Wildfire Smoke and Indoor Air Quality

Evidence of Household Adaptation from Indoor-Outdoor Monitor Pairs

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Motivation

- $PM_{2.5}$ is the largest environmental risk factor for health and mortality in the United States (Liang et al. 2021, *PNAS*).
- Looking ahead, wildfire damages are projected to be the *largest* form of climate-change costs in the US (Qiu 2025, *Nature*).
- People spend ∼90% of their time indoors — the share of outdoor $PM_{2.5}$ that infiltrates homes is a first-order driver of health exposure.
- **Indoor air quality is poorly understood**: nearly all monitoring infrastructure tracks outdoor concentrations.
- **Indoor air may be more amenable to policy intervention** (air purifiers, awareness campaigns) than ambient outdoor concentrations.

Research Question

- The **infiltration ratio** R_{it} = indoor $PM_{2.5}$ / outdoor $PM_{2.5}$ captures how much outdoor smoke reaches residents.
- With repeated wildfire exposure, households may:
  (a) **Reduce** R_{it} over time — learning-by-doing, active adaptation to a changing environment
  (b) **Increase** R_{it} over time — habituation, growing callousness toward smoke events
- **Research question:** with repeated exposure to wildfire smoke, do households reduce their infiltration ratio over time?

Empirical Approach

Panel: monitor i, hour h, day-of-week d, month-of-sample m
Baseline (following Burke et al. 2022):

$$PM^{\text{in}}_{ihdm} = \sum_{k=0}^{6} \beta_{ik} \, PM^{\text{out}}_{i;h-k;dm} + \delta_h + \eta_m + \theta_d + \varepsilon_{ihdm}$$

Infiltration rate: $\beta_i = \sum_{k=0}^{6} \beta_{ik}$
Time-varying (relax constant β_i; add m index to β):

$$PM^{\text{in}}_{ihdm} = \sum_{k=0}^{6} \beta_{imk} \, PM^{\text{out}}_{i;h-k;dm} + \delta_h + \theta_d + \varepsilon_{ihdm}$$

Key question: does β_{imk} decline over time?

Data: ∼3,977 matched indoor-outdoor PurpleAir sensor pairs at US residences (10-min resolution, via API).

Heterogeneous Infiltration by Smoke Conditions

Allow infiltration to vary by smoke presence:

$$PM^{\text{in}}_{ihdm} = \sum_{k=0}^{6} \beta_{imk}\, PM^{\text{out}}_{i;h-k;dm} + \beta_2\, \text{SmokePM}_{isdmy} + \sum_{k=0}^{6} \gamma_{imk} \left(PM^{\text{out}}_{i;h-k;dm} \times \text{SmokePM}_{isdmy} \right) + \delta_h + \theta_d + \varepsilon_{ihdm}$$

- β_2: direct effect of ambient smoke on indoor $PM_{2.5}$
- γ_{imk}: how outdoor-to-indoor transmission changes *during* smoke events
- **Test:** does γ_{imk} decline over time?