Summary: Coupled Agent-based Model and Catastrophic Model

Scope. We couple an annual, tract-resolved behavioral module with a flood loss and finance module to evaluate household (HH) adaptation and financial outcomes. **The model is explicitly designed to capture *dual-scale dynamics*: (1) heterogeneity at the *individual level*—household tenure (owners vs. renters)—and (2) heterogeneity at the *macro-social context*—the tract-level share of marginalized (MG) vs. non-marginalized (NMG) groups.** The social heterogeneity (MG/NMG) is represented *only at the tract-level*. Individual HHs do not carry MG/NMG attributes; instead they act via random draws against tract-level, MG/NMG-weighted action probabilities.

Scientific Questions (Focus)

Modeling household decision-making in flood adaptation is challenging due to behavioral diversity and uncertainty. This heterogeneity spans the two key levels defined in our scope. Our overarching research question is:

> **How can a coupled agent-based model (ABM) capture these dual-scale dynamics and their influence on long-term adaptation and financial outcomes?**

This leads to the following specific inquiries:

1. **Q1 – Adaptation Impact & Asymmetry.** How does the impact of continued adaptation (vs. a no-action scenario) on long-run flood outcomes **differ between *owners* and *renters***, and how do these asymmetric impacts (e.g., payout advantage, damage penalty) evolve over time?

2. **Q2 – Tenure Asymmetry.** Do *renters* and *homeowners* exhibit systematically different adaptation patterns after floods (annual composition, and changes around severe-flood years at $k = 0, 1, 2$), and how does flood-prone vs. non-prone context moderate these patterns?

3. **Q3 – Financial Consequences & Attribution.** How do coverage differences—contents-only for renters vs. structure+contents for owners—translate into asymmetric out-of-pocket (OOP) costs, payout rates, and loss attribution (structure vs. contents) over time?

A. Annual timeline

For each year $t \in \{2011, \ldots, 2023\}$:

Flood hazard $\rightarrow$ Loss computation $\rightarrow$ TP update $\rightarrow$ End-of-year decisions (actions at t) $\rightarrow$ Finance

B. Initialization (baseline at $t = 2011$)

B1. Insurance status. Tracts are labeled *flood-prone* or *non-flood-prone*. Flood-prone tracts receive higher initial take-up rates for both owners and renters; non-flood-prone tracts receive lower rates (anchored to state-level NFIP policies-in-force per household; scenario-tuned).
B2. Tract-level perceptions (SC/PA). For each tract, we draw (SC^{MG}, PA^{MG}) and (SC^{NMG}, PA^{NMG}) from survey-fitted Beta distributions. These inform tract-level threat-perception dynamics; HHs do *not* hold SC/PA or MG/NMG labels.
B3. RCV initialization. Household replacement costs for buildings (and contents where applicable) are sampled from log-normal distributions and scaled so that HH-level totals statistically align with the tract's total RCV.

C. Hazard and vulnerability

C1. Tract flood depth. Let N_{grid} be the number of grids in a tract and $\max(\text{depth}_{g,t})$ the peak depth at grid g in year t. The tract-level depth is

$$d_t \;=\; \frac{1}{N_{\text{grid}}} \sum_g \max(\text{depth}_{g,t}). \tag{1}$$

C2. Effective depth and depth–damage. If an owner has elevated once (see E4), the effective depth for HH i is

$$d_{i,t}^{\text{eff}} \;=\; \max\{d_t - \text{EH\_height}_i,\; 0\}. \tag{2}$$

Building and contents losses use standard depth–damage curves $f_{\text{bld}}(\cdot)$ and $f_{\text{cnt}}(\cdot)$:

$$\text{Loss}_{i,t}^{\text{bld}} = f_{\text{bld}}(d_{i,t}^{\text{eff}}) \cdot RCV_i^{\text{bld}}, \quad \text{Loss}_{i,t}^{\text{cnt}} = f_{\text{cnt}}(d_{i,t}^{\text{eff}}) \cdot RCV_i^{\text{cnt}}.$$

