Pollution exposure and health: The role of private actions and environmental externalities in Nairobi

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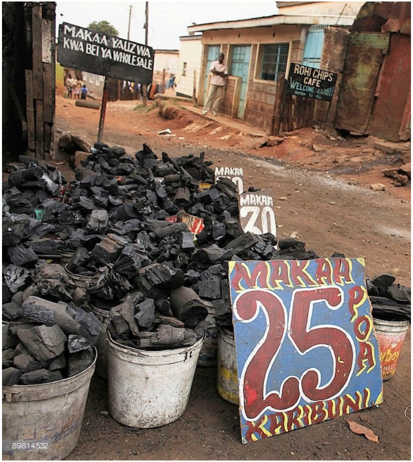
Ambient air pollution (AAP)

Sources include transportation, power sector, industry, wildfires, landfills

Own household-generated air pollution (HAP)

(Other-household-generated air pollution considered AAP)



The urban poor experience both high AAP and HAP

- 3bn to live in slums in Africa and Asia by 2050 (WHO, UN)
- In Africa, >80% of urban households use biomass cooking (FAO)
- Together, AAP and HAP cause 7–9 million premature deaths (10–15% of all deaths) annually (WHO, Lancet)

A large literature studies air pollution

- Health impacts of ambient air pollution (AAP)
  Chay & Greenstone (2003); Currie & Walker (2011); Schlenker & Walker (2016); Ebenstein, Fan, Greenstone, He, Zhou (2017); Isen, Rossin-Slater, Walker (2017); Deryugina, Heutel, Miller, Molitor, Reif (2018); Shapiro & Walker (2020); Simeonova, Currie, Nilsson, Walker (2021); Clay, Lewis, Severnini (2022); Gong, Li, Sanders, Shi (2023)

- Cookstoves
  RESPIRE trials (2007, 2009, 2011); Alexander et al. (2018); Bensch et al. (2015), Bensch and Peters (2019), Chowdhury et al. (2019), Levine et al. (2018), Miller and Mobarak (2013), Mobarak et al. (2012), and Pattanayak et al. (2019); Berkouwer and Dean (2022)

We study HAP in a high-AAP context

- Existing research almost entirely mutually exclusive: HAP **or** AAP
- Studying AAP and HAP jointly is important:
  - 24hr average vs peaks during the worst 15 minutes of the day
  - Mortality, long-term chronic illnesses, short-term respiratory symptoms
  - HAP requires addressing private barriers to adoption; AAP requires regulation of externalities

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  - Mortality, long-term chronic illnesses, short-term respiratory symptoms
  - HAP requires addressing private barriers to adoption; AAP requires regulation of externalities
- We furthermore address two additional shortcomings:
  - AAP research focuses on **daily averages**
  - HAP research primarily **correlational** and **no PM, CO measurements**

Existing research on health impacts of AAP

Chay & Greenstone (2003); Currie & Walker (2011); Schlenker & Walker (2016); Ebenstein, Fan, Greenstone, He, Zhou (2017); Isen, Rossin-Slater, Walker (2017); Deryugina, Heutel, Miller, Molitor, Reif (2018); Shapiro & Walker (2020); Simeonova, Currie, Nilsson, Walker (2021); Clay, Lewis, Severnini (2022); Gong, Li, Sanders, Shi (2023)

- **Impact of** average concentrations (e.g. TSP/PM2.5)
  - Concavity in dose-response often uses average concentration as dose
- **Impact on** mortality and morbidity (e.g. hospital admissions)
  - Less on short-term respiratory symptoms

HAP: Unclear if adoption of clean cooking technologies can generate health improvements

1. Many of the RCTs focus on **adoption** without measuring health impacts
   - Bensch et al. (2015), Bensch and Peters (2019), Chowdhury et al. (2019), Levine et al. (2018), Miller and Mobarak (2013), Mobarak et al. (2012), and Pattanayak et al. (2019).
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3. We find **9** RCTs that estimate the causal impact of improved stove adoption on air pollution concentrations and health
   - Only 2 measure quantitative health outcomes & personal exposure RESPIRE (2011); CHEST (2015)

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3. We find **9** RCTs that estimate the causal impact of improved stove adoption on air pollution concentrations and health
   - Only 2 measure quantitative health outcomes & personal exposure RESPIRE (2011); CHEST (2015)
   - Only **one** RCT in an urban location (sample of pregnant women)
   - **None** measure non-kitchen exposure

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- Leverage experiment where we randomized subsidies for stoves that reduced charcoal use by 40% *(Berkouwer & Dean, 2022)*
- **3+ year** follow-up (86% concordance with initial take-up):

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- **3+ year** follow-up (86% concordance with initial take-up):
  1. Minute-level 48-hour air pollution data (wearable devices)
  2. Hourly activity self-reports
  3. Quantitative & self-reported health outcomes
  4. Quantitative measures of cognitive function
  5. Survey on socio-economic outcomes

