The Long-run Development Impacts of Agricultural Productivity Gains: Evidence from Irrigation Canals in India

Sam Asher
Imperial College London

Alison Campion
Tufts University

Doug Gollin
University of Oxford

Paul Novosad
Dartmouth College

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Overview

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  - Schultz (1953): The food problem
  - Johnston-Mellor (1961): Linkages with non-agricultural sectors
  - Matsuyama (1992): Effects depend on openness of economy

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  - Schultz (1953): The food problem
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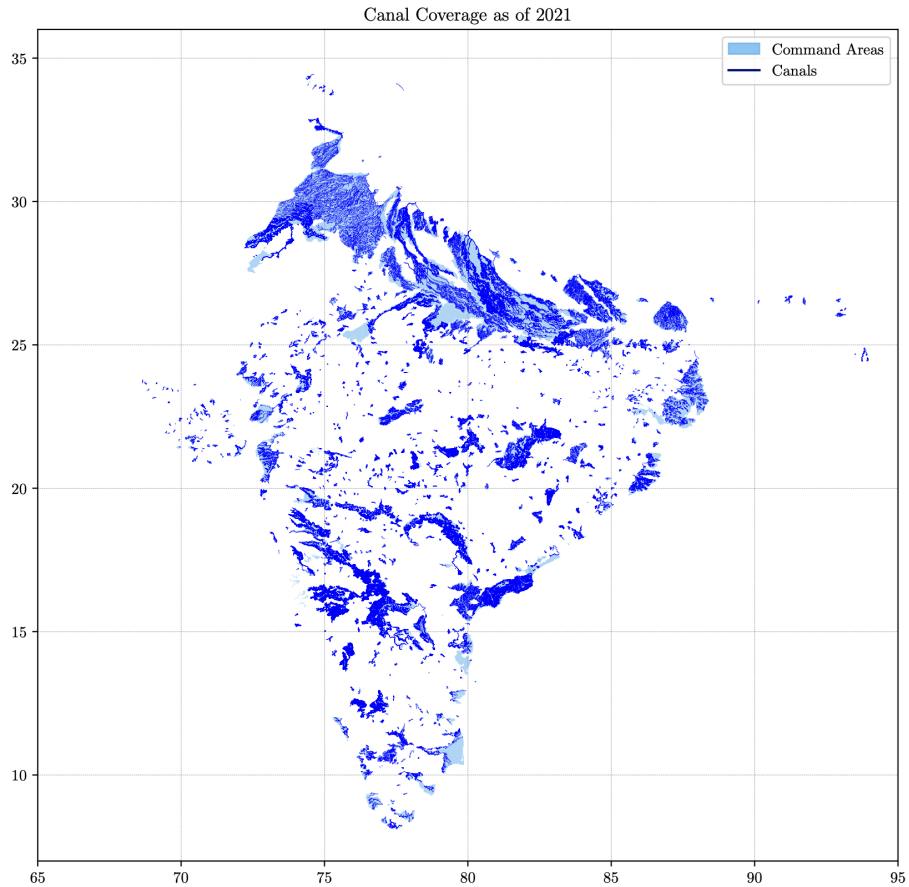
  - Matsuyama (1992): Effects depend on openness of economy
- Modern empirical literature building well-identified body of evidence:
  - Foster and Rosenzweig (1996, 2004): GR villages defer industrialization
  - Gollin, Hansen, & Wingender (2019): National GR increased national GDP
  - Hornbeck & Keskin (2015): Only temporary non-agricultural gains
  - Bustos et al (2016): Industrialization with labor-saving technical change
  - Bustos et al (2020): Industrialization in towns due to capital

Canals as agricultural productivity shock

We study the long-run effects of India's irrigation canals

- Large scale: 300,000 km serving 130k villages
- Long run: generate sustained differences in agricultural productivity across otherwise similar places
    - Most constructed over 40 years ago
- Seasonal: mostly deliver water during dry winter (*Rabi*) growing season



Irrigation canals in India

- High variance of rainfall makes irrigation desirable
- British Raj invested heavily in canal infrastructure, high priority for early independent India
- Dominant irrigation source until rise of groundwater

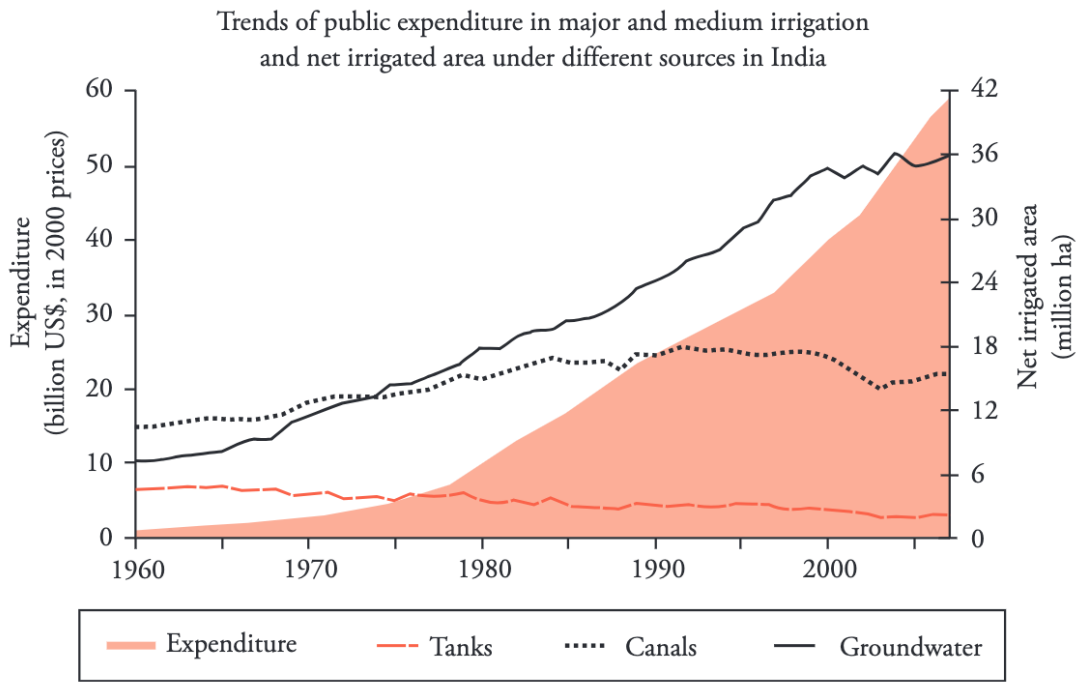


FIGURE 6.1 Accelerating Investment and Decelerating Irrigation Benefits

Source: IWMI (2009).

Canal Construction

Not the Suez Canal!

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This paper

Goal: Estimate the impact of access to canal irrigation

- Assemble settlement-level (village/town) data on irrigation, agricultural and non-farm activity, demographics, and living standards (N=600k)

Three identification strategies estimate different LATEs

1. *Direct:* Exploit gravity-driven nature of surface irrigation in elevation-based RDD
2. *Spillovers:* Analyze spillover effects by comparing to matched distant settlements
3. *Regional:* Exploit timing of canal construction to estimate effects on regional urbanization

Preview of results

Access to canal irrigation causes:

1. Increase in irrigation and agricultural productivity
2. Migration into irrigated areas, significantly increasing population density
3. But...
    - Long-run consumption gains only for landowners
    - No effects on rural industrialization
4. Regional urban growth

Preview of results

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3. But...
    - Long-run consumption gains only for landowners
    - No effects on rural industrialization
4. Regional urban growth

In the long-run,

- Productivity gains are equilibrated by labor flows across space
- Structural change occurred via concentrated urban growth

Empirical strategy

Consider two similar settlements

Empirical strategy

Canal construction gives the lower settlement access to irrigation

Empirical strategy

Improved irrigation leads to greater agricultural productivity

Direct effects: RDD strategy

1. What economic changes do we observe in the canal settlement?

Test: RDD to compare to nearby higher settlement

Spillovers: distant settlements

2. Do we observe spillovers to nearby villages without canal access?

Test: compare both to more distant settlement

Regional urbanization: nearby towns

3. Do we observe growth of regional urban areas?

Test: Difference-in-difference of urban growth and canal construction through time

Data

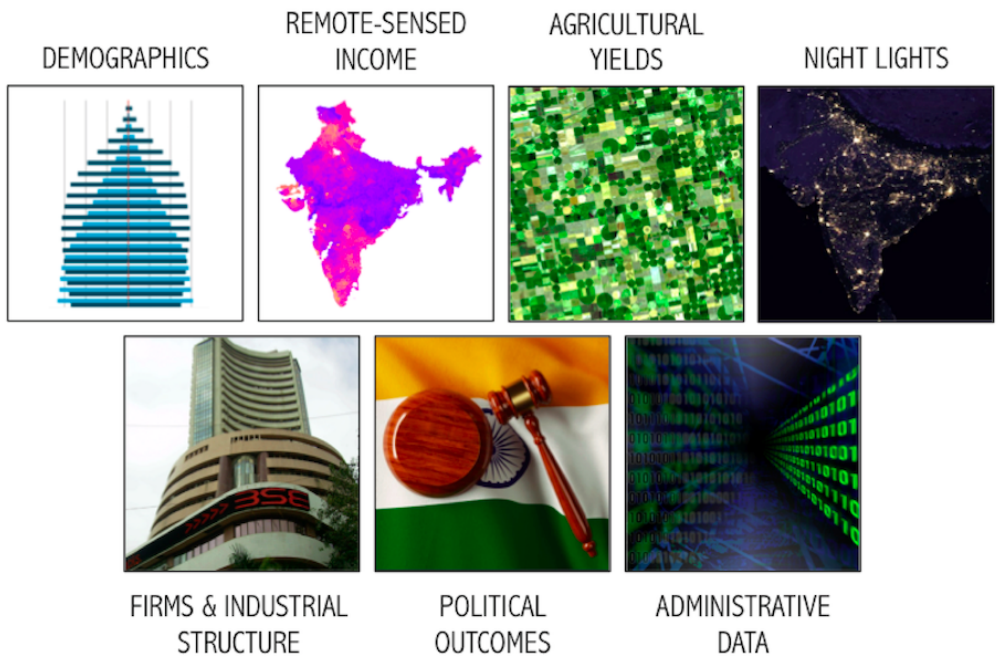
- SHRUG village/town-level data as backbone (N=600,000)
- Irrigation
  - WRIS: canal lines, command area polygons, construction dates
  - GIS: settlement lat/long, elevation $\rightarrow$ distance to nearest canal, command area; relative elevation
  - Pop Census: acres irrigated by source (canal, groundwater, other)
- Agriculture
  - Productivity: EVI (satellite, by growing season)
  - Crop choice (Pop Census), mechanization (SECC)
- Nonfarm outcomes
  - Nonfarm activity (Economic Census, 2013)
  - Population, etc; town pop panel, 1901-2011 (Population Census)
  - HH microdata: predicted consumption (SAE), land, education (SECC)
- Other
  - Potential productivity (FAO GAEZ)
  - GIS: rivers, ruggedness