D. Threat perception (TP): gated growth + decay at tract-level

Let G_t be total tract losses in year t and RCV_t the tract's total replacement cost value. Define the damage ratio $r_t = G_t/RCV_t$. TP is updated separately for MG and NMG:

D1. Gate by damage ratio. TP gains occur only if $r_t > \theta$ (baseline $\theta = 0.5$):

$$\mathbf{1}\{r_t > \theta\}.$$

D2. Half-life dynamics. We adopt an evolving half-life $\tau(t) = \tau_\infty - (\tau_\infty - \tau_0)e^{-kt}$ with $\tau_\infty > \tau_0 > 0$, $k > 0$. The tract-level decay coefficient for group $g \in \{\text{MG}, \text{NMG}\}$ is

$$\mu_t^g \;=\; \frac{\ln 2}{\tau(t)} \left(\alpha\, PA_t^g + \beta\, SC_t^g\right). \tag{3}$$

Empirically, SC tends to lengthen half-life more strongly among MG; for NMG the contributions of SC and PA are comparable.

D3. Discrete annual update. The previous year's flood damage is used to update the current year's threat perception:

$$TP_t^g \;=\; (1 - \mu_t^g)\, TP_{t-1}^g \;+\; \Delta\psi_t \cdot \frac{G_t}{RCV_t}, \quad \text{where } \Delta\psi_t = 1 \text{ if } \frac{G_t}{RCV_t} > \theta \text{ else } 0. \tag{4}$$

E. Decision-making (tract-level probabilities, HH-level randomization)

The decision process involves three main steps to move from tract-level perceptions to individual household actions.

E1. Group-specific action probabilities. First, for each group $g \in \{\text{MG, NMG}\}$ within a tract, we calculate the adoption probability for each action $a \in \{\text{FI}, \text{EH}, \text{BP}, \text{RL}, \text{DN}\}$. This is done using a Bayesian regression model where perceptions (TP, CP, SP) are the inputs:

$$p_t^{(a),g} \;=\; \sigma\Big(w_0^{(a)} + w_1^{(a)} TP_t^g + w_2^{(a)} CP_t + w_3^{(a)} SP_t\Big), \tag{5}$$

where CP_t embeds affordability/income effects, SP_t is stakeholder perception, and $\sigma(\cdot)$ is the logistic link function.

E2. MG/NMG-weighted common threshold. Next, these group-specific probabilities are combined into a single, tract-level adoption probability for each action. This is achieved by weighting the group probabilities by the tract's MG share (w_{MG}):

$$\overline{p}_t^{(a)} \;=\; w_{MG}\, p_t^{(a),MG} \;+\; (1 - w_{MG})\, p_t^{(a),NMG}. \tag{6}$$

E3. Household decision rule (random draw). Finally, each individual household in the tract makes its decision. For each potential action, a random number $u \sim \mathcal{U}(0, 1)$ is drawn and compared against the tract-level probability $\overline{p}_t^{(a)}$. The household adopts the action if its random draw is greater than the threshold and the action is permitted by the sequence constraints below.

E4. Sequences and constraints. Households can take at most one action per year, following a specific sequence:

- **Owner:** *FI* $\rightarrow$ *EH* (at most once, +5 ft; all subsequent years skip EH) $\rightarrow$ *BP* (buyout removes the HH permanently; no backfill) $\rightarrow$ *DN*.
- **Renter:** *FI* $\rightarrow$ *RL* (relocate to a tract with same or lower d_t) $\rightarrow$ *DN*.

F. Feedback from Adaptation Actions

The actions taken by households at the end of each year directly influence the state of the catastrophic model for the following year.

F1. Vulnerability Module Feedback. Elevating a house (EH) directly reduces its physical vulnerability. By raising the structure by 5 feet, the depth-damage curve is shifted to the right, meaning a greater flood depth is required to cause the same percentage of damage. This lowers the potential for damage in future flood events.

F2. Exposure Module Feedback. The buyout program (BP) and relocation (RL) alter the model's exposure database. A buyout removes a household and its structure from the simulation permanently, which reduces the total number of owners and the total RCV in the tract, thus lowering exposure. Relocation moves a renter household to a different tract (one with equal or lower flood depth), thereby reallocating exposure across the study area.