Today

Background

Study design

Data sources

Descriptive statistics

Pollution impacts

Health impacts

The relationship between pollution and health

Conclusion

Today

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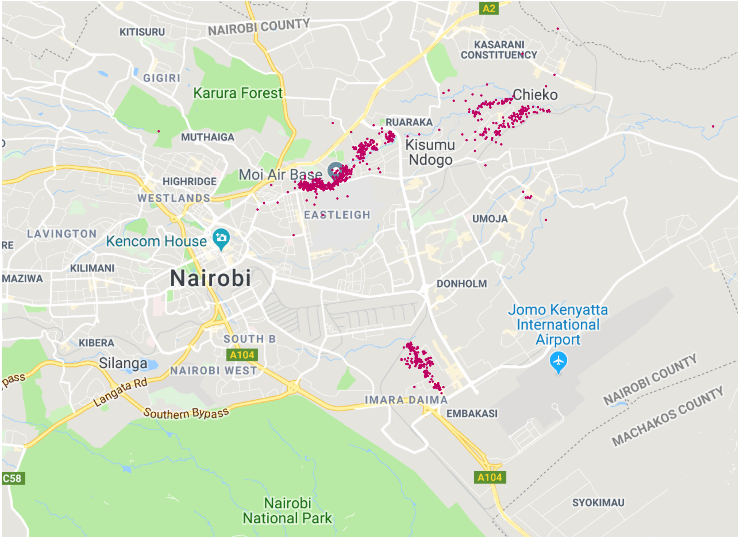
RCT with 955 households in Nairobi, Kenya

Berkouwer & Dean (2022)



Houses in our study areas

These are similar to other urban informal settlements

Figure: Jakarta

Figure: Mumbai

Figure: Lagos

Traditional and energy efficient charcoal cookstoves

Berkouwer & Dean (2022)

KCJ stove
$4

Jikokoa stove
$40

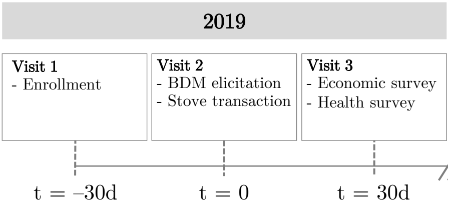
Energy efficient Jikokoa cookstoves

Traditional Stove
\$2-\$5

Jikokoa Stove
\$40 (now \$30)

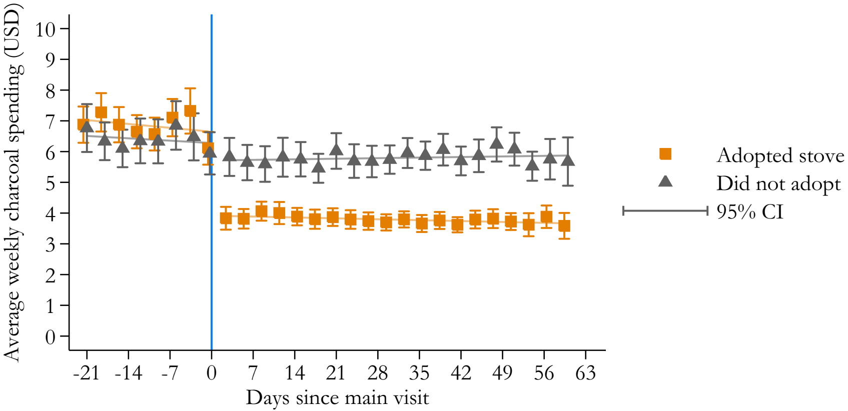
- Identical inputs: same charcoal
- Identical usage: almost no learning or behavior change
- Improved insulation materials
- Better charcoal-to-temperature conversion ratio
- Berkouwer & Dean (2022): 40% reduction in charcoal usage

Experiment Overview



Stove reduces charcoal spending 40% ($2.28/week)

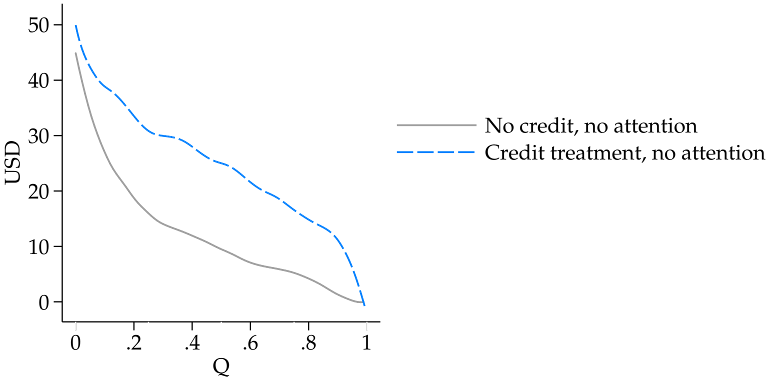
- Randomized subsidies to generate exogenous variation in adoption
- 576 out of 962 respondents (60%) bought stove



(Berkouwer & Dean, 2022)

Access to credit increases adoption

- Credit increases WTP by $13; 104% relative to control



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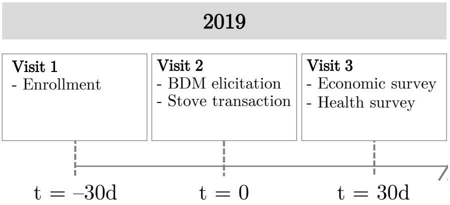

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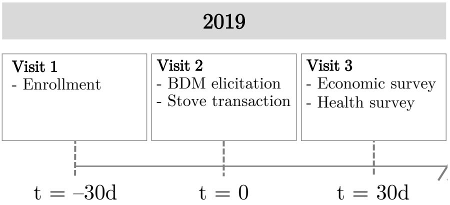