EVI SAE

Data Backbone: The SHRUG

The Socioeconomic High-res Rural-Urban Geographic data platform for India

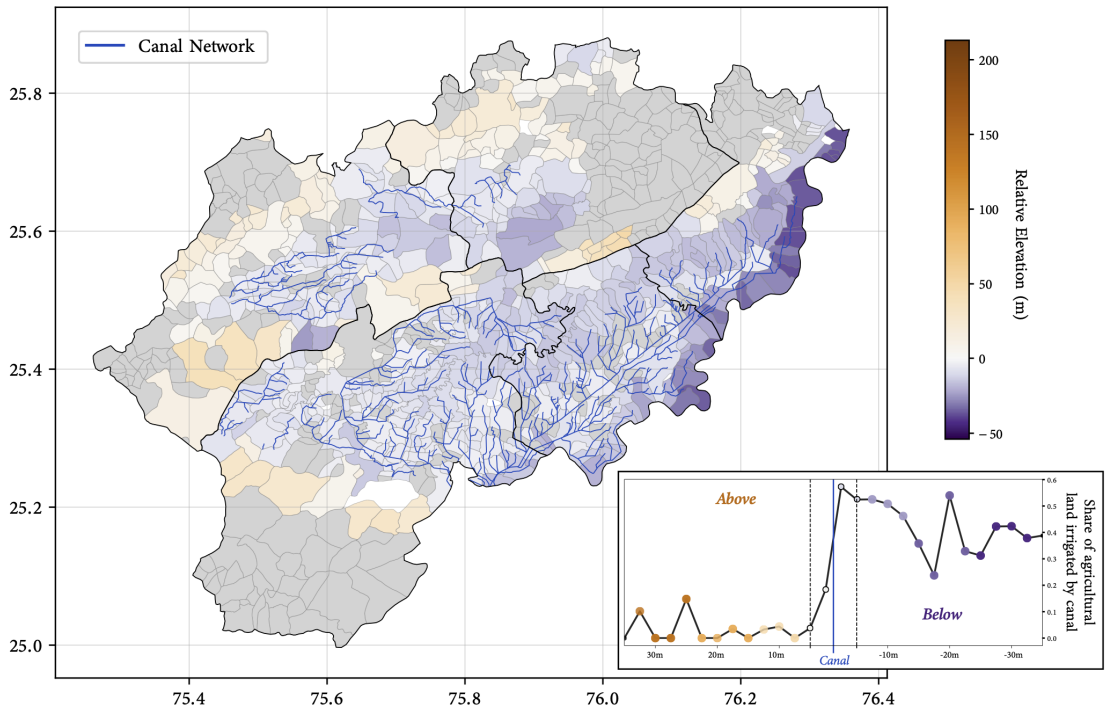
- High resolution aggregation of remote sensing and administrative data
- 600,000 villages, 8000 towns, 4000 ACs from 1990 to the present all standardized to a common geographic unit (shrid)
- Open access at `http://devdatalab.org/shrug`
- SHRUG 2.0 coming soon: GIS, PCs, much more data



RD specification

$$y_{i,s} = \beta_0 + \beta_1 1\{REL\_ELEV_{i,s} > 0\} + \beta_2 REL\_ELEV_{i,s} + \beta_3 REL\_ELEV_{i,s} * 1\{REL\_ELEV_{i,s} > 0\} + \beta_4 X_{i,s} + \nu_s + \epsilon_{i,s}$$

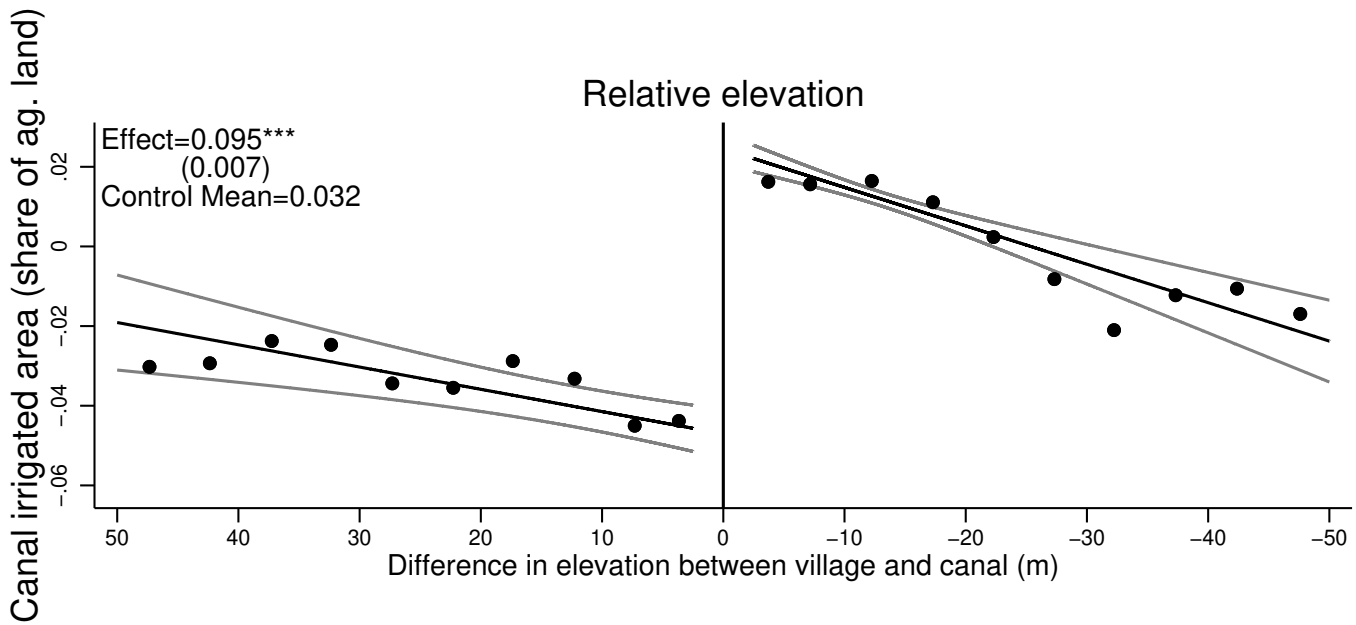
- $y_{i,s}$: outcome in settlement i, subdistrict s
- $REL\_ELEV_{i,s}$: canal elevation minus settlement elevation
- $X_{i,s}$: geographic fundamentals*
- ν_s: subdistrict fixed effect, SEs clustered by subdistricts



* ruggedness, rainfall, temperature, distance to river, distance to coast, GAEZ crop suitability for rice and wheat

Measuring Relative Elevation

Regression discontinuity: canal irrigation

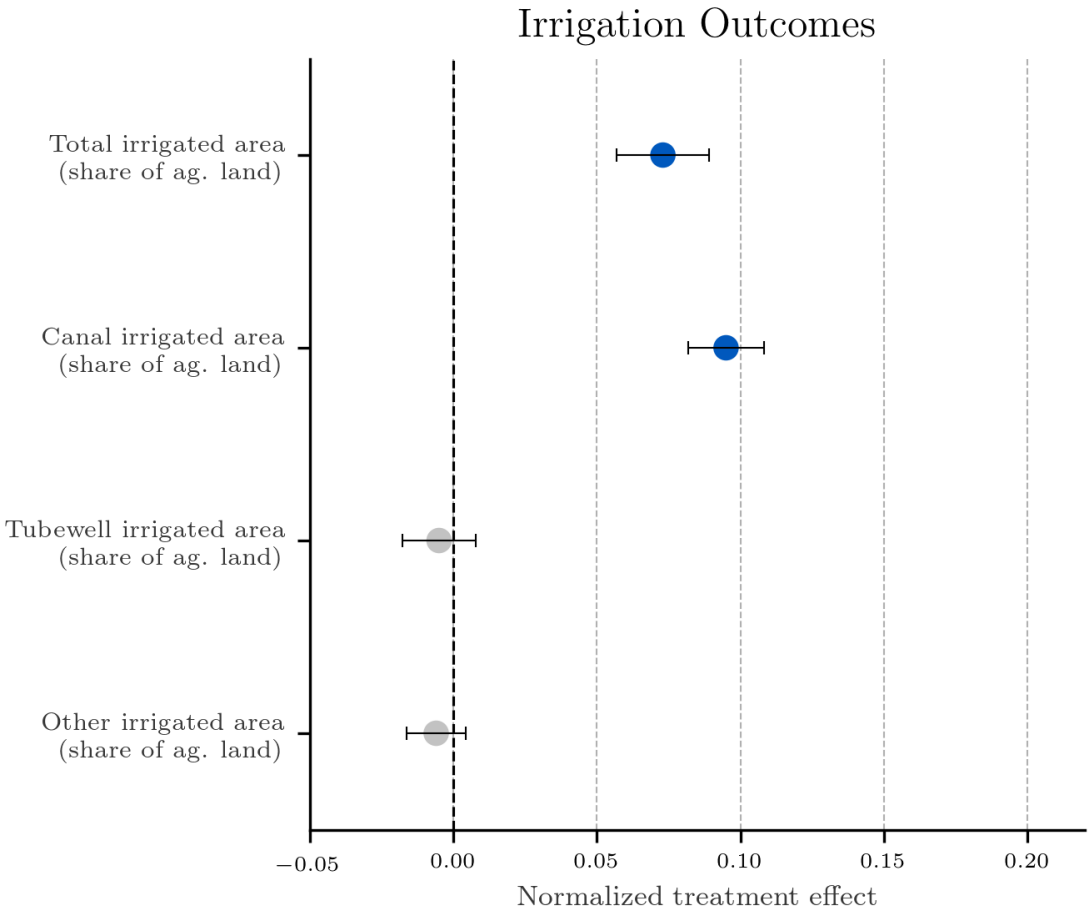


Analysis Sample:

- Settlements $<$10km from canal branch, $\pm$50m elevation from nearest point on canal
- Excluded 2.5m “donut hole” around canal
- Limit to subdistricts with balanced ruggedness (within 25%)

Balance Table

Results: irrigation outcomes



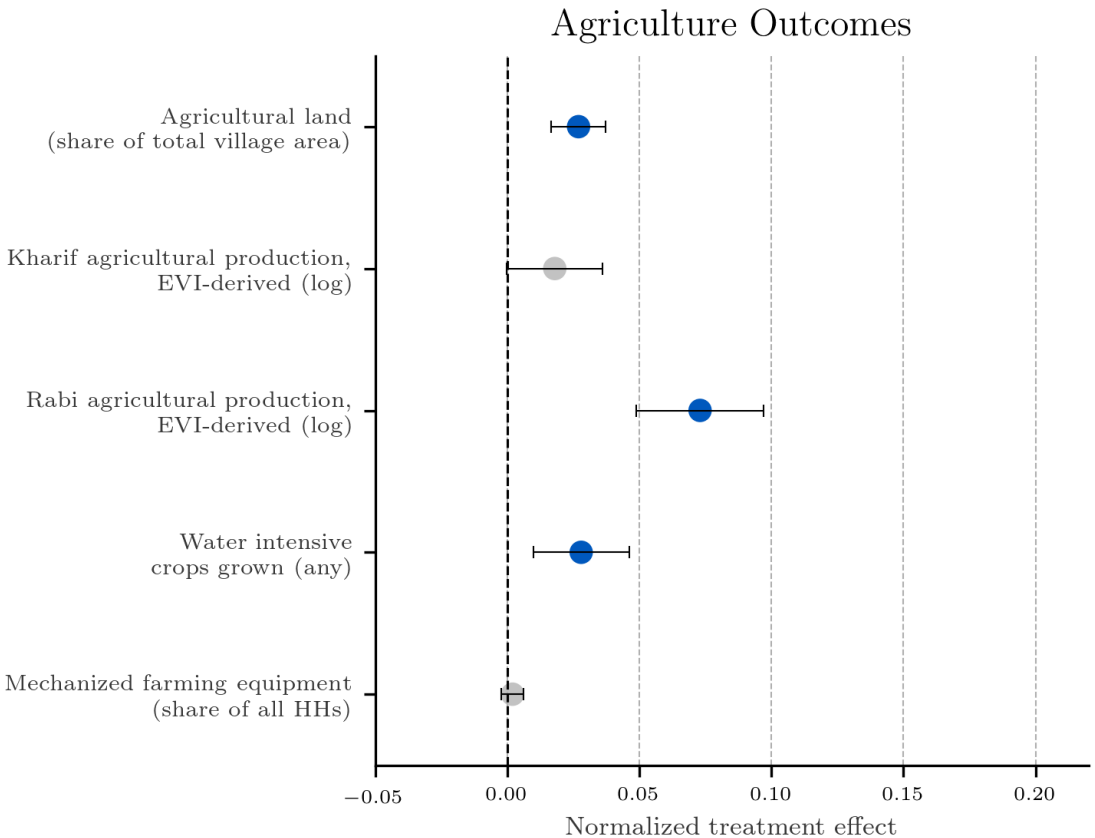
All treatment effects normalized with control group mean and SD

Canal settlements have:

- More irrigated land...
- ...driven by more canals
- No changes in other methods of irrigation

