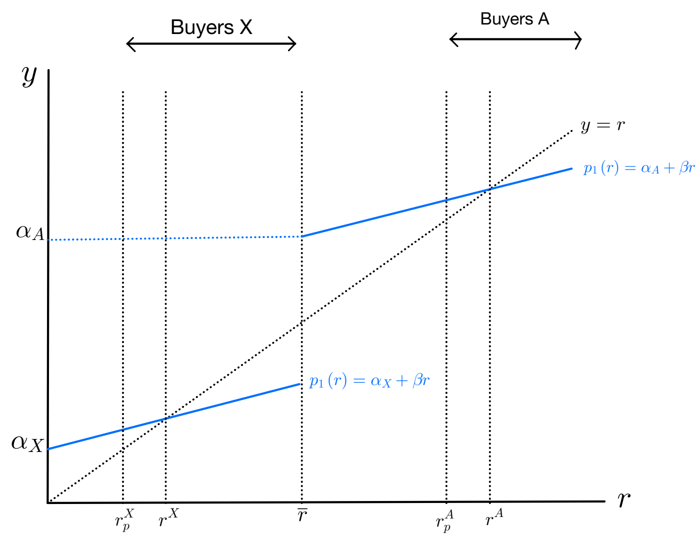
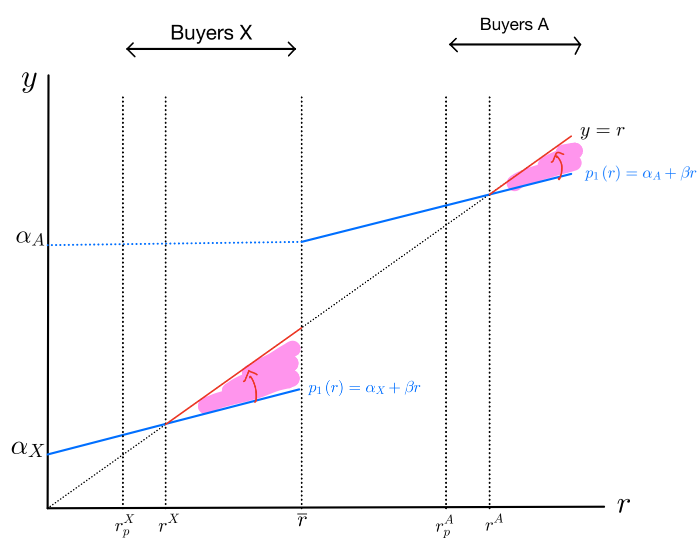
Tables and Figures

Figure 1: Optimal decisions under RR1



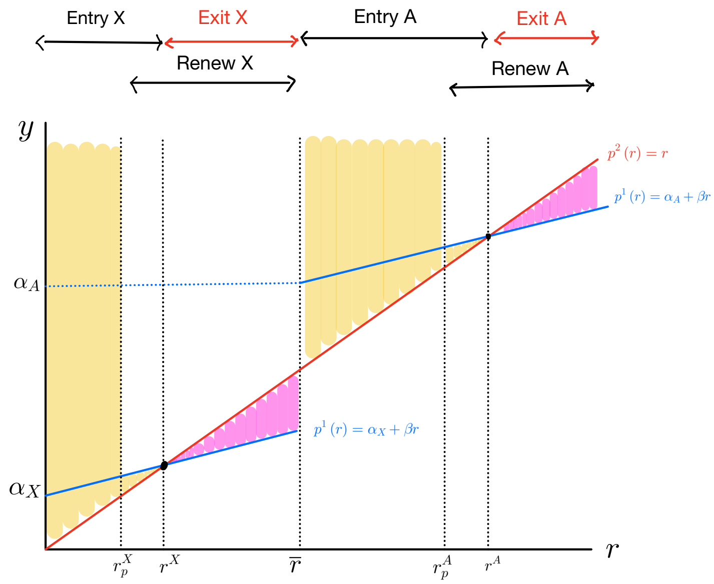
Notes: The pricing function depicted is $p_1(r) = \alpha_z + \beta r$, for $z = A, X$. We assume $0 < \alpha_X < (1-\beta)\overline{r} < \alpha_A < 1-\beta$ and $0 < \beta < 1$.

Figure 2: RR1 with reform



Notes: The pink area denotes exit triggered by the change in the pricing function. The pricing function depicted is $\widehat{p}_1(r) = p_1(r) = \alpha_z + \beta r$ for $r < r^z$ and $\widehat{p}_1(r) = \widehat{\alpha}_z + \widehat{\beta} r$ for r^z, and $z = A, X$. We assume $0 < \alpha_X < (1-\beta)\overline{r} < \alpha_A < 1-\beta$ and $0 < \beta < \widehat{\beta} = 1$.

Figure 3: Entry and Exit due to RR2



Notes: The pink (yellow) area denotes exit (entry) triggered by the change in the pricing function. We assume $0 < \alpha_X < (1-\beta)\overline{r} < \alpha_A < 1-\beta$ and $0 < \beta < 1$. Area shaded in yellow is new entry and area shaded in pink is exit. Area not colored indicates homeowners that did not change their purchase decision when RR2 was introduced.

Figure 4: Distribution insurance prices. Flood zone

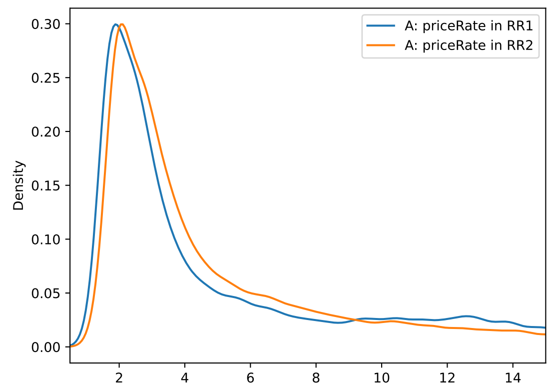


Figure 5: Distribution insurance prices. Flood zone, post-FIRM

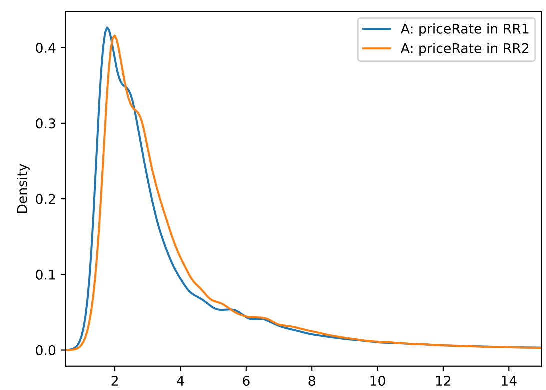
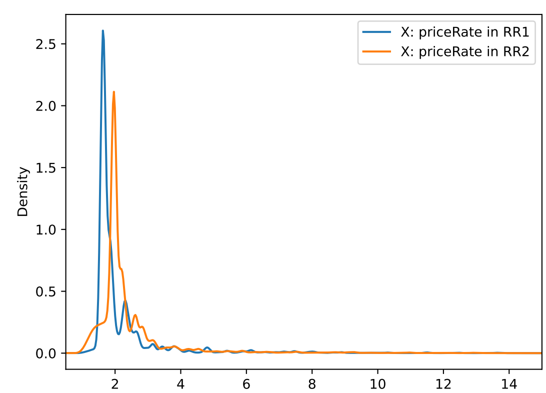