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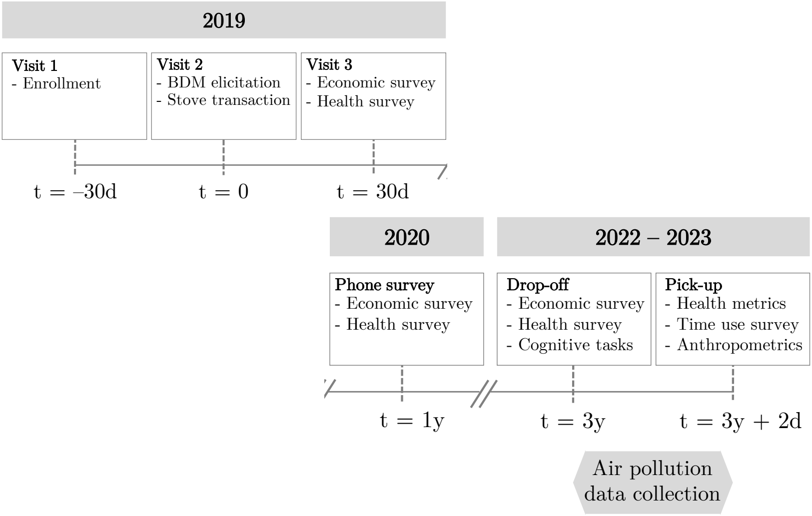

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1. Air pollution measurements

Particulate Matter (PM1.0, PM2.5)

- Purple Air device
- One reading every 2 minutes
- Calibrated using Ward et al. (AGU 2021)

PM1.0: Any particles $< 1.0\mu m$ *diameter*
PM2.5: Any particles $< 2.5\mu m$ *diameter*

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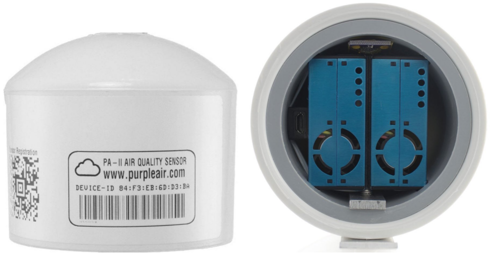


Carbon Monoxide (CO)

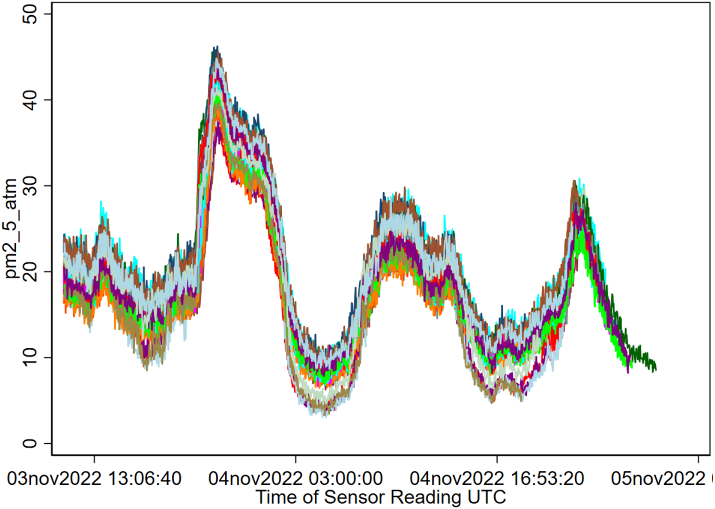
- Lascar Electronics device
- One reading every minute
- Calibrated every 2 months

1. Air pollution measurements

- Each backpack contains 2 devices and a battery
- Dropped off during visit 1, picked up ∼48 hours later
- Best practices (Chillrud et al 2021; Burrowes 2019; Gould 2023; Berkeley Air)


Co-located PM2.5 readings for 30 devices

- We include device fixed effects in all regressions



2. Quantitative physical health measurements

1. **Blood pressure** using a sphygmomanometer
   - Following procedures set out by CDC NHANES (2019)
   - Average of 3 measurements of systolic and diastolic BP
   - Respondent to sit on a chair, straight back, feet flat on the floor, etc.
2. **Blood oxygen saturation** using pulse oximeter
3. **Weight, height and arm circumference:**
   - Children (infant development)
   - Adults (controls)

3. Self-reported health and socioeconomic outcomes

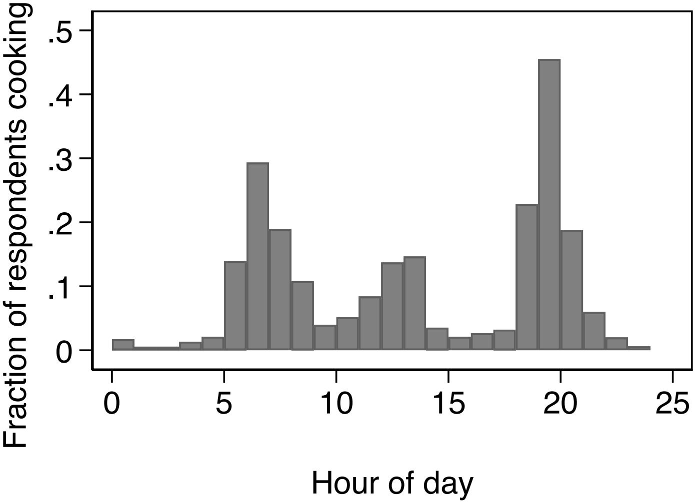
- **Self-reported symptoms**
  - Headache, sore throat, cough, breathlessness, fever, malaria, stomach pain, worms, myalgia, etc.
- **Official diagnoses of diseases**
  - Asthma, pneumonia, COPD, hypertension, diabetes, TB, COVID, etc.
  - **Pneumonia diagnosis** in line with UNICEF MICS6 (2020) methodology
- **Maternal outcomes:** pregnancy outcomes, baby weight/length
- **Socioeconomic outcomes:** cookstove ownership and usage, cooking behavior, charcoal spending, control group adoption, network adoption, work/school attendance, earnings, savings, etc.