Binscatters Table

Results: agricultural outcomes

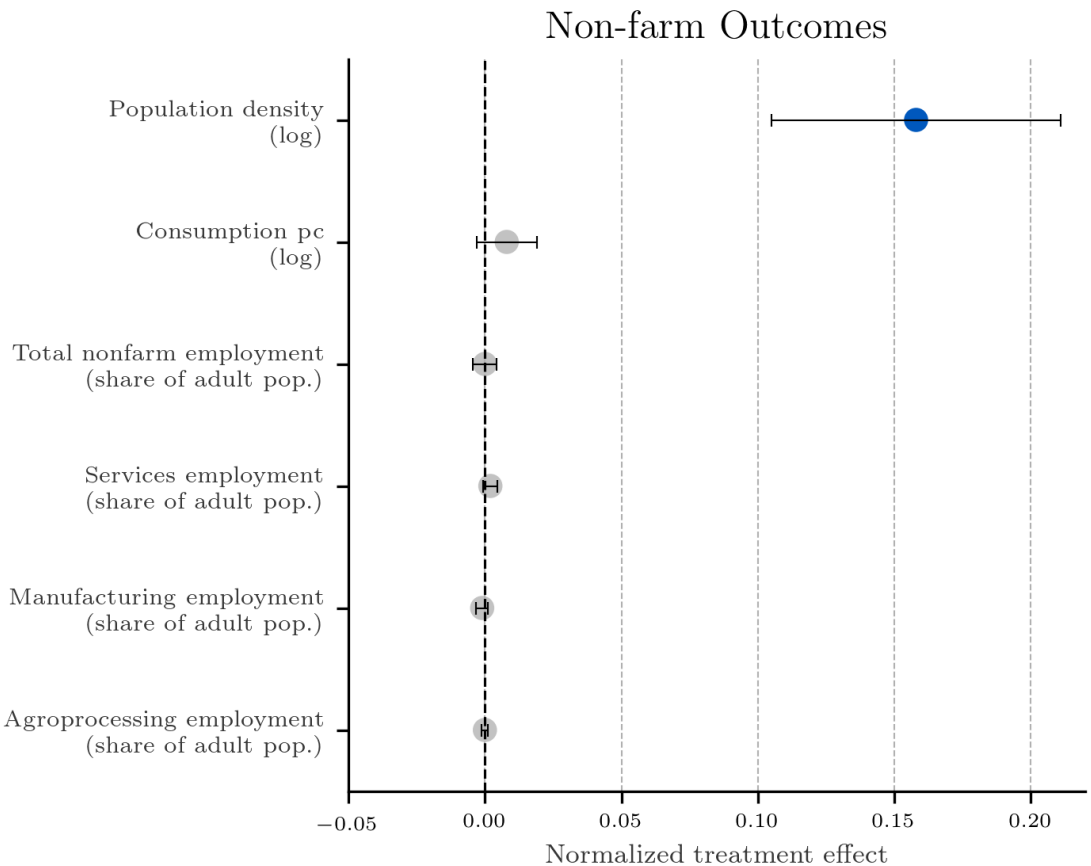


Canal settlements have:

- More agricultural land
- Greater dry season agricultural productivity
- Higher prob of water-intensive crops

Binscatters Table

Results: nonfarm outcomes

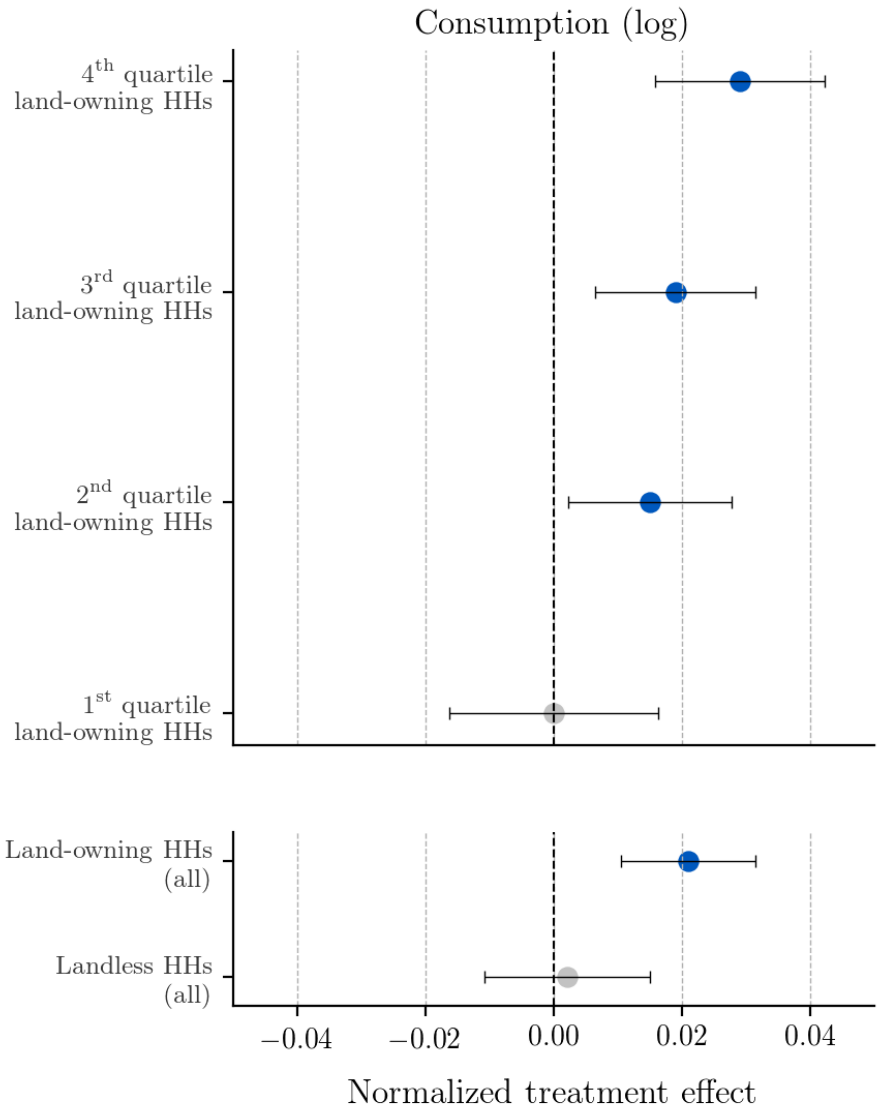


Canal settlements have:

- No effect on nonfarm employment of any type
- Higher population density
- Population increase driven by migration (evidence from NSS)

Binscatters Table

Differential returns to land and labor



- Benefits are limited to land owners, increasing in landholding size
- Productivity gains accrue to the fixed factor

Table

Robustness checks

1. All canal-area settlements Table Coefplot
2. All canal-area settlements, minus the donut hole Table Coefplot
3. Canal-area settlements balanced on ruggedness, using median settlement elevation Table Coefplot
4. Canal-area settlements balanced on ruggedness, using 25^{th} percentile settlement elevation Table Coefplot
5. Main analysis sample, excluding villages intersected by a canal Table Coefplot
6. Main analysis sample, with additional control on distance to canal Table Coefplot
7. Main analysis sample, restricted to straight canals (> 10km, sinuosity < 1.2) Table
8. Alternative identification strategy: spatial RDD using command area boundary Table Coefplot

Spillover effects

There are many reasons why canal effects may not be strictly localized:

- Groundwater recharge
  - Though we find zero effect on pump usage
- Labor and goods could flow between upstream and downstream villages
- Capital could flow to nearby towns / villages as in Bustos et al. (2020)
- Canals could create comparative disadvantage in agriculture for nearby villages

Spillovers: comparing with distant settlements

Estimating equation:

$$y_{i,d} = \beta_1 T_{i,d} + \beta_2 D_{i,d} + X_{i,d} + \nu_d + \epsilon_{i,d}$$

- $T_{i,d}$: indicator for settlements **below** the canal
- $D_{i,d}$: indicators for settlements **distant** from the canal

Spillovers: comparing with distant settlements

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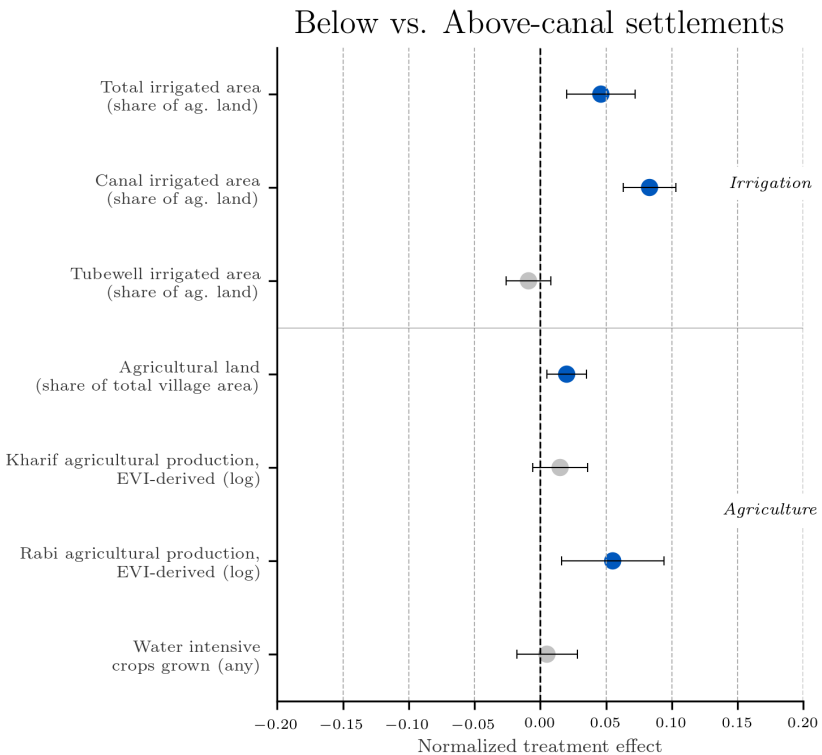
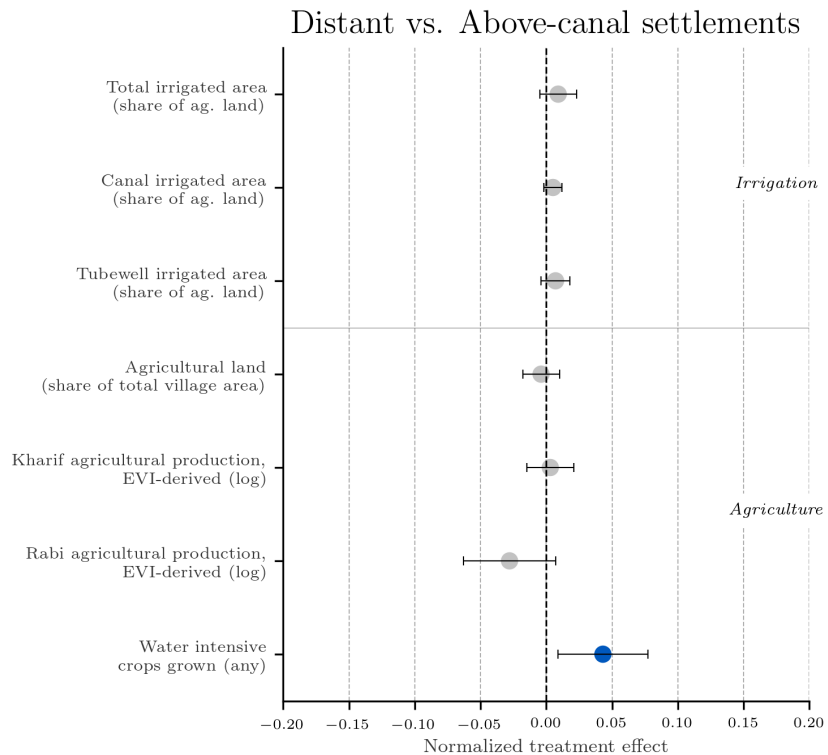
- $T_{i,d}$: indicator for settlements **below** the canal
- $D_{i,d}$: indicators for settlements **distant** from the canal
- $X_{i,d}$: Time-invariant geographic controls (rainfall, ruggedness, distance to river, distance to coast, and GAEZ crop suitability for rice and wheat)
- ν_d: District fixed effects
- Weighting: entropy balancing (Hainmueller, 2012)