Figure 6: Distribution insurance prices. Periphery



Notes: The figures report the insurance price in the last round of purchases under RR1 and the first under RR2. The flood zone (FZ) is defined as flood zone designations A and V. The individual insurance price is calculated as the annual cost of a policy (premium plus fees) divided by the total coverage (of contents and building). The units are $ per $1,000 of coverage. All purchases are included (new or renewals).

Figure 7: CDF insurance price changes around RR2 for renewers. Flood zone

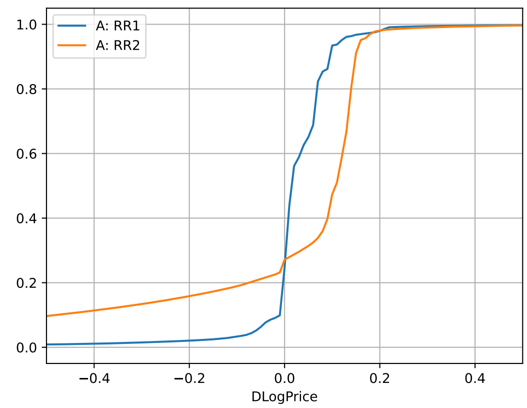


Figure 8: CDF insurance price changes around RR2 for renewers. Flood zone, post-FIRM

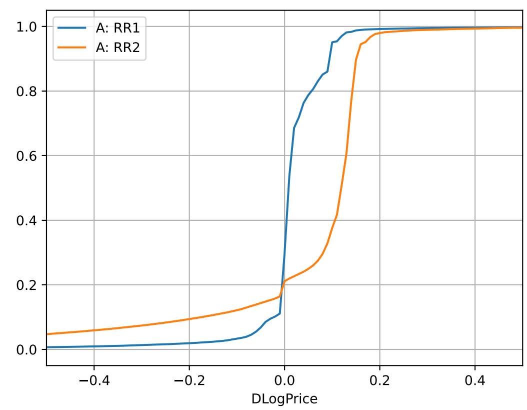
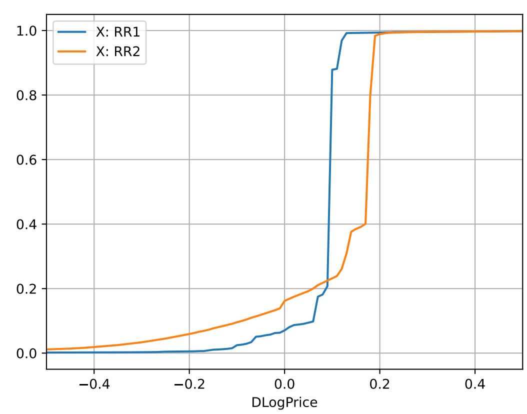


Figure 9: CDF insurance price changes around RR2 for renewers. Periphery



Notes: The figures report the CDF for annual changes in the log of the insurance price between the first round of purchases under RR2 (fy21-fy22) and the last round of purchases under RR1 (fy20-fy21) for policyholders that continuously purchased insurance in fy20, fy21 and fy22. The flood zone (FZ) is defined as flood zone designations A and V. The individual insurance price is calculated as the annual cost of a policy (premium plus fees) divided by the total coverage (of contents and building). The units are $ per $1,000 of coverage.

Figure 10: Purchases, renewals and entry. Periphery only

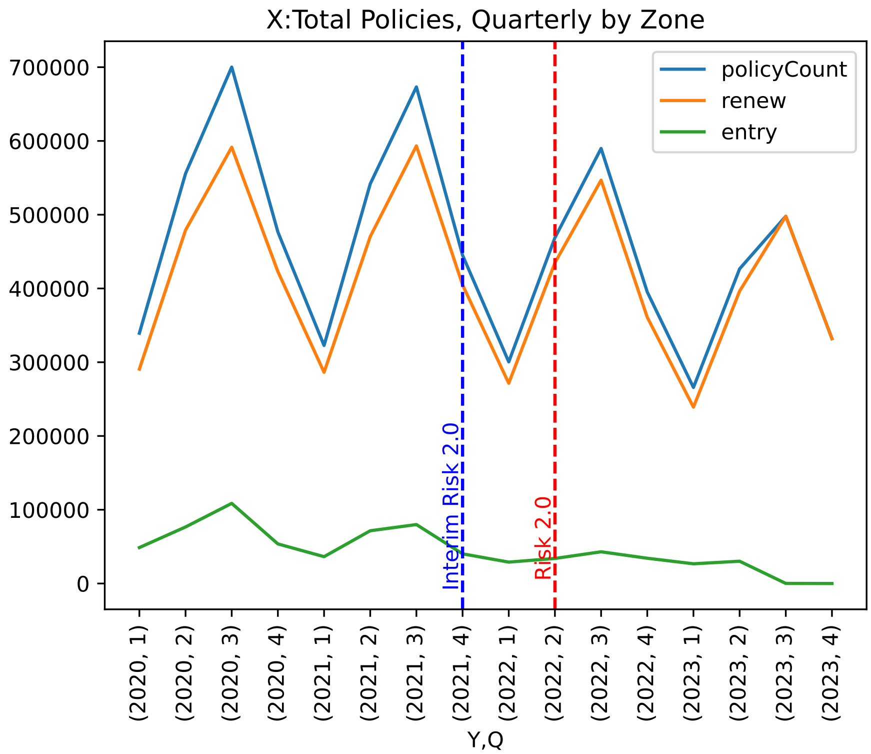
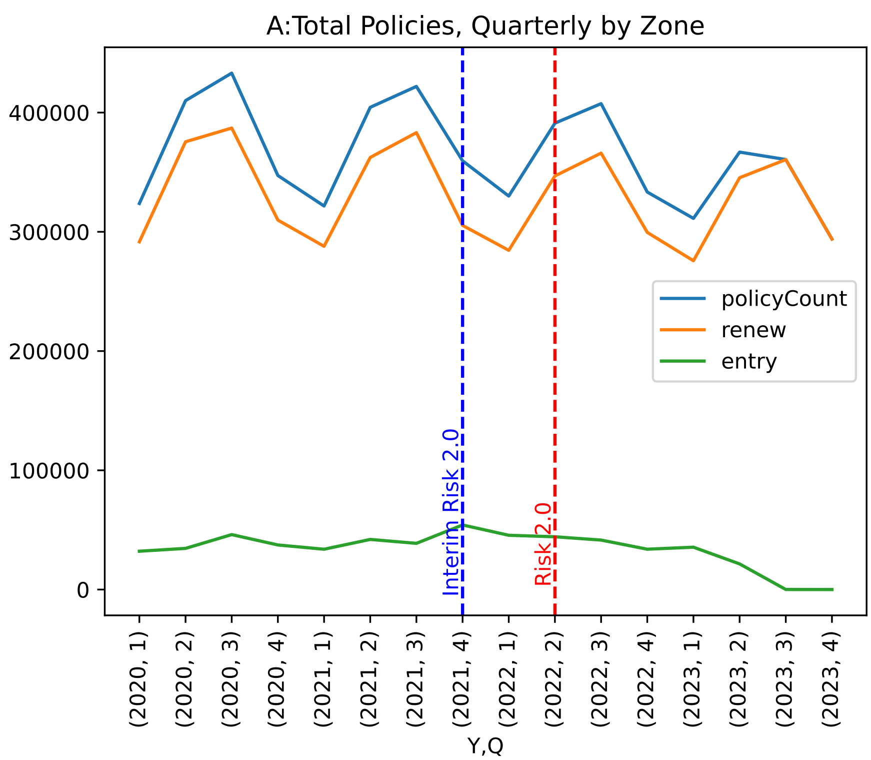