4. Time-use survey

For each hour during which the respondent had the device:

- Whether they were indoor or outdoors
- Their primary activity(ies)
- If the primary activitiy was cooking, which cookstove(s) they used

4. Breakfast, (lunch) and dinner:

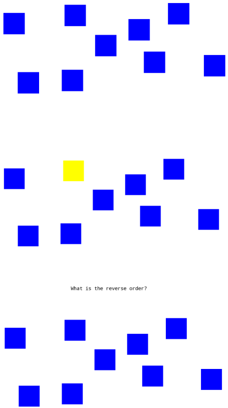


5. Cognition

Working memory

Ability to store and manipulate information in your mind

Reverse Corsi Blocks:



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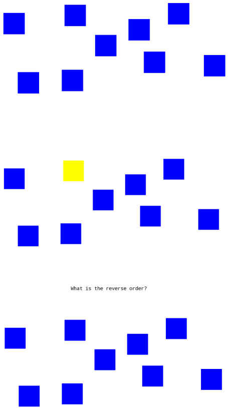
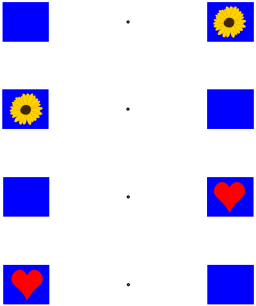


Inhibitory control
Ability to resist tempting impulses
Hearts and Flowers:



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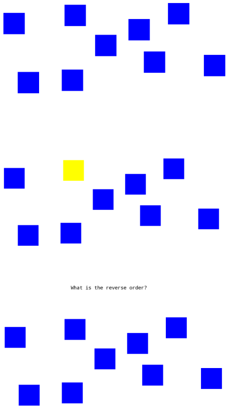

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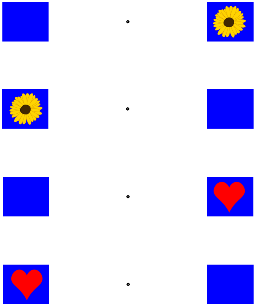
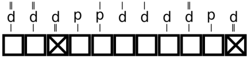


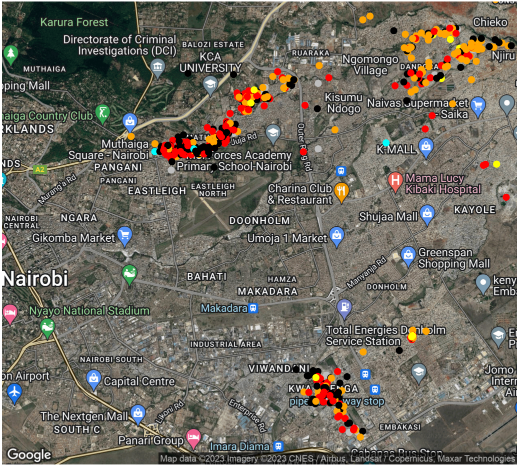
Attention
Ability to ignore distractions
d2 task:



Today

Average PM2.5 concentrations far exceed WHO guidelines

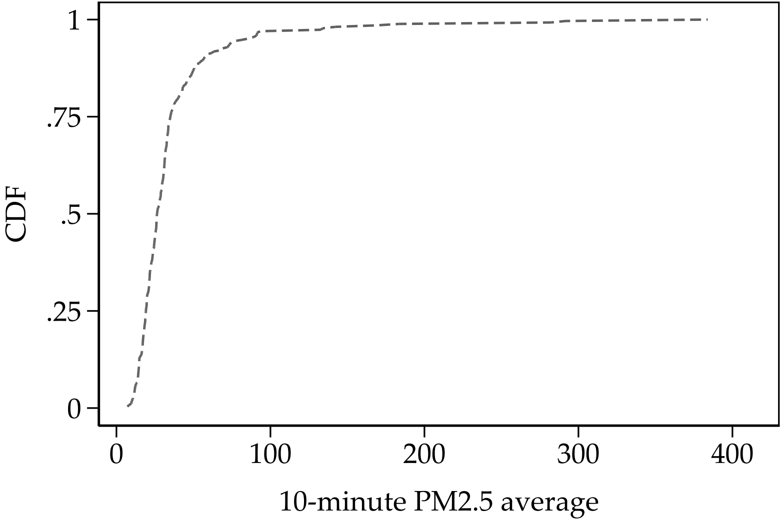
- 700 households surveyed; 600 in original study areas