Results: spillovers in irrigation and agriculture outcomes

β_1 : *Replicating RDD*



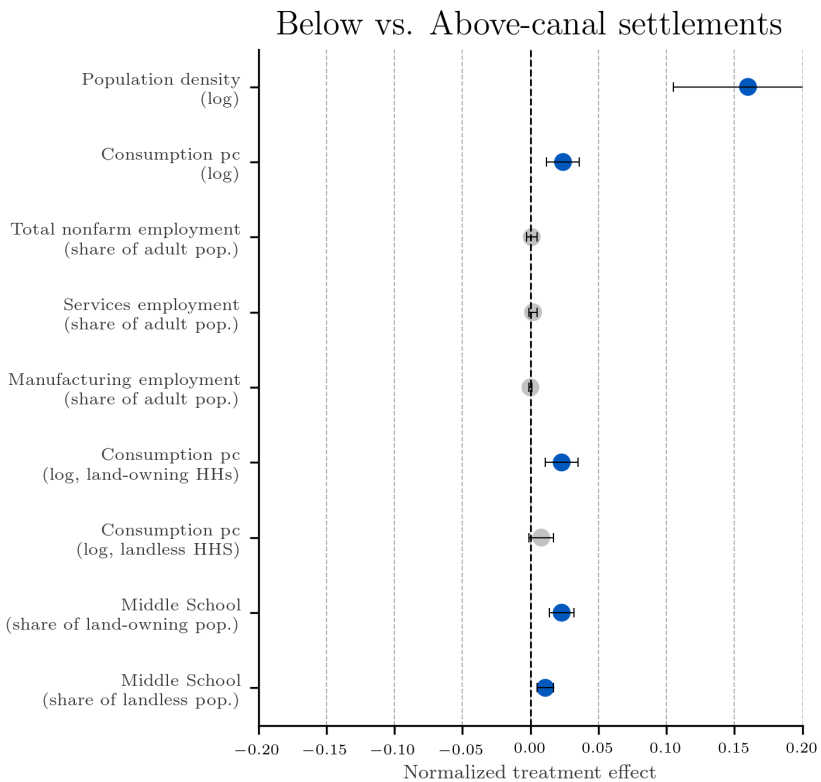
β_2 : *Spillovers*



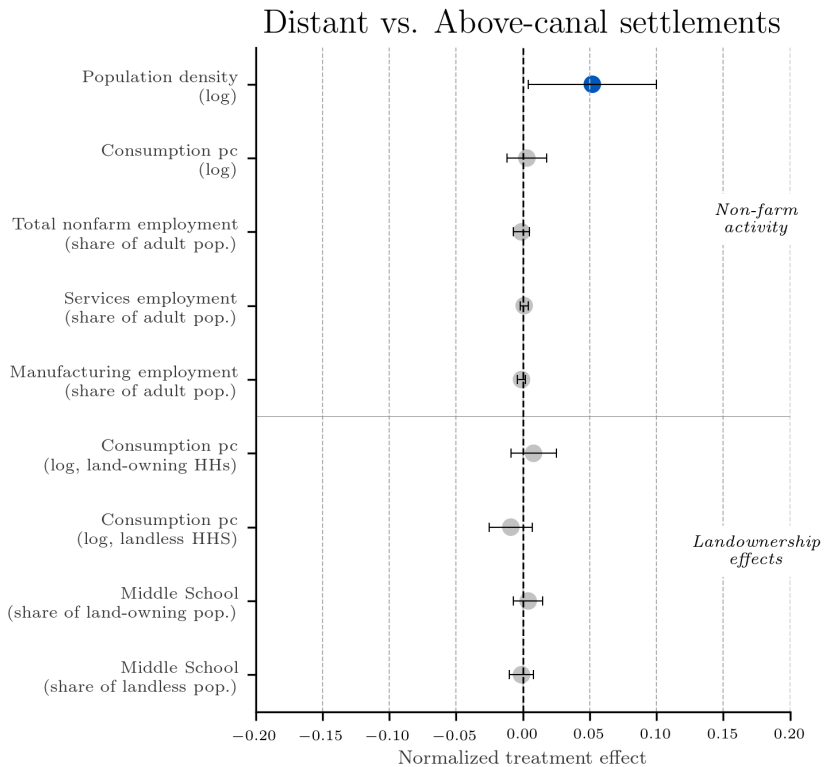
Regression Table

Results: spillovers in non-agricultural outcomes

β_1 : *Replicating RDD*



β_2 : *Spillovers*

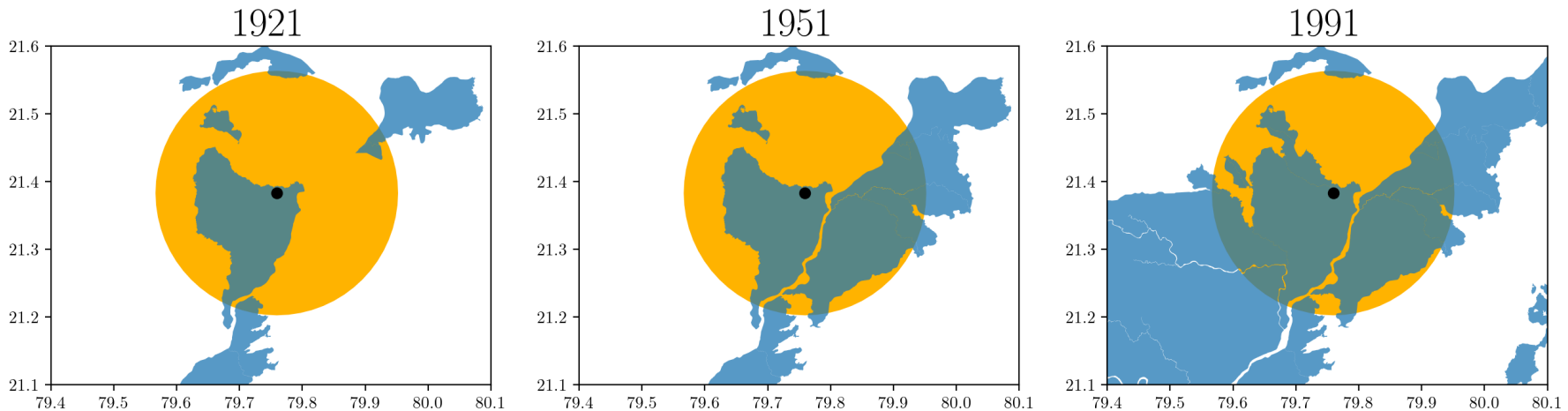


Regression Table

Diff-in-diff: effects on regional urban growth

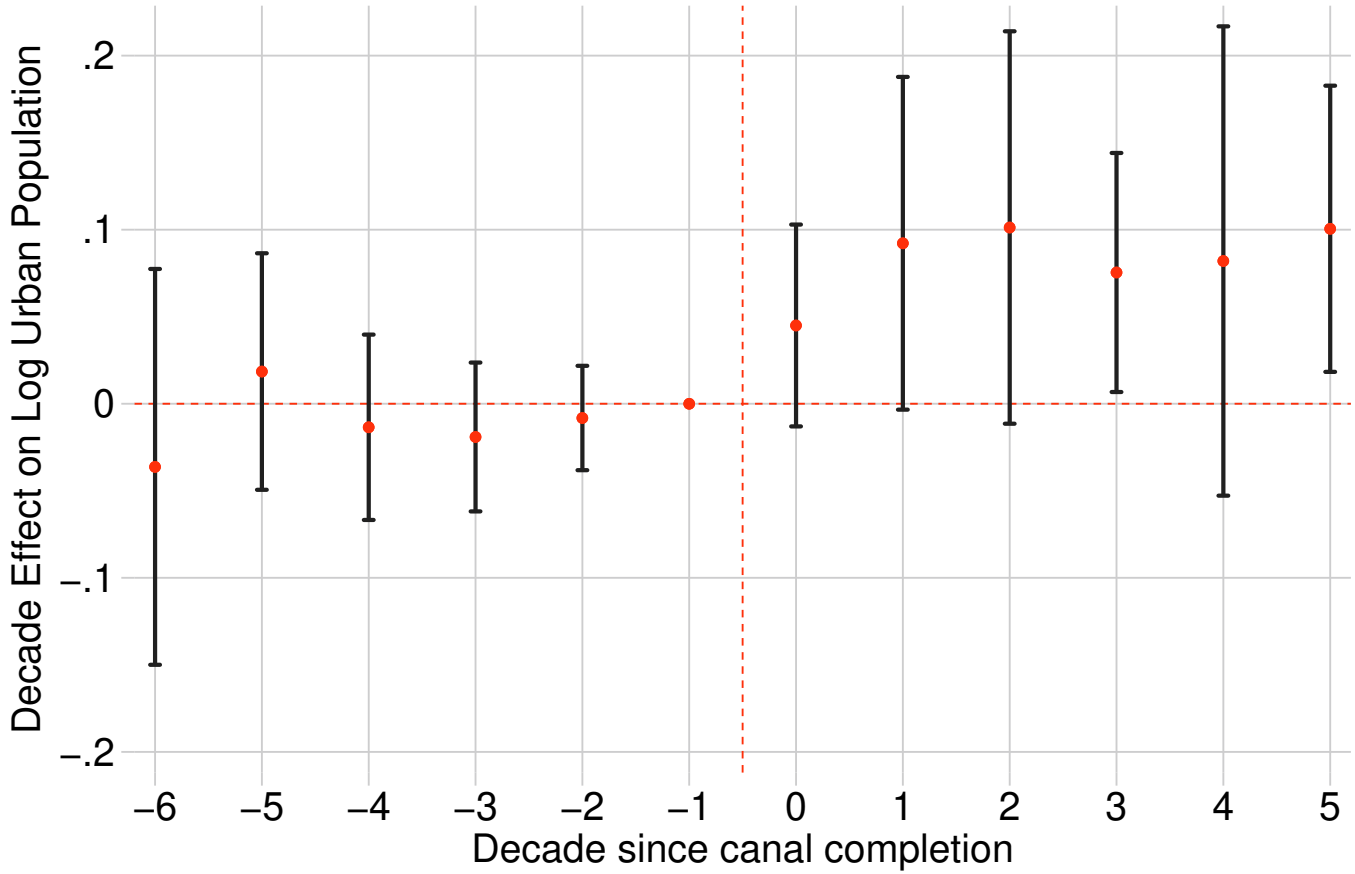
No rural industrialization, what about regional urban growth?

- Town panel data: population of from every decadal census since 1901
- Estimate DID_M following de Chaisemartin and D'Haultfoeuille (2020)
- Treatment: share of town's surrounding area served by canals



Diff-in-Diff results

Effect of canal construction on urban population growth:



Diff-in-diff results

Effect of canal construction on town appearance by size:

Panel B. Town appearance

	Pop. 5000		Pop. 10,000		Pop. 50,000		Pop. 100,000		Pop. 500,000	
Command area in town catchment area	0.032***		0.041***		0.015**		0.005		-0.001	
(binary treatment)	(0.013)		(0.016)		(0.007)		(0.004)		(0.001)	
Share of town catchment area in command area		0.079***		0.101***		0.040***		0.016*		-0.004
(continuous treatment)		(0.018)		(0.021)		(0.012)		(0.009)		(0.002)
Observations	302691	64260	302691	64260	302691	64260	302691	64260	302691	64260
R^2		0.700		0.650		0.520		0.470		0.350

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$

Robustness

How large are these population movements?

Canals drove both rural-rural and rural-urban migration.

- Assumptions
  - Net population flows are migration
  - Long-run urban pop effect: 10.3%
    - Urban effects only apply to cities under 100k people
  - Long-run rural pop effect (combining direct and spillovers): 16% and 5%

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- Total population flows
  - Urban: 5 million
  - Rural: 29 million

- Perspective:
  - 17 million displaced due to Partition (Bharadwaj et al, 2008)
  - 6 million Black people moved north in US Great Migration
  - 13 million emigrated from Italy 1880-1915

Conclusion

Canals created long-run differences in agricultural productivity

- In the long run, productivity effects of canals were equilibrated by labor flows across *space* rather than across *sectors*
- Structural change was concentrated in urban areas, not directly in rural areas receiving canal water
- Sustained living standard changes concentrated among landowners
    - Relevant distributional effects even if there are unobserved aggregate gains to landless