Figure 11: Purchases, renewals and entry. 100-year FZ only



Notes: Quarterly purchases from 2020Q1 through 2023Q4. The flood zone (FZ) is defined as flood zone designations A and V.

Table 1: Summary statistics NFIP policies 2019-2023. Up to 4 residential units

	count	mean	std	min	max
100-year Flood Zone (FZ)	17,053,299	0.440	0.496	0.000	1.000
Single Family	17,053,299	0.969	0.173	0.000	1.000
Construction Year	17,053,083	1,983.166	24.861	1,690.000	2,024.000
Primary Residence	17,053,299	0.819	0.385	0.000	1.000
Mandatory Purchase	17,053,299	0.152	0.359	0.000	1.000
Subsidized	17,053,299	0.074	0.262	0.000	1.000
Florida	17,053,299	0.274	0.446	0.000	1.000
Texas	17,053,299	0.191	0.393	0.000	1.000
BRC	16,150,207	308,502.769	437,031.195	0.000	8,000,000.000
Coverage Total	17,053,299	280,013.876	91,194.361	200.000	2,505,000.000
Coverage Building	17,053,299	214,101.636	62,065.010	0.000	2,500,000.000
Coverage Contents	17,053,299	65,912.240	40,911.631	0.000	475,000.000
Total cost	17,053,299	940.901	952.872	1.000	58,912.000
Premium	17,053,299	711.159	798.622	-292.000	49,321.000
Price per $1,000 of Coverage	17,053,299	4.488	6.742	0.004	491.000
Deductible	16,969,390	2,048.854	1,876.853	200.000	50,000.000

Notes: Nationwide NFIP policies 2019-2023 for residential buildings with up to 4 residential units. BRC stands for building replacement cost. The 100-year flood zone (FZ) is the same as the Special Flood Hazard Area defined by the FEMA flood maps and is defined as flood zone designations A and V.

Table 2: Algorithm comparison

	(1) Groups	(2) Duplicates % policies	(3) Avg spell years	(4) Lapses % groups	(5) Chg. elev. vars. % groups	(6) SalesEndorse % groups	(7) Chg. FZ % groups
MK algorithm							
CensusTract	71,156	98.02	3.75	85.15	43.58	79.77	55.45
+OCD	2,436,741	45.24	2.84	22.04	11.21	20.43	7.98
+ONBD	4,738,859	2.15	2.52	1.24	1.06	1.32	0.74
+rFZ	4,781,663	1.85	2.50	1.21	0.53	1.09	0.00
+ElevVars	4,817,422	1.35	2.49	1.18	0.00	0.84	0.00
+EffectiveM	4,872,852	1.26	2.46	0.08	0.00	0.81	0.00
OP algorithm							
CBg+LatLon+Map+OCD+floors	3,562,488	24.65	2.61	13.41	5.29	10.98	2.79
+ONBD	4,817,922	1.49	2.49	1.16	0.49	0.54	0.37
+SaleEndorse	4,845,509	1.27	2.48	1.14	0.38	0.00	0.29

Notes: The attributes listed in the table are census tract, original construction date (OCD), original new business date (ONBD), rated flood zone status (rFZ), changes in elevation variables (base flood elevation, lowest floor elevation, lowest adjacent grade), month policy becomes effective, census block group (CBG), latitude and longitude (one decimal), flood map number, number of floors, and house sale with flood insurance policy endorsement. The Mulder & Kousky (MK), Ortega & Petkov (OP) are defined in subsubsection 3.2.2 and subsubsection 3.2.3, respectively.

Table 3: Summary Insurance Purchases by Renewers in fy2021 (RR1)

	count	mean	std	min	max
Renew	3,571,840	0.860	0.347	0	1
FZ	3,571,840	0.481	0.500	0	1
Single Family	3,072,898	0.973	0.161	0	1
Primary Residence	3,571,840	0.827	0.378	0	1
Mandatory Purchase	3,571,840	0.161	0.367	0	1
Construction Year	3,571,791	1,983.387	24.647	1,690	2,023
BRC	3,571,804	306,307.920	431,590.473	0	8,000,000
Total Coverage	3,072,898	282,248.602	90,350.358	200	551,200
Coverage Building	3,072,898	214,924.765	61,224.788	0	501,400
Coverage Contents	3,072,898	67,323.836	40,369.205	0	100,000
Total Cost	3,072,898	955.128	1,084.418	2	58,912
Premium	3,072,898	724.393	904.502	-292	49,321
Price per $1,000 of Coverage	3,072,898	4.544	7.110	0.007	472.500
Deductible	3,060,046	1,971.509	1,832.696	1,000	10,000
Subsidized	3,571,840	0.107	0.309	0	1

Notes: Sample is homeowners who purchased during fy2020 (2020Q2-2021Q1) for 1-to-4 family houses (i.e. excluding condos and coop apartments) with positive values for total coverage and policy cost, and non-missing census tract. The table reports policy attributes for fy2021 (2021Q2-2022Q1) FZ status is a dummy variable taking the value of one for all policies referring to properties in the 100-year flood zone (with designation A or V). BRC stands for building replacement cost. There are 3.57 million homeowners in our sample and 3.07 million renewed their policy in fy2021. For non-renewers in fy21 we report the lagged value of the time-invariant attributes (e.g. FZ or mandatory purchase).