PM2.5 ($\mu g/m^3$):
- 0 – 5
- 5 – 10
- 10 – 15
- 15 – 25
- 25 – 35
- 35+

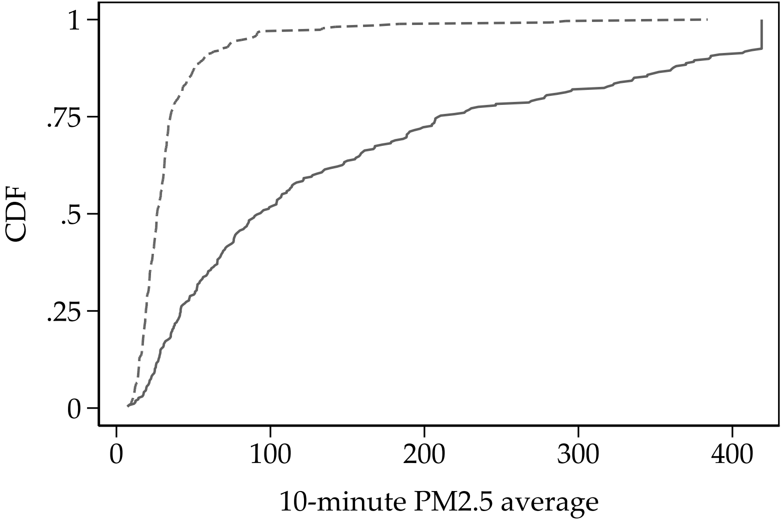
Each respondent's median 10-minute PM2.5:

("10-minute PM2.5" averages five PM2.5 readings, one every 2 minutes)



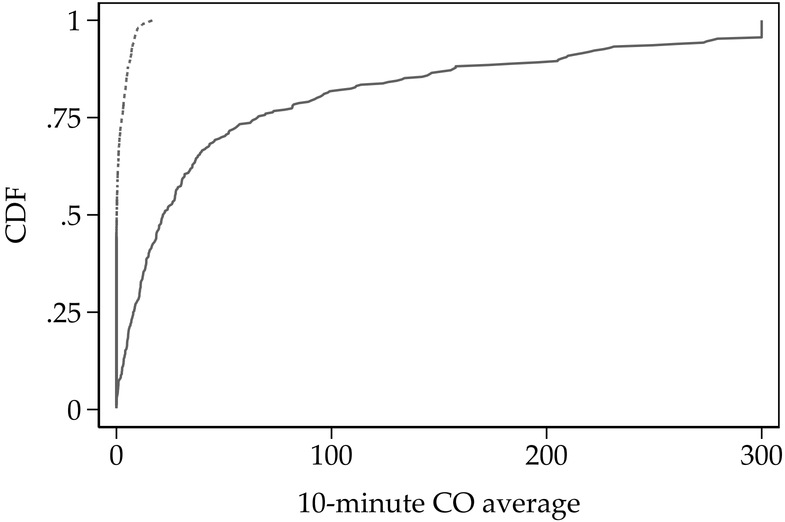
Respondent 99th percentile of 10-minute PM2.5 average:

(99th percentile is approx. 15 minutes per day)



50th & 99th percentile of 10-minute CO average:

>100ppm: "Headache, tiredness, dizziness, nausea, damage to hearts and brains within 2–5 hours" (EPA)



Jikokoa ownership is very persistent between 2019–2022

- Random subsidy, credit, and interaction instrument for 2019 adoption
- Outcome is ownership in 2022-2023

	Control Mean	Treatment Effect of 2019 Jikokoa Ownership	N
Owns other wood/charcoal stove in 2022	0.88	-0.54***	702
	[0.33]	(0.05)	
Owns Jikokoa in 2022	0.10	0.74***	702
	[0.31]	(0.04)	
Owns LPG stove in 2022	0.57	0.05	702
	[0.50]	(0.06)	
Owns bio-ethanol stove in 2022	0.15	0.01	702
	[0.36]	(0.04)	
Owns electric stove in 2022	0.00	0.02*	702
	[0.06]	(0.01)	

Reduction in charcoal expenditures persist

	(1) 2022	(2) 2019
Own Jikokoa	-1.50***	-1.12***
	(0.47)	(0.35)
Own Jikokoa (Urban)		
Own Jikokoa (Rural)		
rural	-1.05***	-1.08***
	(0.36)	(0.38)
Control Mean	3.84	3.65
Weak IV F-Statistic	64.22	217.30
Observations	702	702

Regressions use the randomly assigned subsidy, offer of credit and their interaction as instruments for Jikokoa adoption

Reduction in charcoal expenditures persist; concentrated in urban areas

- Charcoal and wood often gathered rather than purchased in rural areas

	(1) 2022	(2) 2019	(3) 2022	(4) 2019
Own Jikokoa	-1.50***	-1.12***		
	(0.47)	(0.35)		
Own Jikokoa (Urban)			-1.64***	-1.20***
			(0.51)	(0.37)
Own Jikokoa (Rural)			-0.45	-0.40
			(1.05)	(0.98)
rural	-1.05***	-1.08***	-1.74**	-1.58*
	(0.36)	(0.38)	(0.85)	(0.82)
Control Mean	3.84	3.65	3.84	3.65
Weak IV F-Statistic	64.22	217.30	26.75	96.17
Observations	702	702	702	702

Regressions use the randomly assigned subsidy, offer of credit and their interaction as instruments for Jikokoa adoption