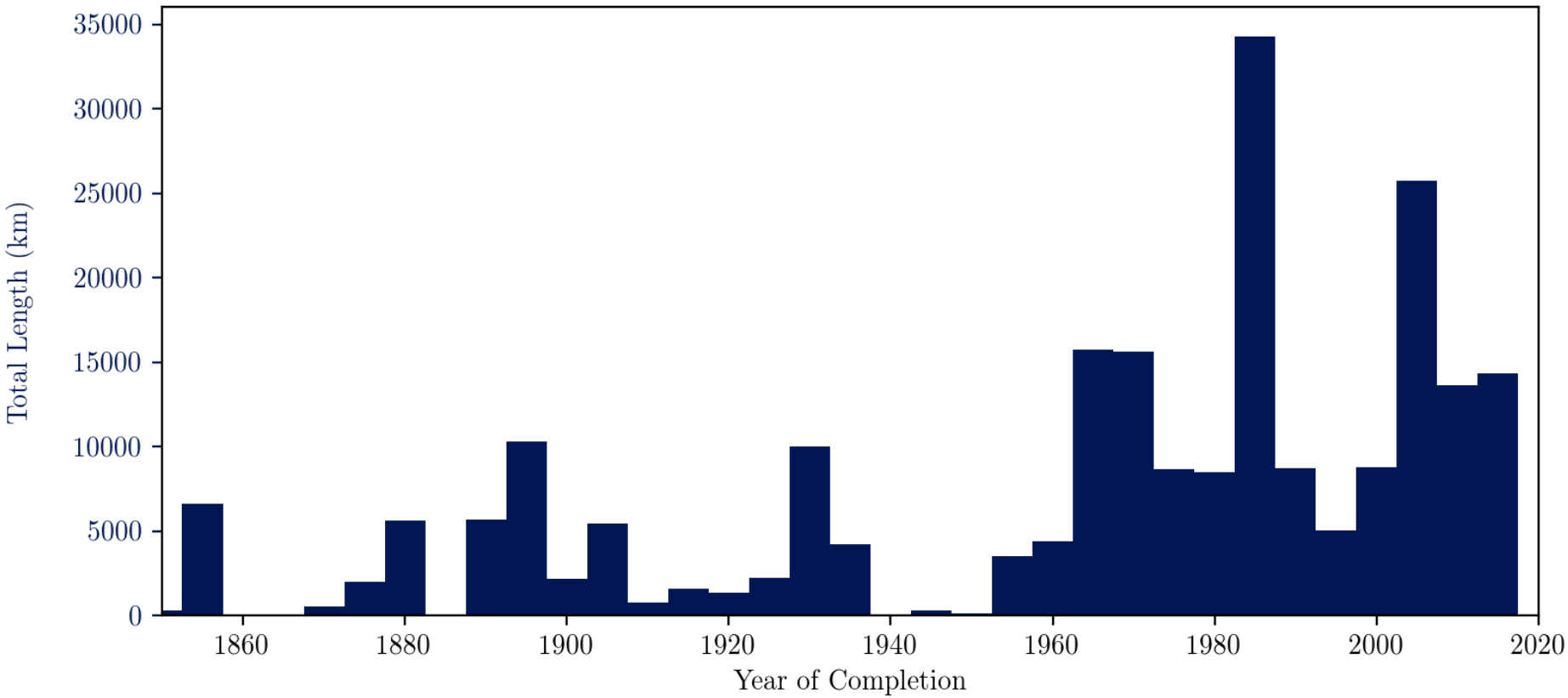
Conclusion

Some implications:

- In the long run, development generally entails substantial movement across space
- Rural infrastructure may not lead to in situ transformation
- Removing barriers to flows of labor to cities may be a more effective driver of structural change than bringing jobs to villages

APPENDIX

Canal completion in our data



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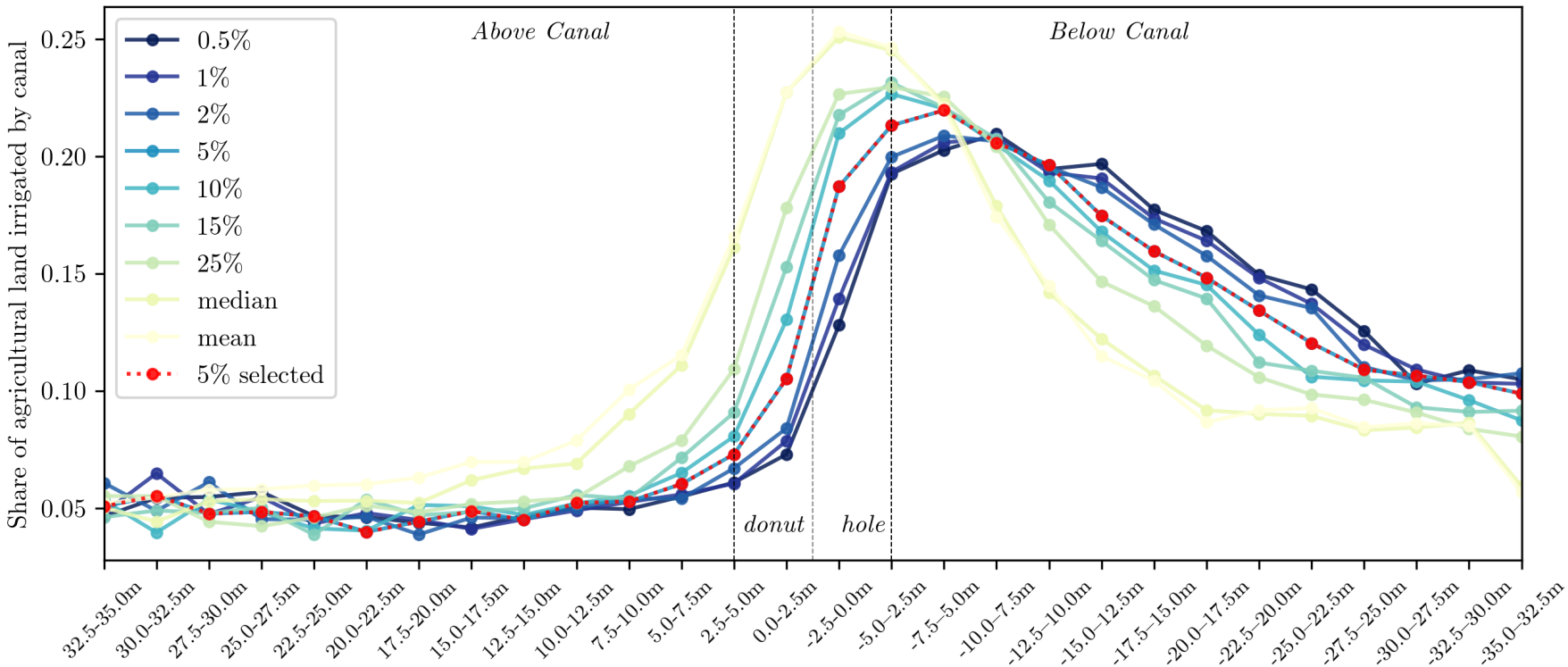
Measuring relative elevation



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Balance on geographic variables

	Ruggedness (TRI)	Annual rainfall avg. 2010-2014 (mm)	Max monthly temp. avg. 2010-2014 (°C)	Soil quality
Below canal	0.053	-0.402	0.037***	0.005
	(0.068)	(1.576)	(0.008)	(0.007)
Control group mean	4.809	1049.216	32.540	0.841
Observations	84,763	84,763	84,763	84,763
R^2	0.63	0.99	0.98	0.55

	Distance to coast (km)	Distance to river (km)	Wetland rice (GAEZ)	Wheat (GAEZ)
Below canal	-0.177	-1.481***	0.000	0.000
	(0.387)	(0.341)	(0.012)	(0.004)
Control group mean	328.402	24.293	2.119	0.547
Observations	84,763	84,763	84,763	84,763
R^2	1.00	0.88	0.93	0.98

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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Balance on 1951 village characteristics

	Population	Sex ratio	Population density (log)	HH size	Literacy rate
Below canal	7.267	0.090	-0.249	-0.363	0.033
	(78.010)	(0.215)	(0.353)	(0.335)	(0.067)
Control group mean	570.897	1.492	-4.816	4.818	0.338
Observations	4,172	4,039	820	767	402
R^2	0.24	0.22	0.36	0.31	0.24

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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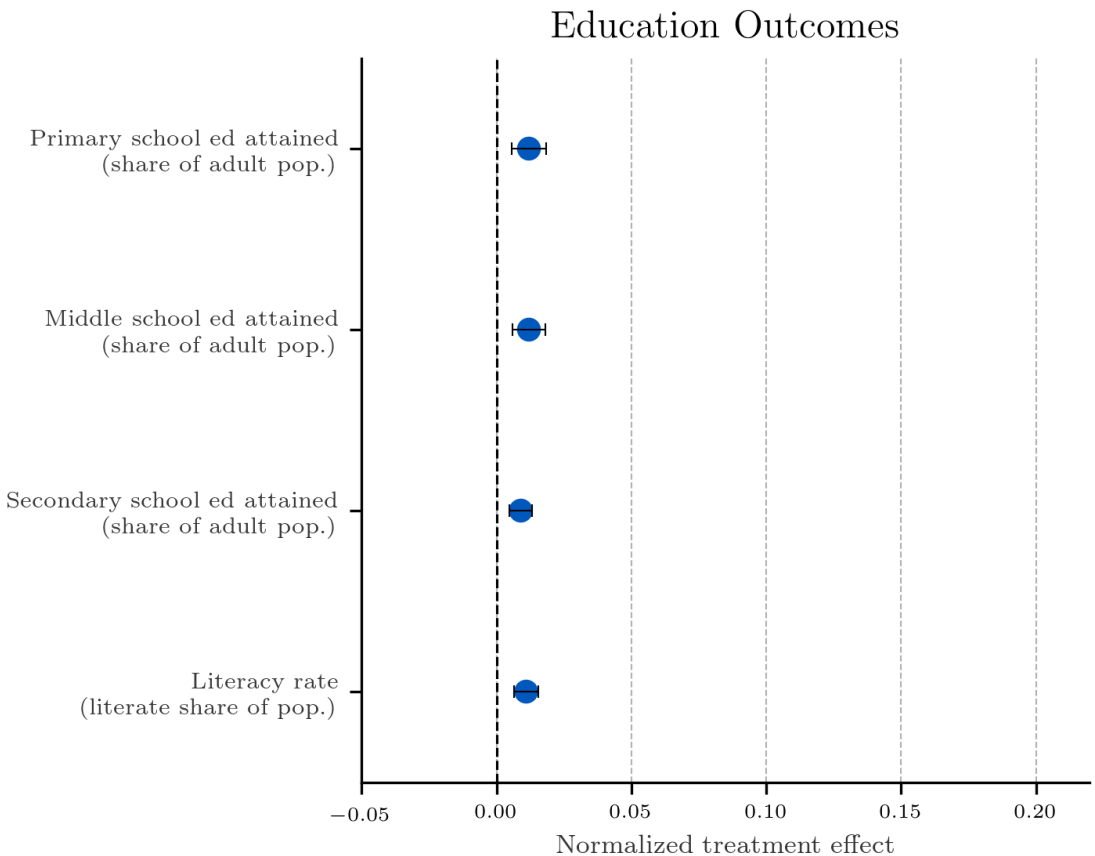
Results: education outcomes



Canal settlements have:

- Higher rates of primary, middle, and secondary school education
- Higher literacy rate

Binscatters Table

Model sketch: setup

We build on standard models in this literature (Matsuyama 1992, Bustos 2016) but allow for labor mobility in the long run

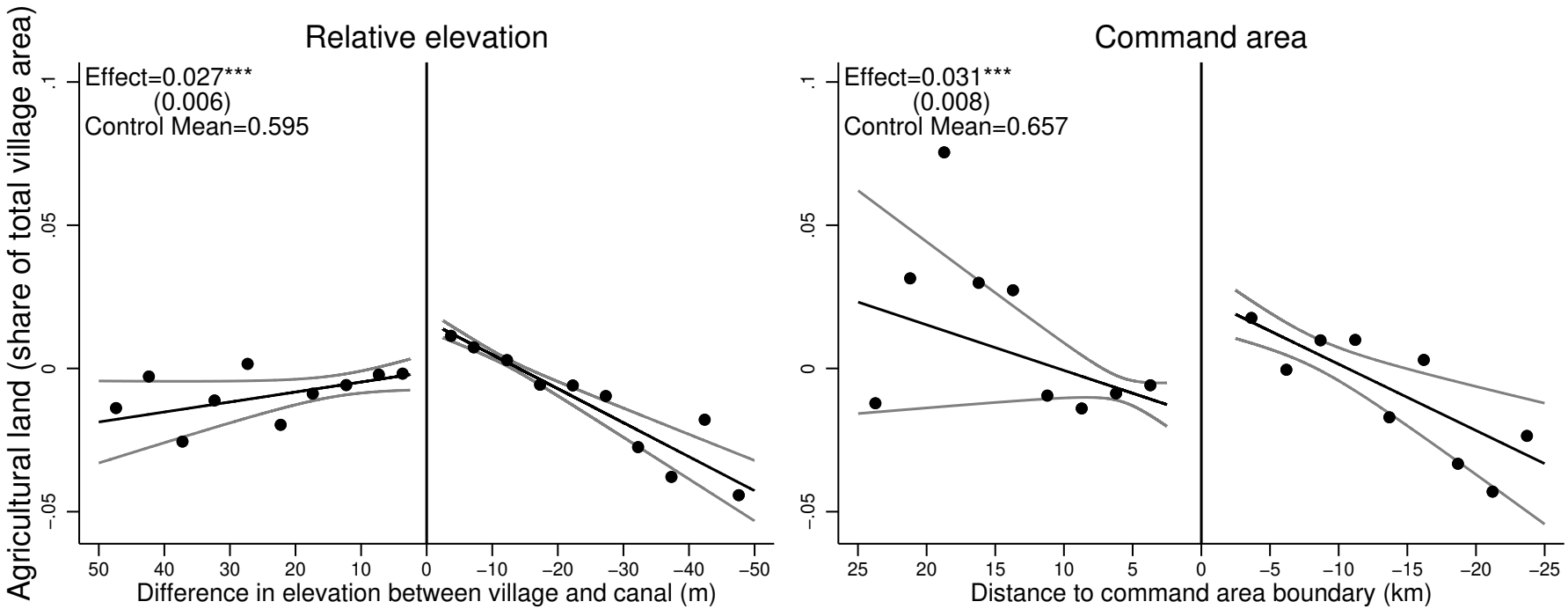
- Local rural economy embedded in larger national economy
  - Two types of locations: V villages, one town
  - Villages endowed with land, labor; town only labor
- Production
  - Agriculture (a): $Y_a = A\left(N_a\right)^{\theta} L^{1-\theta}$, p_a fixed
  - Local non-tradeable (c): $Y_c = CN_c$, p_c endogenous
  - Fully tradeable (m): produced in outside world (gasoline, etc), p_t fixed
  - Urban areas have productivity advantage that makes them sole location for production of local non-tradeable
- Labor: supplied inelastically, mobile only within region in the short run, across regions in long run
- Utility: Cobb-Douglas