Table 4: Comparison FZ and periphery in fy2021 (RR1)

Variable	A:mean	X:mean	Dif Mean	p-val
Single Family	0.966	0.98 0	-0.014	0.000
Primary Residence	0.775	0.876	-0.101	0.000
Mandatory Purchase	0.288	0.042	0.246	0.000
Construction Year	1979.974	1986.546	-6.572	0.000
Renew	0.881	0.841	0.04 0	0.000
BRC	290157.212	321259.052	-31101.839	0.000
Total Coverage	250960.012	312604.291	-61644.279	0.000
Coverage Building	205611.147	223960.69	-18349.543	0.000
Coverage Contents	45348.866	88643.602	-43294.736	0.000
Total Cost	1308.304	612.481	695.823	0.000
Premium	1004.631	452.509	552.122	0.000
Price per $1, of Coverage	6.913	2.245	4.668	0.000
Deductible	2693.254	1268.882	1424.372	0.000
Subsidized	0.217	0.005	0.212	0.000

Notes: The sample is the same as in Table 3, but split by zone: A 100-year flood zone (which also contains flood designation V) and X its periphery (500-year flood zone). The corresponding sample sizes can be computed using the share of policies in FZ times the number of observations (from previous table). For instance, in zone A (plus designation X) the number of policies is $3.57 \times 0.481 = 1.72$ million. The p-values reported in the last column are all below 0.001.

Table 5: Who exits? Characteristics fy2021 (RR1) quitters and renewers

	(1)	(2)	(3)	(4)	(5)	(6)
Dep. Var. Lags of	LogPrice	Log BRC	Prim. Res.	LogPrice	Log BRC	Prim. Res.
Observations	3574164	3499228	3574164	3474020	3251482	3474020
Cov. Est.	Robust	Robust	Robust	Robust	Robust	Robust
Constant	0.6146***	12.436***	0.8803***	0.6821***	12.467***	0.8843***
	(0.0003)	(0.0006)	(0.0003)	(0.0003)	(0.0006)	(0.0003)
FZ	0.8275***	-0.1353***	-0.0951***	0.7424***	-0.1127***	-0.0943***
	(0.0008)	(0.0008)	(0.0004)	(0.0008)	(0.0008)	(0.0004)
Exit	0.1094***	-0.0151***	-0.0292***	0.1391***	-0.0932***	-0.0187***
	(0.0010)	(0.0014)	(0.0007)	(0.0009)	(0.0014)	(0.0006)
Exit x FZ	0.1963***	-0.0025	-0.0626***	0.2758***	-0.1582***	-0.0308***
	(0.0026)	(0.0023)	(0.0013)	(0.0022)	(0.0022)	(0.0011)

Notes: In columns 1-3 the sample contains homeowners who purchased insurance in the second-to-last round of RR1 (2020m4-2021m3) and estimate linear regression models for various lagged outcomes (such as log insurance price and log of the building replacement cost) where we include an *exit* indicator as a regressor, which takes a value of one for homeowners who did **not** purchase insurance in the last round of RR1, and zero if they did. Instead in columns 4-6 the sample contains policies purchased by homeowners who purchased insurance in the last round of RR1 (2021m4-2022m3) and the *exit* indicator now takes a value of one for homeowners who did **not** purchase insurance in the first round of RR2. Heteroskedasticity-robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 6: Effect of RR2 on Renewal Probability

	(1) US	(2) US	(3) US FullRisk	(4) FL	(5) TX	(6) NY
Dep. Variable	renew	renew	renew	renew	renew	renew
No. Obs.	7049527	7049527	6318906	1918549	1395789	255736
R-squared	0.0060	0.0091	0.0220	0.0063	0.0088	0.0233
Constant	0.8409***	0.8409***	0.8753***	0.8308***	0.8349***	0.8867***
	(0.0003)	(0.0003)	(0.0004)	(0.0006)	(0.0005)	(0.0014)
FZ	0.0403***	0.0522***	0.0797***	0.0511***	0.0611***	0.0675***
	(0.0004)	(0.0004)	(0.0004)	(0.0007)	(0.0010)	(0.0017)
FZ x Subsidized		-0.0532***		-0.0371***	-0.0604***	-0.0821***
		(0.0006)		(0.0014)	(0.0023)	(0.0022)
RR2	-0.0392***	-0.0392***	-0.0045***	-0.0263***	-0.0486***	-0.0517***
	(0.0004)	(0.0004)	(0.0005)	(0.0008)	(0.0008)	(0.0021)
RR2 x FZ	0.0082***	0.0131***	0.0332***	0.0034***	0.0090***	0.0323***
	(0.0005)	(0.0006)	(0.0006)	(0.0011)	(0.0015)	(0.0026)
RR2 x FZ x Subsidized		-0.0338***		-0.0211***	-0.0491***	-0.0386***
		(0.0010)		(0.0021)	(0.0037)	(0.0035)
LagLnp			-0.0546***			
			(0.0004)			
RR2 x LagLnp			-0.0434***			
			(0.0006)			

Notes: The sample contains policies purchased in the last year of RR1 and the first year of RR2 (2021m4-2023m3), and drop policyholders that did not purchase insurance in the last year of RR1 (2021m4-2022m3). Dummy variable $RR2$ takes a value of one for purchases that took place during the first year of RR2 (2022m4-2023m3) and zero otherwise. Dummy variable *Subsidized* takes a value of one for policyholders with policies based on subsidized rates (prior to RR2) linked to pre-FIRM construction. *LagLnp* denotes the previous period insurance price (in logs). Columns 1-3 use the national sample whereas columns 4-6 restrict the analysis to the corresponding state. Heteroskedasticity-robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 7: Intensive-margin change in log price