Socio-economic impacts of Jikokoa adoption

- Random subsidy, credit offer, and interaction instrument for ownership
- Persistent **40% reduction** in charcoal expenditures

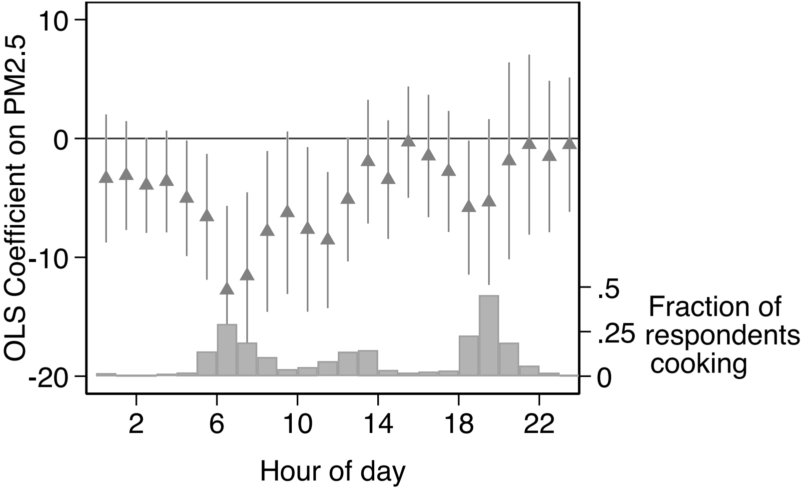
	Control Mean	Treatment Effect (2022 Ownership)	Treatment Effect (2019 Ownership)	N
Charcoal expenditures past 7 days (USD)	3.84	-1.50***	-1.12***	702
	[3.16]	(0.47)	(0.35)	
Earnings past 2 weeks (USD)	32.53	4.73	3.45	563
	[35.41]	(7.83)	(5.38)	
Total savings (USD)	53.64	-8.63	-7.07	701
	[86.62]	(19.88)	(14.67)	
Has formal bank account (=1)	0.13	0.11	0.08	702
	[0.34]	(0.07)	(0.05)	
Minutes cooking per day	136.72	3.49	2.60	702
	[57.76]	(8.32)	(6.15)	
People in network who adopted Jikokoa	0.78	1.13***	0.84***	702
	[2.04]	(0.40)	(0.29)	

Cost-benefit calculations

- Adoption is persistent: after 3 years, 83% of adopters still own Jikokoa, whereas only 10% of non-adopters have since adopted
- 70% of subsidies are marginal: 16% of population are always-takers, but 52% of subsidy recipients adopted
- No crowding in/out of other cooking technologies
- Adoption reduces emissions by 3.5 tCO_2e/yr
- **Abatement costs $4/ton**

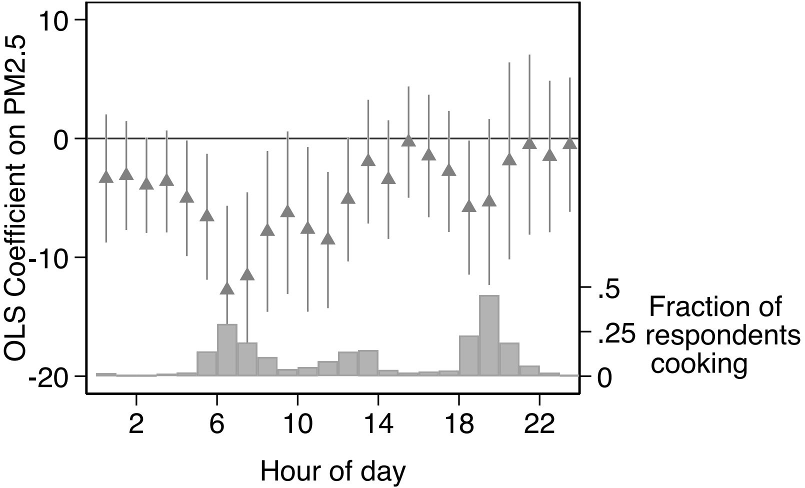
Today

PM2.5 reductions occur during cooking times (OLS):



PM2.5 reductions occur during cooking times (OLS):

- Planetary Boundary Layer Height (PBLH): 1,500–1,700 meters at 8am, 60-200 meters at 8pm



Effects on PM2.5 during cooking peaks vs. averages:

- IV regressions: random subsidies and credit as instruments
- Median (ambient) concentration is $25\mu g/m^3$ (AQI 75)
- Cooking increases PM2.5 by $122\mu g/m^3$

Panel A) All hours

	(1) Median	(2) Mean	(3) Max Hour	(4) 99th
Own Jikokoa	0.2	-0.9	-17.2	-8.5
	(1.7)	(3.4)	(19.0)	(23.0)
Control mean	25.1	37.5	152.4	197.9
N	651	651	651	651

Panel B) When self-reporting cooking

	(1) Median	(2) Mean	(3) Max Hour	(4) 99th
Own Jikokoa	-5.7	-14.2**	-31.1**	-49.4**
	(5.9)	(7.0)	(15.2)	(23.3)
Control mean	35.0	48.9	89.9	147.4
N	599	599	598	599

Effects on PM2.5 during cooking peaks vs. averages:

- IV regressions: random subsidies and credit as instruments
- Cooking increases PM2.5 by $122 \mu g/m^3$
- Improved stove reduces peak emissions by $49 \mu g/m^3$ (40%)

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- Cooking increases PM2.5 by $122\mu g/m^3$
- Cooking 9% of time: no detectable change in daily average

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IV using average hourly data shows similar, noisier results:

	Cooking	PM 2.5	
	(1)	(2)	(3)
	IV	OLS	IV
Own Jikokoa	-0.00	-1.63	-0.03
	(0.01)	(1.54)	(3.01)
Cooking and Own Jikokoa		-8.28***	-7.93
		(3.16)	(7.15)
Cooking		9.83***	9.66**
		(2.68)	(3.75)
DoW*HoD*Geocluster FE	Yes	Yes	Yes
Control Mean	0.10	35.96	35.96
Weak IV F-Statistic	39		28
Households	661	652	652
Observations	29445	23584	23584

However, **no change in CO**

- Plausible hypothesis: Jikokoa stove does not sufficiently improve oxygen inflow; less oxygen means more CO, less CO_2

Panel A) All hours

	(1) Median	(2) Mean	(3) Max Hour	(4) 99th
Own Jikokoa	-0.5	1.9	19.9	24.6
	(0.4)	(1.6)	(12.7)	(15.1)
Control mean	1.8	6.3	48.2	60.2
N	656	656	656	656

Panel B) When self-reporting cooking

	(1) Median	(2) Mean	(3) Max Hour	(4) 99th
Own Jikokoa	0.8	2.5	11.9	10.3
	(2.9)	(3.9)	(10.8)	(15.0)
Control mean	5.0	10.6	28.7	43.9
N	609	609	609	609

'Cooking hours': 9% (time use survey). N=607. Weak IV F-statistic = 49. All regressions use IV with randomized subsidies and credit as instruments.

The reduction in peak PM2.5 cooking levels is big

- Median (ambient) concentration is $25\mu g/m^3$ (AQI 75)
- Peak control group exposure concentration reaches $147\mu g/m^3$ (AQI 200) when cooking (a $122\mu g/m^3$ increase)
- Jikokoa reduction of $49\mu g/m^3$ is **40%** of this increase
  - Matches the charcoal spending decrease in Berkouwer & Dean (2022): PM2.5 is proportional to charcoal use

Health impacts

- Large reduction in PM2.5 peaks during cooking
- No impact on aggregate average PM2.5 pollution exposure
- Persistent effects over three years

How does this affect health?

Today

Health symptom indices: respiratory & non-respiratory

- Split pre-specified in analysis plan
- Unlikely to be experimenter demand: no correlation with subsidy

	Control Mean	Treatment Effect	N
Health symptoms index (z-score)	0.00	-0.15	702
	[1.00]	(0.16)	
Number of health symptoms	2.78	-0.72*	702
	[2.93]	(0.42)	
Non-respiratory health symptom index	-0.00	-0.03	702
	[1.00]	(0.19)	
Number of non-respiratory health symptoms	1.09	-0.24	702
	[1.54]	(0.25)	
Respiratory health symptom index	-0.00	-0.24*	702
	[1.00]	(0.13)	
Number of respiratory health symptoms	1.70	-0.48**	702
	[1.76]	(0.23)	

Reductions in sore throat, headache, cough, runny nose

	Control Mean	Treatment Effect	N
Respiratory health symptom index	-0.00	-0.24*	702
	[1.00]	(0.13)	
Number of respiratory health symptoms	1.70	-0.48**	702
	[1.76]	(0.23)	
Persistent cough	0.24	-0.09	702
	[0.43]	(0.07)	
Always feeling tired	0.30	-0.07	702
	[0.46]	(0.07)	
Breathlessness at night	0.08	-0.01	702
	[0.27]	(0.04)	
Frequent diarrhea	0.02	-0.02	702
	[0.15]	(0.03)	
Difficulty breathing / Chest tightness	0.07	-0.01	702
	[0.26]	(0.04)	
Runny nose	0.23	-0.05	702
	[0.42]	(0.07)	
Sore throat	0.16	-0.12*	702
	[0.37]	(0.06)	
Headache	0.52	-0.12	702
	[0.50]	(0.08)	
Wheezing	0.03	0.01	702
	[0.17]	(0.03)	
Persistent mucus problems	0.04	-0.01	702
	[0.19]	(0.02)	

Heterogeneity & robustness tests

- Ruling out experimenter demand:
    - Controlling for Jikokoa ownership, no correlation between subsidy and self-reported symptoms
    - Effect driven by pollution-related symptoms
- No heterogeneity by baseline health, beliefs about health, age, WTP, or background pollution
- Attrition not correlated with treatments or adoption status

No impact on quantitative health measures

	Control Mean	Treatment Effect	N
Blood oxygen	96.61	0.31	696
	[2.53]	(0.37)	
Average systolic blood pressure	122.16	0.49	696
	[18.97]	(3.30)	
Average diastolic blood pressure	81.32	0.58	696
	[11.73]	(2.15)	
Hypertension: Stage 1 or higher (>130/80)	0.51	0.02	696
	[0.50]	(0.09)	
Hypertension: Stage 2 or higher (>140/90)	0.27	-0.02	696
	[0.44]	(0.08)	