$$u(a, c, m) = \alpha ln(a) + \beta ln(c) + (1 - \alpha - \beta) ln(m)$$

Model sketch: predictions

- Period 0: spatial equilibrium across sectors and regions at reservation utility $\bar{u}$
- In the SR, shocks get equilibrated by wage increase and flows across villages/towns
    - Labor flows out of non-canal villages towards ag in canal villages and non-ag in town
- In the LR, equilibration is through labor movement into the region
    - Sufficient labor inflows wipe out the entire short run wage gains
    - Spillover effects onto urban areas due to increase in demand for local non-tradeable

Extensification



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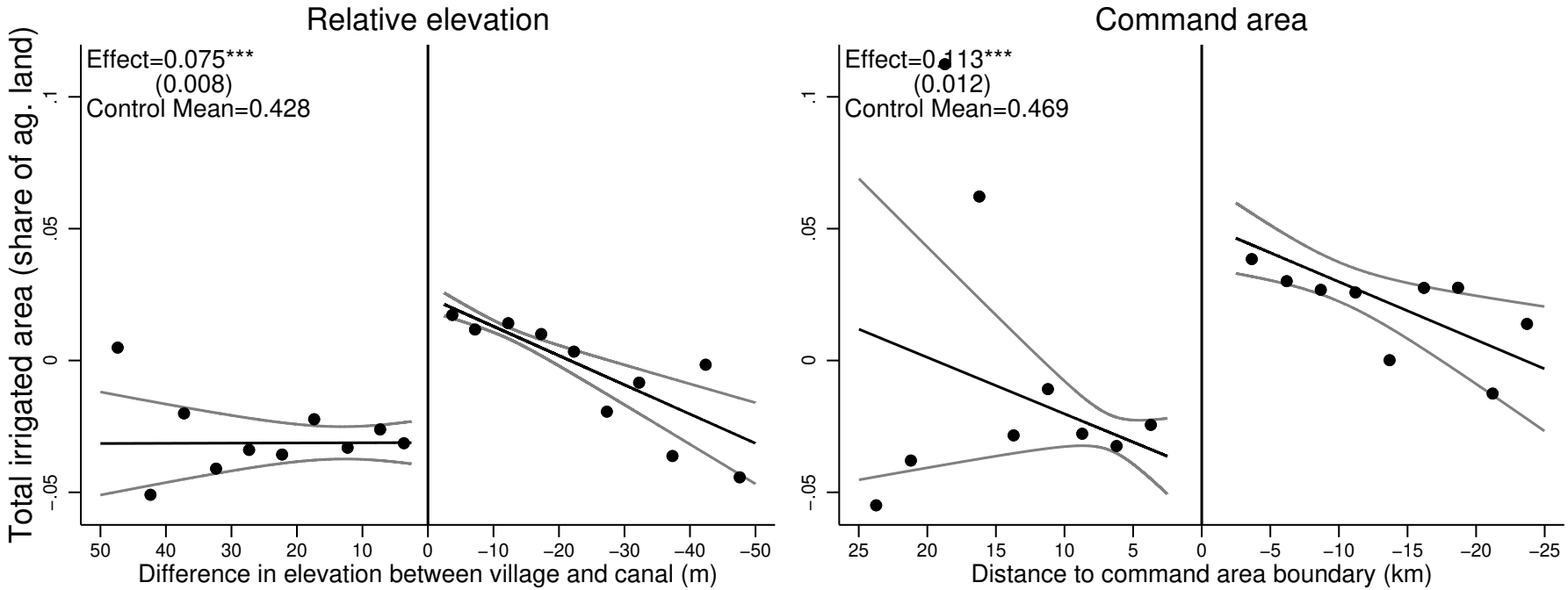
Irrigation (any)



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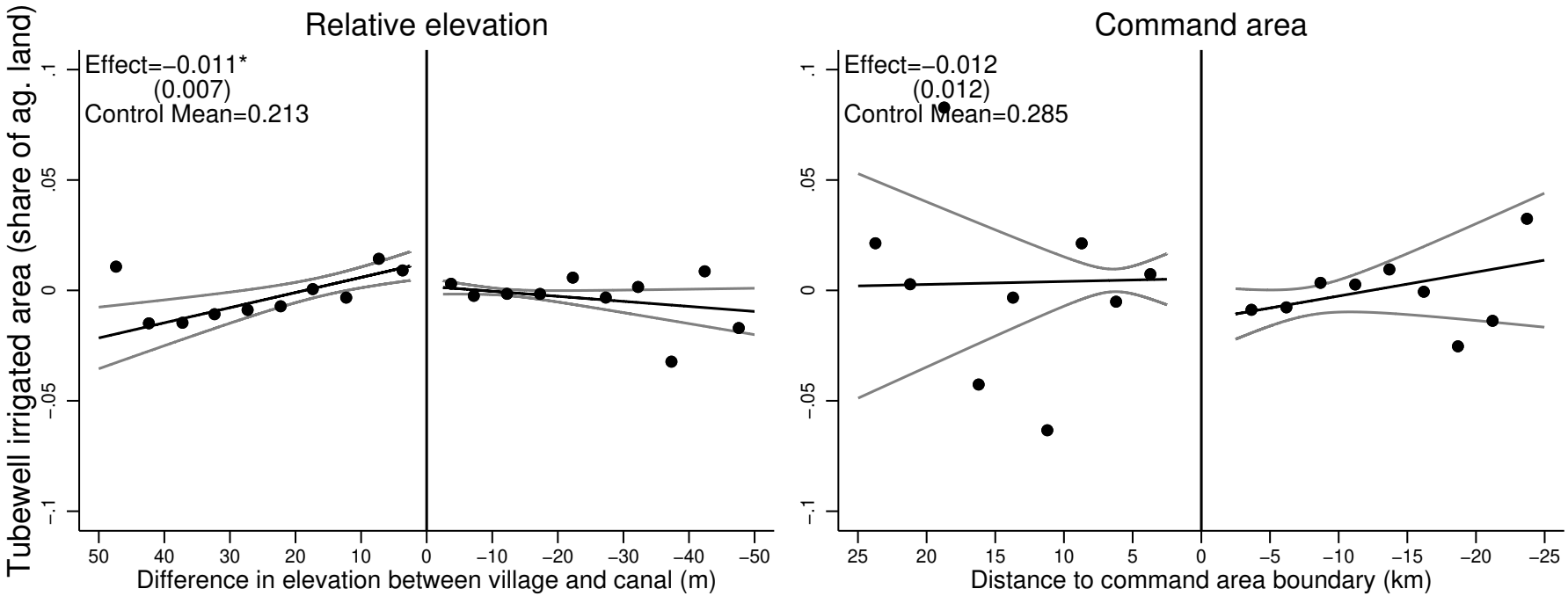
Irrigation (tubewell)



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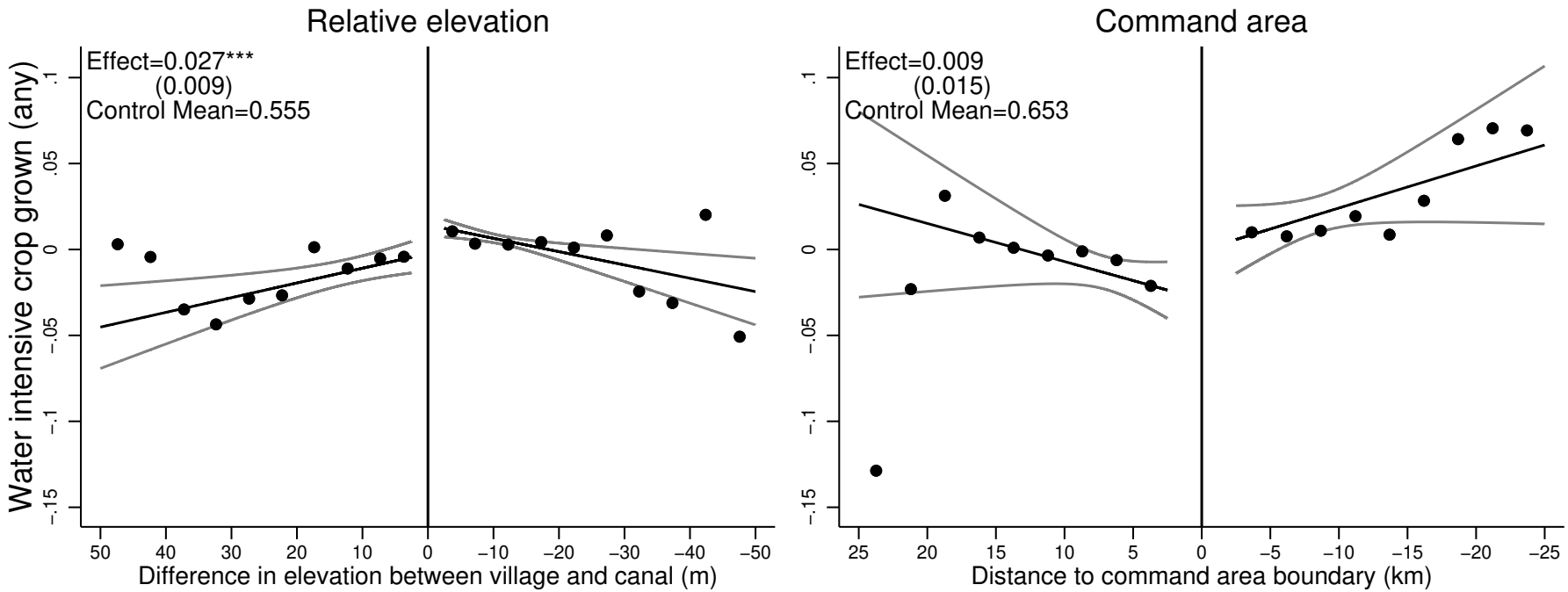
Crop choice