	(1) US	(2) US	(3) US FullRisk	(4) FL	(5) TX	(6) NY
Dep. Variable	DLogPrice	DLogPrice	DLogPrice	DLogPrice	DLogPrice	DLogPrice
No. Observations	5632787	5632787	5055086	1530174	1086406	216382
R-squared	0.0588	0.1747	0.1735	0.0621	0.2348	0.2204
Constant	0.0882***	0.0882***	0.1185***	0.0885***	0.0903***	0.0930***
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)	(0.0003)
FZ	-0.0614***	-0.0705***	-0.0468***	-0.0713***	-0.0696***	-0.0596***
	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0004)	(0.0007)
FZ x Subsidized		0.0431***		0.0482***	0.0367***	0.0310***
		(0.0003)		(0.0006)	(0.0013)	(0.0011)
RR2	0.0251***	0.0251***	0.1142***	0.0171***	0.0537***	0.0107***
	(0.0002)	(0.0002)	(0.0004)	(0.0003)	(0.0002)	(0.0009)
RR2 x FZ	-0.0795***	0.0040***	0.0547***	0.0338***	-0.0442***	0.0067***
	(0.0004)	(0.0003)	(0.0003)	(0.0005)	(0.0010)	(0.0018)
RR2 x FZ x Subsidized		-0.4393***		-0.2050***	-0.5421***	-0.4327***
		(0.0012)		(0.0019)	(0.0042)	(0.0043)
LagLnp			-0.0485***			
			(0.0003)			
RRW x LagLnp			-0.1266***			
			(0.0007)			

Notes: Sample contains only policyholders that continuously purchased insurance in the two last rounds of RR1 (fy20 and fy21) and the first round of RR2 (fy22). Variable $RR2$ takes a value of one for purchases that took place during the first year of RR2 (2022m4-2023m3) and zero otherwise. *Subsidized* takes a value of one for policyholders with policies based on subsidized rates (prior to RR2) linked to pre-FIRM construction. *LagLnp* denotes the previous period insurance price (in logs). Columns 1-3 use the national sample whereas columns 4-6 restrict the analysis to the corresponding state. Heteroskedasticity-robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 9: Entry models by census tract

	(1) FZ	(2) FZ	(3) Periphery	(4) Periphery
Dep. Variable	entry	entryR	entry	entryR
No. Observations	442739	402490	664950	604500
R-squared	0.0069	0.0345	0.0532	0.1807
Constant	16.366***		21.466***	
	(0.5022)		(0.7211)	
RR2 Interim	-1.3775	0.2262	-14.832***	-5.4294***
	(0.8591)	(0.4207)	(0.7749)	(0.3458)
RR2 Full	-4.5329***	-3.8391***	-13.735***	-10.111***
	(0.6355)	(0.3105)	(0.7720)	(0.3766)

Notes: The units of observation are segments defined by the intersection of the 100-year flood zone and census tracts. In this analysis the time period is quarterly and covers 2021Q4 through 2023Q1 (so 6 quarters). The interim period consists of quarters 2021Q4-2022Q1 and the full adoption period ranges from 2022Q2 onward. Heteroskedasticity-robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 8: Intensive-margin changes in policy attributes

	(1) US	(2) FL	(3) TX	(4) NY	(5) US	(6) FL	(7) TX	(8) NY
Dep. Variable	Dln Cov	Dln Cov	Dln Cov	Dln Cov	Dln Deduc	Dln Deduc	Dln Deduc	Dln Deduc
No. Observations	5300327	1436063	997607	209470	5282322	1431720	993154	208696
R-squared	0.0029	0.0116	0.0035	0.0012	0.0963	0.0518	0.1028	0.2543
Constant	0.0109***	0.0096***	0.0128***	0.0048***	0.0010***	0.0010***	0.0014***	0.0009***
	(0.0001)	(0.0001)	(0.0001)	(0.0004)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
FZ	-0.0038***	-0.0026***	-0.0025***	-0.0029***	0.0010***	0.0013***	-0.0006**	0.0013***
	(0.0001)	(0.0002)	(0.0003)	(0.0005)	(0.0001)	(0.0001)	(0.0003)	(0.0004)
FZ x Subsidized	-0.0020***	0.0010**	0.0006	-0.0020**	0.0040***	0.0058***	0.0034***	0.0047***
	(0.0002)	(0.0004)	(0.0008)	(0.0008)	(0.0002)	(0.0005)	(0.0008)	(0.0008)
RR2	-0.0062***	-0.0048***	-0.0071***	-0.0034***	0.1154***	0.0830***	0.1055***	0.2410***
	(0.0001)	(0.0002)	(0.0002)	(0.0005)	(0.0002)	(0.0004)	(0.0003)	(0.0012)
RR2 x FZ	0.0114***	0.0207***	0.0079***	0.0045***	-0.0636***	-0.0428***	-0.0616***	-0.1360***
	(0.0001)	(0.0003)	(0.0004)	(0.0007)	(0.0003)	(0.0005)	(0.0008)	(0.0017)
RR2 x FZ x Subsidized	0.0144***	0.0213***	0.0204***	0.0099***	-0.0760***	-0.0679***	-0.0734***	-0.1269***
	(0.0004)	(0.0009)	(0.0011)	(0.0012)	(0.0004)	(0.0009)	(0.0018)	(0.0018)

Notes: Dependent variable in columns 1-4 is total coverage (building and contents) and 5-8 is deductible (building only). Estimation sample contains only policyholders that continuously purchased insurance in the two last rounds of RR1 (fy20 and fy21) and the first round of RR2 (fy22). Subsidized policies also included in the sample. Heteroskedasticity-robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 10: Effect of RR2 on NFIP Revenue

	Zone X	Zone A	Both Zones
Counts			
Δ Entry	-79,914	-29,041	-108,955
Δ Exit	69,112	53,241	122,353
Renewers	1,412,207	1,459,108	2,871,315
at lower price	106,357	646,921	753,278
at higher price	1,305,850	812,187	2,118,037
% Chg. annual premiums			
Renewers			5.0
at lower price	2.9	-16.5	-13.8
at higher price	12.1	11.1	11.7
Average premium			
Entry (RR2)			$1,320
Exit (RR1)			$1,021
Renewers (RR1)			$955
Chg. Revenue ($Mn)			
Entry			-143.8
Exit			-125.0
Renewers			137.1
Total			**-131.7**

Notes: The table computes the change in premiums revenue for 1-to-4 unit houses in the NFIP comparing the last year of RR1 (2021m4-2022m3) to the first year of RR2 (2022m4-2023m3). The top panel reports the counts of homeowners who exited, entered or stayed in the market in those two years. Exits and entry net out the corresponding values in the last year before RR2 was adopted. The second panel reports the percent change in annual premiums for each group. Renewers (in each zone) are split into those who experienced an increase in the price of insurance (defined as total annual cost over total coverage) and those who experienced a reduction. Because policyholders responded to changes in the price by adjusting coverage, renewers in zone X who experienced a price reduction in fact saw a small increase in their annual premium. The third panel reports the average annual premium for each group in the last period of RR1. The bottom panel tallies up the overall change in revenue.

Appendix

A Proofs

Proof of Proposition 1.

Claim 1 follows from the assumptions on u (continuous, increasing and strictly concave), the definition of no-insurance certainty equivalent, and implicit differentiation.