F3. Indirect Financial Impacts. These changes in vulnerability and exposure have direct consequences for the finance module. Reduced vulnerability (from EH) leads to lower calculated damages, which in turn results in smaller insurance payouts and lower out-of-pocket costs for insured households. Reduced or reallocated exposure (from BP and RL) changes the total potential losses and, therefore, the aggregate financial risk within tracts.

G. Finance

Renters can purchase *contents-only* coverage; owners can purchase *structures + contents*. The module calculates premiums, deductibles, limits, payouts, and out-of-pocket (OOP) costs.

$$\text{Premium} \rightarrow \text{Deductible} \rightarrow \text{Limit} \rightarrow \text{Payout} \rightarrow \text{Out-of-Pocket (OOP)}.$$

Key outputs: FI take-up/retention, payout ratio, OOP median/IQR/P95, average annual loss (AAL), and premium distributions among insured only.

H. State variables (minimal set)

- **Per-tract:** TP_t^{MG}, TP_t^{NMG}, SC^g, PA^g, w_{MG}, CP_t, SP_t, d_t, r_t, RCV_t.
- **Per-HH:** owner/renter flag; `has_EH` (bool), `EH_height_ft` $\in \{0, 5\}$; `removed_by_BP` (bool); `tract_id`; `insured_type` (owner: bld+cnt; renter: cnt-only); `action_t` $\in \{\text{FI}, \text{EH}, \text{BP}, \text{RL}, \text{DN}\}$.

I. Pseudocode (per tract, per year)

```
# Draw tract-level perceptions
(SC_MG, PA_MG), (SC_NM, PA_NM) ~ survey-fitted distributions

# Update TP for MG and NMG based on last year's damage
mu_MG = ln(2)/tau(t) * (alpha*PA_MG + beta*SC_MG)
mu_NM = ln(2)/tau(t) * (alpha*PA_NM + beta*SC_NM)
TP_MG = (1 - mu_MG)*TP_MG_prev + kappa*(r_t > theta)*r_t
TP_NM = (1 - mu_NM)*TP_NM_prev + kappa*(r_t > theta)*r_t

# Group-specific probabilities and MG-weighted common threshold
for action a in {FI, EH, BP, RL, DN}:
    p_MG = sigmoid(w0[a] + w1[a]*TP_MG + w2[a]*CP_t + w3[a]*SP_t)
    p_NM = sigmoid(w0[a] + w1[a]*TP_NM + w2[a]*CP_t + w3[a]*SP_t)
    p_bar[a] = w_MG*p_MG + (1 - w_MG)*p_NM

# Household decisions (random draw vs p_bar)
for hh in tract:
    if hh.is_owner:
        if rand() > p_bar['FI']: hh.buy_insurance()
        elif not hh.has_EH and rand() > p_bar['EH']: hh.elevate(+5 ft)
        elif rand() > p_bar['BP']: hh.remove() # permanent; no backfill
        else: hh.do('DN')
    else: # renter
        if rand() > p_bar['FI']: hh.buy_contents_only()
        elif rand() > p_bar['RL']: hh.relocate_to_same_or_lower_depth_tract()
        else: hh.do('DN')
```

J. Notation

Symbol	Meaning
d_t	Tract mean of grid-level peak flood depths in year t
G_t, RCV_t	Tract total losses and total replacement cost in year t
r_t	Damage ratio G_t/RCV_t
θ	TP gain trigger threshold on r_t (baseline 0.5)
$\tau(t)$	Time-varying half-life; $\mu_t^g = \ln 2\,(\alpha PA^g + \beta SC^g)/\tau(t)$
TP_t^g	Threat perception for group $g \in \{\text{MG}, \text{NMG}\}$
$p_t^{(a),g}$	Action probability for action a and group g
$\overline{p}_t^{(a)}$	MG/NMG-weighted tract-level action probability
w_{MG}	MG share

CRS/subsidies. Community Rating System discounts and targeted subsidies are not yet implemented but can be incorporated as multiplicative factors on premiums and/or as additive offsets to elevation or relocation costs in the finance/decision layers.