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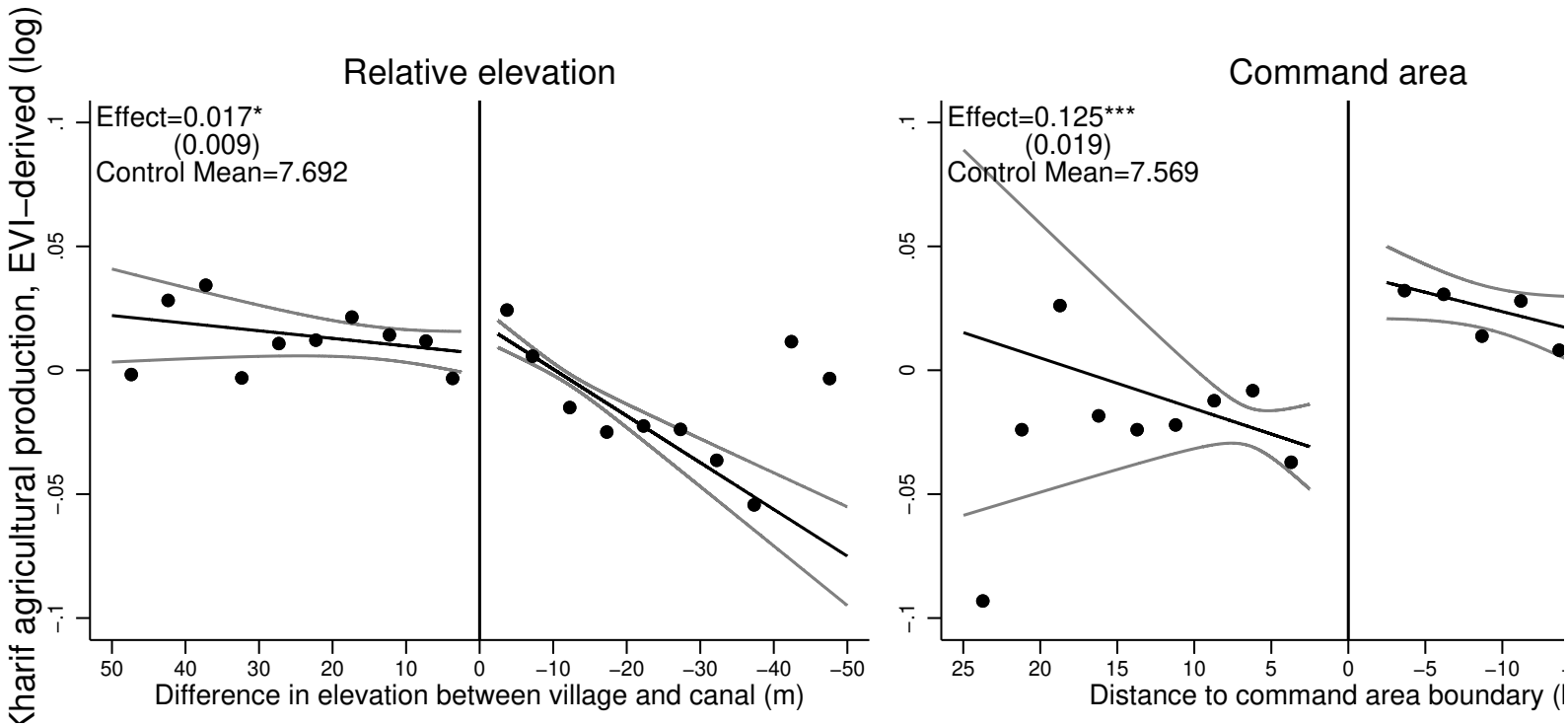
Agricultural productivity (Kharif)



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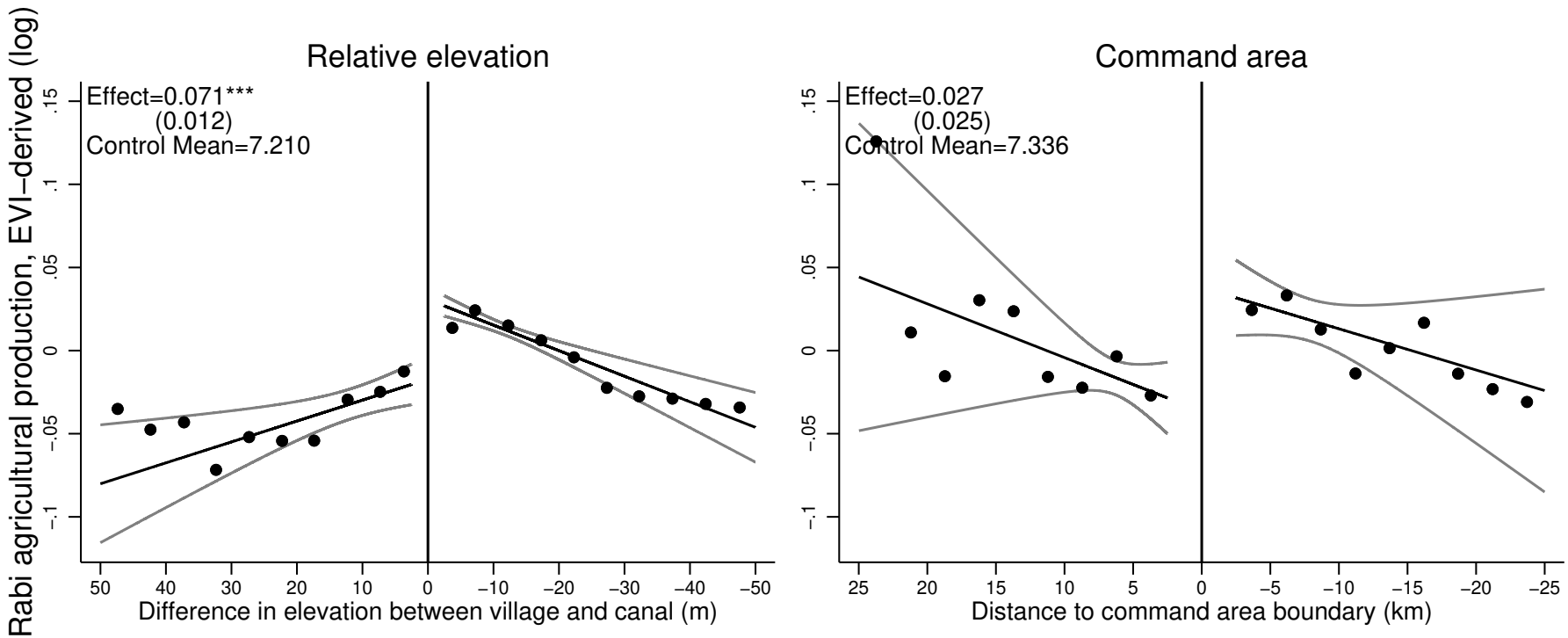
Agricultural productivity (Rabi)



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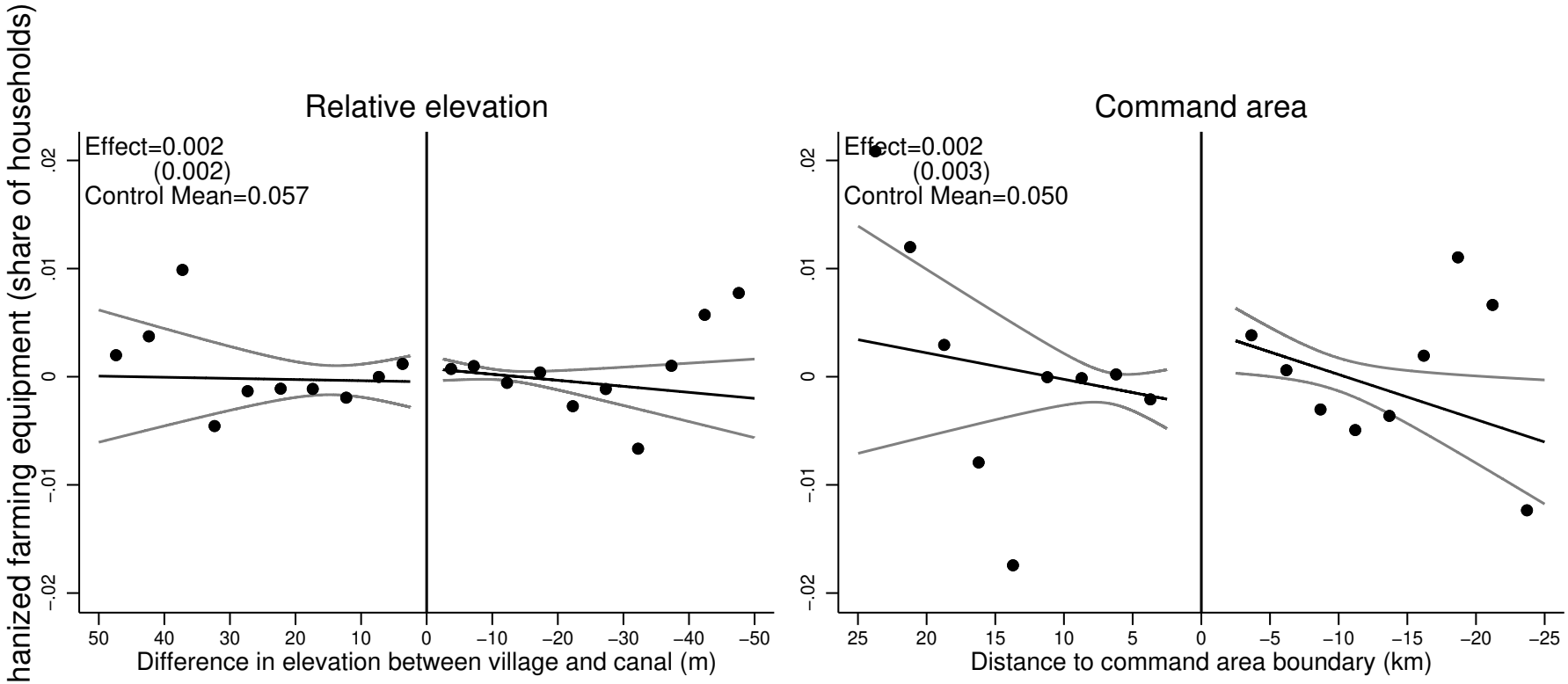
Mechanization



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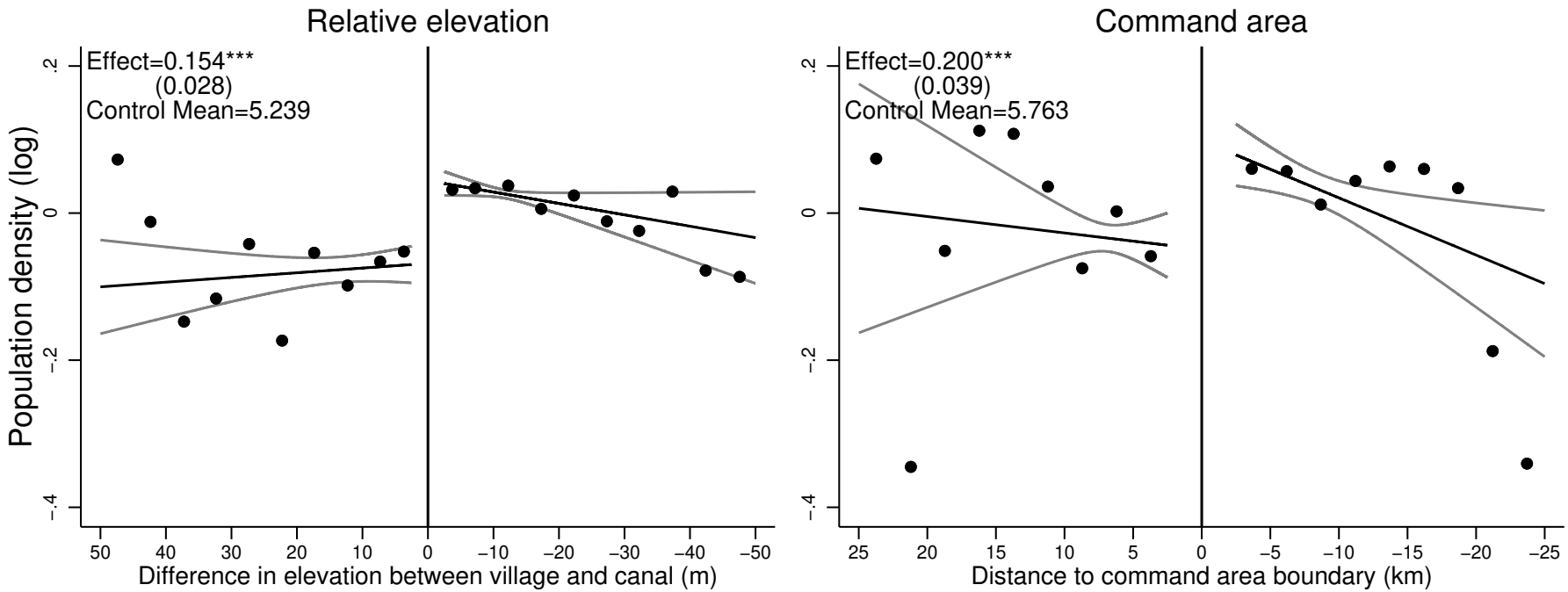
Population density