Claim 2 follows from Jensen's inequality and the observation that the risk-neutrality certainty equivalent is simply $(1-r)V + rV$.

Let us now turn to the proof for **claim 3**. Let r_p be the risk level for indifference for purchasing insurance: $u(x(r_p)) = u(V-p)$, given that insurance fully eliminates consumption risk. Thus, $x(r_p) = V - p$. As shown in claim 1, $x(r)$ is continuous and decreasing in r, ranging between V and $V-1$. Hence, since $0 < p < 1$, there exists a unique value r_p such that $x(r_p) = V - p$. Households with $r < r_p$ will not purchase insurance, regardless of their income. Households with $r \geq r_p$ will purchase insurance if they can afford it $(y \geq p)$.

Claim 4 follows from specializing Equation 4 and Equation 6 to the case of risk neutrality. ■

Proof of Proposition 2.

We shall prove **claim 1** in three steps. First, let us show that homeowners with vanishingly small flood risk will not purchase insurance. It will be helpful to define the surplus from buying insurance (in terms of non-contingent consumption levels):

$$S^1(r;\rho) = V - p_1(r) - x(r;\rho),$$

where $S^1(r;\rho)$ and $x(r;\rho)$ denote the surplus and no-insurance certainty equivalent under risk aversion $(\rho > 0)$ or risk neutrality $(\rho = 0)$.[33] By **Proposition 1**, the surplus function is continuous in r and $S^1(0;\rho) = -\alpha^X < 0$. Thus, $r_p^X > 0$.

The second step to prove claim 1 is to show that, under *risk neutrality*, there exists a level of risk $r^X < \overline{r}$ above which homeowners are willing to buy insurance. This threshold risk level is pinned down by

$$\begin{aligned} S^1(r^X;\rho=0) &= V - p_1(r^X) - x(r^X;\rho=0) \\ &= V - p_1(r^X) - (1-r^X)V - r^X(V-1) \\ &= -\alpha^X + (1-\beta)r^X = 0. \end{aligned}$$

Solving the equation delivers $r^X = \alpha_X/(1-\beta)$. It is straightforward to check that if $\alpha_X + (\beta-1)\overline{r} < 0$ then $r^X < \overline{r}$.

The third step in proving claim 1 entails showing that, under *risk aversion*, there exist values of $r < r^X$ for which homeowners are willing to purchase insurance. Now consider a

[33] We use ρ simply as an indicator to denote risk averse (versus risk neutral) preferences. When we specialize to CRRA utility, ρ will coincide with the coefficient of relative risk aversion.

risk averse homeowner ($\rho > 0$) with flood risk given by the risk-neutral threshold $r = r^X$:

$$S(r^X;\rho) = V - p_1(r^X) - x(r^X;\rho) > S(r^X;0) = 0, \tag{28}$$

where the inequality follows from the definition of threshold r^X as the indifferent risk level under risk neutrality and claim 2 in **Proposition 1**, which established that the no-insurance certainty equivalent is lower under risk aversion than under risk neutrality (for a given r). Hence, Equation 28 implies that a risk averse individual with risk r^X will be willing to buy insurance because of a strictly positive surplus. Since $S(r;\rho)$ is continuous in r, there exists $\varepsilon > 0$ such that if $r^X - \varepsilon < r < r^X$ then $S(r^X - \varepsilon;\rho) > 0$. Hence, the threshold for willingness to purchase insurance (under risk aversion) is given by $0 < r_p^X < \overline{r}$. To conclude the proof of claim 1, we simply need to add the affordability constraint.

Let us now turn to **claim 2**, which focuses on zone $z = A$. The thrust of the proof of the previous claim also applies here. The risk-neutral indifference threshold r^A is defined by

$$\begin{aligned} S^1(r^A;\rho=0) &= V - p_1(r^A) - x(r^A;\rho=0) \\ &= -\alpha^A + (1-\beta)r^A = 0. \end{aligned}$$

To ensure $r^A > \overline{r}$, we need to verify that $S^1(\overline{r};\rho=0) = -\alpha^A + (1-\beta)\overline{r} < 0$, which holds by our parametric assumption. Similarly, $r^A < 1$ holds because $S^1(1;\rho=0) = -\alpha^A + (1-\beta) > 0$, proving that $\overline{r} < r^A < 1$. By the continuity argument provided in the previous claim, there exists $\varepsilon > 0$ such that if $r \in (r^A - \varepsilon, r^A)$ then a *risk averse* homeowner will be willing to buy insurance. Hence, $\overline{r} \leq r_p^A < 1$.

Claim 3 follows easily from the observation that the no-insurance certainty equivalent under risk neutrality is simply the expected level of consumption under no-insurance. It is straightforward to verify that if $r > r^z$ (for $z = X, A$), then $r > p_1(r)$. In words, homeowners are only willing to purchase insurance if their expected loss is higher than the premium.

Claim 4 is trivial. Simply, recall that the expected loss and the premium have been normalized in units of loss ($L). To show **claim 5** simply integrate over the regions of buyers in the (y, r) space under the RR1 pricing system. The affordability constraints become irrelevant when $G(r) = 0$ for all $r < 1$, which simplifies the expressions. ■

Proof of Proposition 3. In each zone $z = X, A$, the pricing schedule $\widehat{p_1}(r) = p_1(r)$ for $r < r^z$ and therefore the utility maximizing choices do not change over this range of risk levels. Above the corresponding risk-neutral thresholds, homeowners are willing to purchase insurance but the affordability constraint is more stringent under the reform: $y \geq \widehat{p_1}(r) > p_1(r)$ for $r > r^z$. The second claim follows from evaluating Equation 10 under both pricing systems.■

Proof of Proposition 4. The claims in the proof are straightforward given the parametric assumptions and the pricing functions. One simply needs to verify that each region depicted in Figure 3 is non-empty, which is the case under the parameter values for $(\alpha_X, \alpha_A, \beta)$. In particular, this requires verifying that $b_j = 1$ provided $x(r) \leq V - p_j(r)$ and $y \geq p_j(r)$, for $j = 1, 2$, whereas $b_j = 0$ when $x(r) > V - p_j(r)$ or $y < p_j(r)$ (or both). ■

Proof of Proposition 4. Under risk neutrality ($\rho = 0$), for any r, everyone who can afford the premiums is willing to buy insurance (out of indifference) since

$$\begin{aligned} S^2(r;\rho=0) &= V - p_2(r) - x(r;0) \\ &= V - r - [(1-r)V + r(V-1)] = 0, \end{aligned}$$

where $x(r;0) = (1-r)V + r(V-1)$ is the no-insurance certainty equivalent under risk neutrality. Since the no-insurance certainty equivalent is *lower* for risk averse individuals ($\rho > 0$) than for risk neutral individuals, the surplus from purchasing insurance is higher under risk aversion:

$$S^2(r;\rho) > S^2(r;\rho=0) = 0.$$

Hence, at any r, all homeowners are (strictly) willing to purchase insurance and everyone who can afford the premium will do so.