No impact on diagnoses

	Control Mean	Treatment Effect	N
Number of health diagnoses	0.30	0.13	702
	[0.58]	(0.09)	
Asthma	0.01	-0.01	702
	[0.08]	(0.01)	
Pneumonia	0.13	0.02	702
	[0.34]	(0.05)	
Chronic Pulmonary Disease	0.00	0.01	702
	[0.06]	(0.01)	
Tuberculosis	0.01	0.02	702
	[0.08]	(0.01)	
COVID	0.01	-0.01	702
	[0.08]	(0.01)	
Other lung disease	0.01	-0.01	702
	[0.08]	(0.01)	
Stroke or cardiovascular disease	0.01	-0.00	702
	[0.08]	(0.01)	
Hypertension	0.05	0.11***	702
	[0.22]	(0.04)	
Diabetes	0.02	-0.00	702
	[0.14]	(0.02)	
Other	0.04	0.01	702
	[0.19]	(0.03)	

No impact on cognitive function

	Control Mean	Treatment Effect	N
Cognitive index	-0.00	-0.01	587
	[1.00]	(0.15)	
Working memory (Corsi)	-0.00	-0.48**	305
	[1.00]	(0.22)	
Attention (d2)	0.00	-0.09	564
	[1.00]	(0.15)	
Inhibitory control (HF - % correct)	-0.00	0.18	516
	[1.00]	(0.16)	
Inhibitory control (HF - reaction time)	0.00	0.14	516
	[1.00]	(0.19)	

No impact on health expenditures

	Control Mean	Treatment Effect	N
Non-hospital health expenditures (USD)	4.34	0.80	702
	[7.64]	(1.07)	
Hospital visits in past 30 days	0.33	-0.01	702
	[0.57]	(0.09)	
Hospital visit expenditures (USD)	3.39	1.03	702
	[11.17]	(1.48)	

No impact on children's outcomes

	Control Mean	Treatment Effect	N
Child weight (kg)	17.73	-1.02	224
	[7.57]	(1.80)	
Child height (cm)	98.59	6.02	199
	[31.07]	(6.08)	
Child arm circumference (cm)	16.37	1.24	220
	[7.26]	(1.41)	
Number of child health symptoms	1.19	0.34	343
	[1.50]	(0.40)	
Child health symptom index	0.00	0.32	343
	[1.00]	(0.29)	
Fever	0.18	-0.01	343
	[0.38]	(0.09)	
Vomiting	0.10	-0.01	343
	[0.30]	(0.06)	
Cough	0.40	0.03	343
	[0.49]	(0.12)	
Diarrhea	0.10	0.00	343
	[0.30]	(0.07)	
Breathlessness	0.04	0.08	343
	[0.19]	(0.06)	
Persistent headache	0.08	0.05	343
	[0.27]	(0.05)	
Very bad cough	0.25	0.10	343

Today

Moments of air pollution

1. Mean pollution exposure
2. Median pollution exposure
3. Peak pollution exposure (highest hourly average)
4. Duration of high pollution exposure
   "Hours above" 100 $\mu g/m^3$ (PM2.5)

Correlations between health and pollution (PM2.5)

	Mean SD	Mean Pollution (SD)	Median Pollution (SD)	Max Hourly Pollution (SD)	Hours Above $100\mu g/m^3$	N
	(1)	(2)	(3)	(4)	(5)	(6)
Hypertension (>130/80)	0.51	0.01	-0.02	0.00	0.00	645
	[0.50]	(0.02)	(0.02)	(0.02)	(0.01)	
Blood oxygen	96.72	0.12	0.12	-0.03	0.03	645
	[2.43]	(0.10)	(0.11)	(0.10)	(0.06)	
Health symptoms index (z-score)	-0.09	0.01	-0.01	0.07**	0.01	651
	[0.92]	(0.04)	(0.04)	(0.04)	(0.02)	
Number of health symptoms	2.52	0.02	-0.00	0.23**	0.02	651
	[2.66]	(0.11)	(0.11)	(0.10)	(0.06)	
Health diagnoses index	-0.04	-0.04	-0.05	0.00	-0.03	651
	[0.89]	(0.04)	(0.04)	(0.04)	(0.02)	
Number of health diagnoses	0.29	-0.03	-0.02	-0.00	-0.02	651
	[0.56]	(0.02)	(0.03)	(0.02)	(0.01)	
Hospital visits in past 30 days	0.30	-0.01	-0.01	0.01	-0.00	651
	[0.55]	(0.02)	(0.02)	(0.02)	(0.01)	
Hospital visit expenditures (USD)	2.82	0.66	0.40	0.62	0.26	651
	[10.14]	(0.44)	(0.45)	(0.42)	(0.24)	

Conclusion

- **HAP:** 34% reduction in peak PM2.5 exposure from cooking, 0.23 SD reduction in self-reported respiratory symptoms
- No change in **AAP**, which dominates average exposure: no impacts on quantitative measurements or diagnoses
- More research needed to explore heterogeneity in air pollution:
  - Different causes (HAP v AAP)
  - Different impacts (short- and long-term exposure)
  - Require different policy interventions

Conclusion

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- More research needed to explore heterogeneity in air pollution:
  - Different causes (HAP v AAP)
  - Different impacts (short- and long-term exposure)
  - Require different policy interventions
- Large climate & financial benefits continue: mitigation at $4 per ton plus private savings of $86 per year

Thank you!

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