To prove the second part of the proposition, simply integrate over the regions of buyers in the (y,r) space under the RR2 pricing system. The affordability constraints become irrelevant when $G(r) = 0$ for all $r < 1$, which simplifies the expressions. ■

Proof of Proposition 5. The claims in the proof are straightforward given the parametric assumptions and the pricing functions. One simply needs to verify that each region depicted in Figure 3 is non-empty, which is the case under the parameter values for $(\alpha_X, \alpha_A, \beta)$. In particular, this requires verifying that $b_j = 1$ provided $x(r) \leq V - p_j(r)$ and $y \geq p_j(r)$, for $j = 1, 2$, whereas $b_j = 0$ when $x(r) > V - p_j(r)$ or $y < p_j(r)$ (or both). ■

Proof of Proposition 6. When switching from RR1 to RR2, there are four different experiences for homeowners: new entry ($(b_1, b_2) = (0,1)$), exit ($(b_1, b_2) = (1,0)$), renewal ($(b_1, b_2) = (1,1)$) and those that stay out of the market ($(b_1, b_2) = (0,0)$). The change in total revenue is a weighted sum of the change in the revenue for each of these four groups. Clearly, those that stay out of the market generate zero revenue both under RR1 and RR2. ■

B Social welfare

Let us now consider the welfare effects of the switch to RR2. To set the stage, consider an allocation that characterizes the state-contingent consumption of all homeowner types $(c_1(r,y), c_2(r,y))$ for homeowners with flood risk and income (r,y), where $c_1(r,y)$ and $c_2(r,y)$ denote the consumption levels in the good state (no flooding) and bad state (flooding), respectively. The corresponding expected utility is given by

$$U(r,y) = (1-r)u(c_1(r,y)) + ru(c_2(r,y)). \tag{29}$$

As discussed above, homeowners can choose between buying (full) insurance or remaining uninsured. The former enjoy a non-contingent consumption level $c_1 = c_2 = V - p(r)$ whereas the latter's consumption bundle is given by $(c_1, c_2) = (V, V-1)$. The corresponding expected utility levels are thus given by

$$U(r, y) = \begin{cases} u(V - p(r)) & \text{if insured} \\ (1 - r)u(V) + ru(V - 1) & \text{if uninsured.} \end{cases} \tag{30}$$

We will evaluate allocations by means of a (utilitarian) social welfare function (where all homeowners are given the same weight):

$$W^u = \int_{r=0}^{r=1} \int_{y=0}^{y=\infty} U(r, y)h(r)g(y)drdy. \tag{31}$$

We can specialize this equation taking into account the two classes of homeowners (fully insured or uninsured):

Proposition 7. *For pricing system $j = 1, 2$, let $B_j = \{(r, y) : b(r, y) = 1\}$ and $\widetilde{B_j} = \{(r, y) : b(r, y) = 0\}$ denote the sets of insured and uninsured homeowners, respectively. Then*

1. *Social welfare under pricing $j = 1, 2$ is given by*

$$W^u = \int_{r \in B_j} u(V - p_j(r))h(r)dr + \int_{r \in \widetilde{B_j}} [(1 - r)u(V) + ru(V - 1)]drdy \tag{32}$$

$$W^c = \int_{r \in B_j} (V - p_j(r))h(r)dr + \int_{r \in \widetilde{B_j}} x(r)drdy, \tag{33}$$

where social welfare in Equation 32 and Equation 33 is measured in utils and units of the income numeraire, respectively.

2. *The switch from RR1 ($j = 1$) to RR2 ($j = 2$) produces winners and losers. Let U_j denote expected utility under pricing system $j = 1, 2$. Then*

$$U_2(r, y) \geq U_1(r, y) \iff r \in (0, r^X) \cup (\overline{r}, r^A), \tag{34}$$

with strict gains if $b_2(r, y) = 1$. In words, homeowners for which $p_2(r) < p_1(r)$ will strictly benefit (if they purchase insurance under RR2). Conversely, those for which $p_2(r) > p_1(r)$ will strictly lose out (if they purchased insurance under RR1).

3. *The change in social welfare as we switch from RR1 ($j = 1$) to RR2 ($j = 2$) in units of the income numeraire can be written as*

$$\begin{aligned} \Delta W^c &= Prob(Entry)E\left(V - p_2(r) - x(r)|Entry\right) & (35)\\ &- Prob(Exit)E\left(V - p_1(r) - x(r)|Exit\right) & (36)\\ &+ Prob(Renew)E\left(p_1(r) - p_2(r)|Renew\right). & (37) \end{aligned}$$

Proof of Proposition 7. The proof of **claim 1** follows simply from observing that

$$\begin{aligned} b_j(r) = 1 &\iff c_1(y,r) = c_2(y,r) = V - p_j(r) \\ b_j(r) = 0 &\iff (c_1(y,r), c_2(y,r)) = (V, V-1) \end{aligned}$$

and the definition of $x(r)$ as the no-insurance certainty equivalent.

Claim 2 identifies the individual homeowners gaining / losing from the switch to RR2. Observe that the utility maximization problem has a choice set with only two options: full insurance or no insurance at all. In the former case, expected utility is given by $u(V - p_j(r))$ whereas the no-insurance expected utility can be written as $u(x_r)$, where x_r is the no-insurance certainty equivalent. Clearly, individuals for which $p_2(r) \leq p_1(r)$ will be weakly better off and the improvement will be strictly positive whenever they purchase insurance under RR2 ($b_2 = 1$). By definition of the risk-neutral threshold r^X, these individuals are characterized by $r < r^X$ in each zone $z = X, A$. The same argument in reverse identifies the homeowners that lose out from the switch to RR2.

To derive the expression for the change in social welfare (in units of numeraire) in **claim 3**, it helps to proceed region by region, keeping Figure 3 in mind. First, consider the region (r, y) for which there is entry ($b_1 = 0, b_2 = 1$). By virtue of **claim 2** above, $U_2(r, y) > U_1(r, y)$ for all new entrants. Hence, integrating over the entry region, we obtain Equation 35, where the integrand is strictly positive. Next, we turn to the region with exit ($b_1 = 1, b_2 = 0$). Again by **claim 2**, $U_1(r, y) < U_2(r, y)$ for all quitters. Integrating over the exit region, we obtain Equation 36, where the integrand is again strictly positive as it represents a strict welfare loss. Third, consider now the set of renewers. As discussed earlier, there are renewers for which the switch to RR2 will entail a strict welfare loss (since $p_2(r) > p_1(r)$) and renewers for which the opposite will hold. But, either way, the change in consumption entailed by the switch to RR2 is given by $(V - p_2(r)) - (V - p_1(r)) = p_2(r) - p_1(r)$. Integration delivers Equation 37, which may be positive or negative depending on the relative size of each of the two groups. Last, the remaining homeowners do not purchase insurance under either system ($b_1 = b_2 = 0$). Hence, their expected utility does not change when switching to RR2 (and equals $u(x_r)$). ■

It is clear that entry and premium reductions increase social welfare, whereas exit and premium increases lower it. However, the overall change in social welfare depends on parameter values. In other words, the adoption of RR2 could entail a net gain or a net loss and its determination is an empirical question.

Empirical estimation of the social welfare gains (or losses) from the adoption of RR2 requires knowledge of the expected no-insurance certainty equivalent among entrants and quitters (along with the value of V). Unfortunately, these terms are hard to identify in the data. The following corollary provides guidance for the estimation of the change in social welfare arising from the adoption of RR2.

Corollary. *In regards to the empirical estimation of ΔW^c,*

1. *The intensive margin in Equation 37 can be estimated as the average within-policyholder*

change in premium.[34]

2. *Only Prob(Exit) and Prob(Entry) can be estimated in Equation 35 and Equation 36.*

3. *If we assume that the average surplus from purchasing insurance ($V - p_j(r) - x(r)$) is higher for homeowners exiting the market ($r > r^z$) than for entrants ($r < r^z$), the volume of exit matters more for social welfare than the volume of entry. Moreover, a sufficient condition for $\Delta W^c < 0$ is (i) average increase in premiums among renewers and (ii) net exit from the market.*

C Dynamic model

Let us consider a simple overlapping generations setup where a cohort of homeowners (of size one) is born each period and each one lives for two periods. At birth each individual is drawn from the joint density function $f(r, y) = g(r)h(y)$, as discussed above. Let's denote the measures of young and old individuals in year t as n_t and m_t, respectively, and note that $n_t + m_t = 2$ in each period t. Each homeowner decides whether to purchase (full) insurance under pricing function $p_t(r)$. The utility-maximizing choices of all homeowners are summarized in indicator function $b_t(r, y)$ (as in Equation 9).

In this setup, there are four possible individual insurance histories:

$$(b^n_t, b^m_{t+1}) \in \{(0, 0), (0, 1), (1, 0), (1, 1)\},$$

where the first (second) term indicates if the individual purchased insurance in her youth (old age). Clearly, if the pricing function remains unchanged between two consecutive periods, there will be no switchers and only two possible individual histories $(b^n_t, b^m_{t+1}) \in \{(0, 0), (1, 1)\}$.

At any point in time, insurance purchases can be partitioned into renewals and first-time purchases (entry). **Renewals** correspond to old homeowners who purchased insurance throughout their lifetimes ($b^n_{t-1} = b^m_t = 1$) and can be aggregated as[35]

$$Renewers_t = m_t \int\int b_{t-1}(r, y)b_t(r, y)h(r)g(y), \tag{38}$$

where the integration limits cover all permissible values for r and y. In turn, **entry** can take place among young homeowners or old first-time buyers:

$$Entry_t = n_t \int\int b_t(r, y)h(r)g(y) + m_t \int\int (1 - b_{t-1}(r, y))b_t(r, y)h(r)g(y). \tag{39}$$

In each period, there is also **exit** from the insurance market, either because some old homeowners who purchased insurance while young now decide not to, or due to the death of homeowners who purchased insurance in the last period. Thus,

$$Exit_t = m_t \int\int b_{t-1}(r, y)(1 - b_t(r, y))h(r)g(y) + m_{t-1} \int\int b_{t-1}(r, y)h(r)g(y). \tag{40}$$

[34] In settings where insurance take-up is compulsory, this term fully sums up the change in social welfare.
[35] To lighten notation we omit $drdy$ from the integrals.

Consider now two consecutive periods during which the pricing function remains **unchanged**. Obviously, the purchase allocations will not vary either: $b_{t-1}(r,y) = b_t(r,y) = b(r,y)$. Thus, there will be no switching of insurance status over anyone's lifetimes and

$$Renewers_t = Entry_t = Exit_t = \int\int b(r,y)h(r)g(y),$$

where we also used that $n_t = m_t = 1$ at all t. Note also that total insurance purchases in each period are simply given by $2\int\int b(r,y)h(r)g(y)$. Moreover, absent population growth and changes in the pricing schedule, the measures of renewers, entry, exit and take-up (purchases) remain constant over time.

D Subjective Flood Risk Beliefs

Consider zone $z = X, A$ and suppose that the subjective probability of flooding for an individual with objective flood risk r is given by $\pi(r) = \lambda r$ where $0 < \lambda \leq 1$. Naturally, lower values of λ entail a larger degree of underestimation of the objective risk.

The essential departure relative to the standard case with objective beliefs is that premiums depend on objective risk (r) but homeowners' rank consumption bundles on the basis of subjective risk ($\pi = \lambda r$). This generates a clash between flood risk skepticism (inversely related to λ) and risk aversion: for a given degree of risk aversion, insurance take-up falls in the discount placed on objective flood risk probabilities. Put otherwise, there is a threshold value of skepticism $\lambda^*(\rho)$, which depends on the degree of risk aversion, below which no homeowner purchases insurance.

It is easy to illustrate this relationship when homeowners are risk neutral. Under RR1 pricing, a homeowner with flood risk r is willing to purchase insurance provided that $p_1(r) \leq \lambda r$, that is,

$$r \geq \frac{\alpha_z}{\lambda - \beta}.$$

It is also straightforward to see that for $0 < \lambda \leq \beta$, no one will buy (because $p_1(r) > \lambda r$ for all r). In addition, for $\beta < \lambda < 1$, as λ increases, the threshold risk value falls and it goes to infinity as λ approaches β (from above). Hence, for $\lambda \leq \alpha_A - \beta$, not even homeowners with $r = 1$ will purchase insurance. Combining both observations, $\lambda \leq \lambda^* = min\{\beta, \alpha_A - \beta\}$, no homeowner will buy insurance. With risk averse homeowners, there's a greater preference for insurance. However, at any given level of risk aversion, there exists a threshold value of skepticism below which no homeowner is willing to purchase insurance.[36]

[36] When premiums are actuarially fair, as under RR2, the situation is similar. In fact, under risk neutrality, no homeowner is willing to purchase insurance for any $0 < \lambda < 1$. Under risk aversion, there is also a threshold value of skepticism below which no homeowner purchases insurance.