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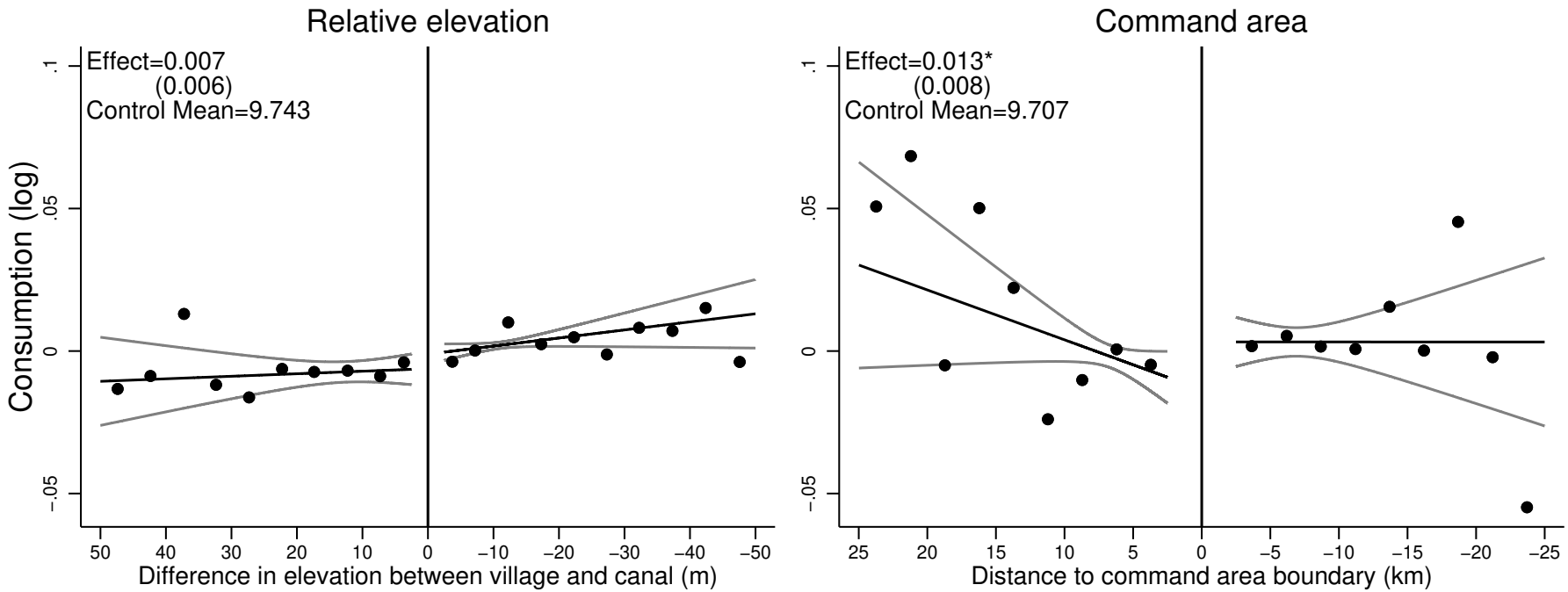
Consumption



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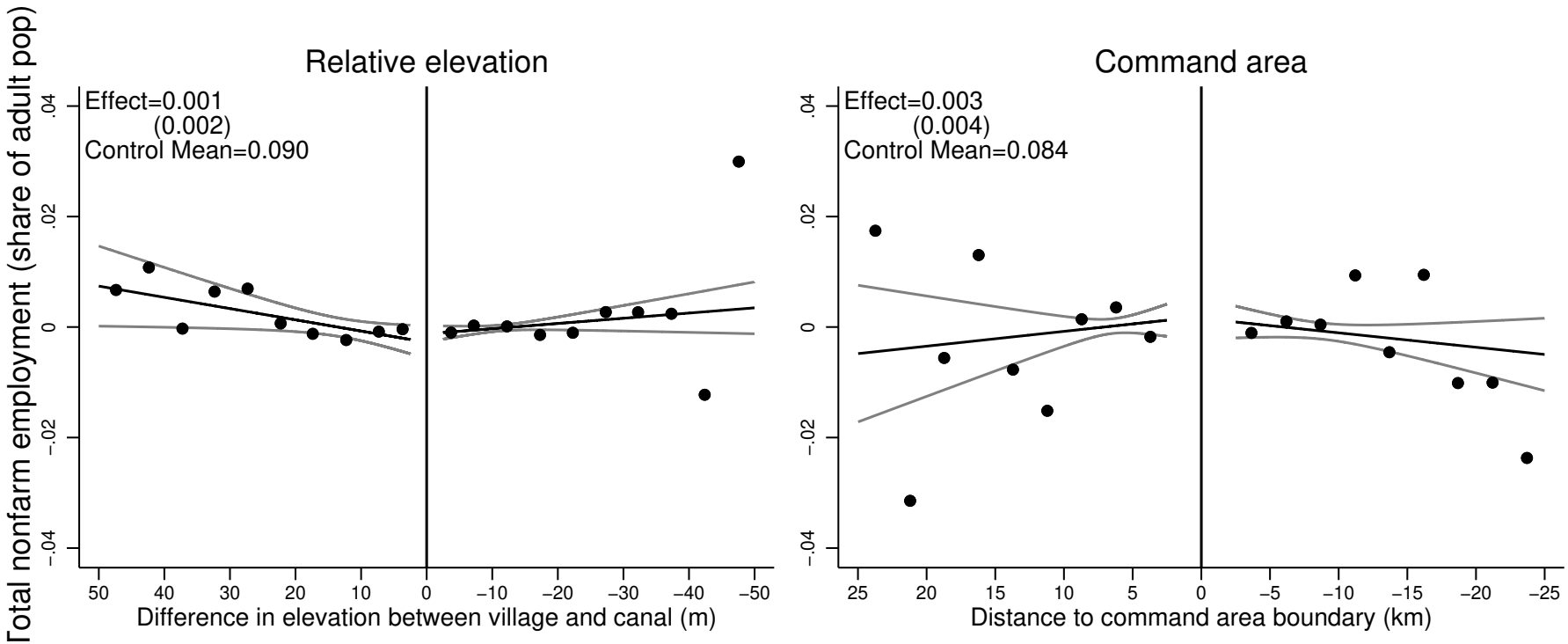
Nonfarm employment (total)



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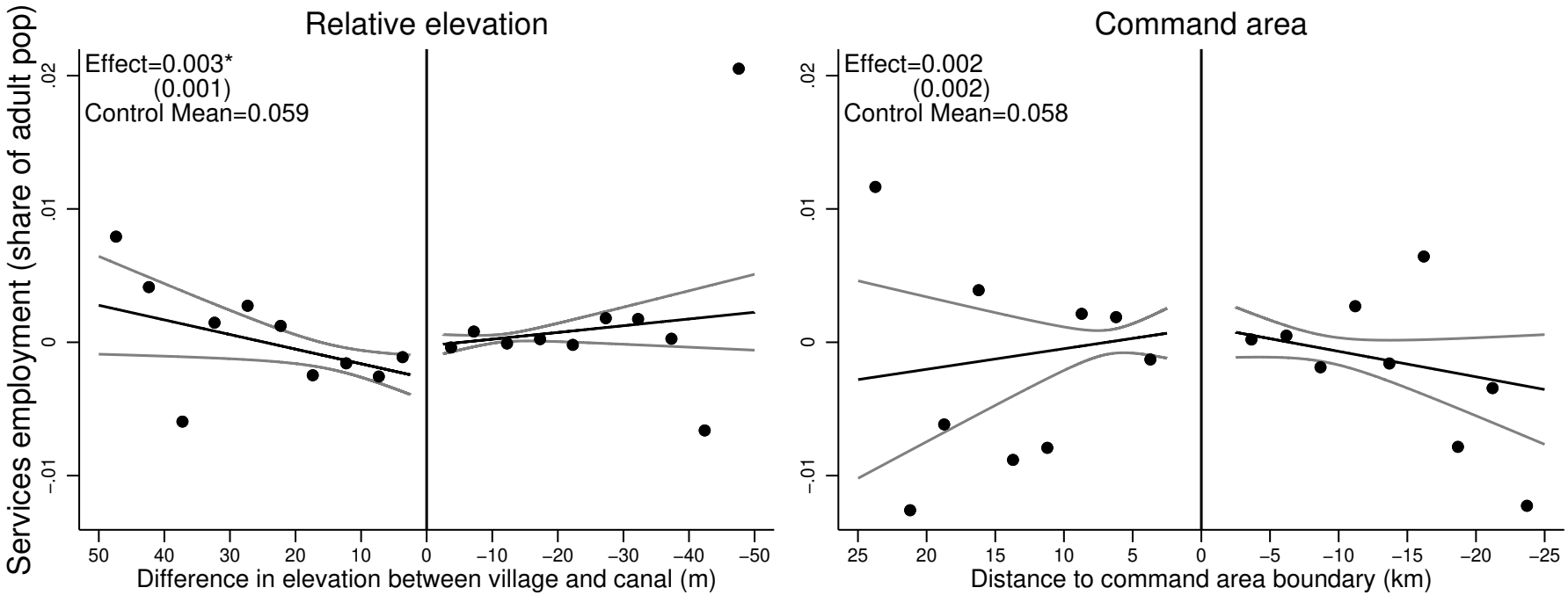
Nonfarm employment (services)



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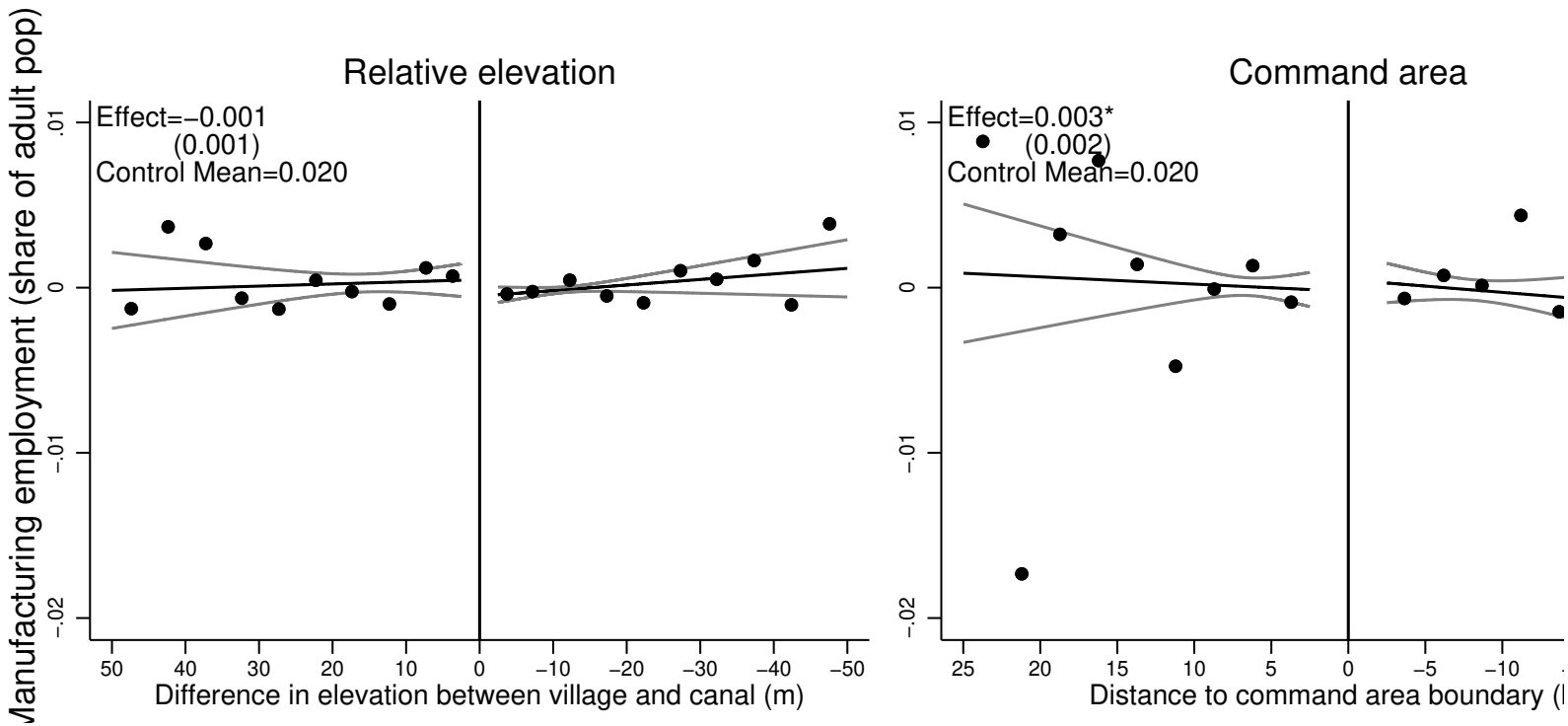
Nonfarm employment (manufacturing)



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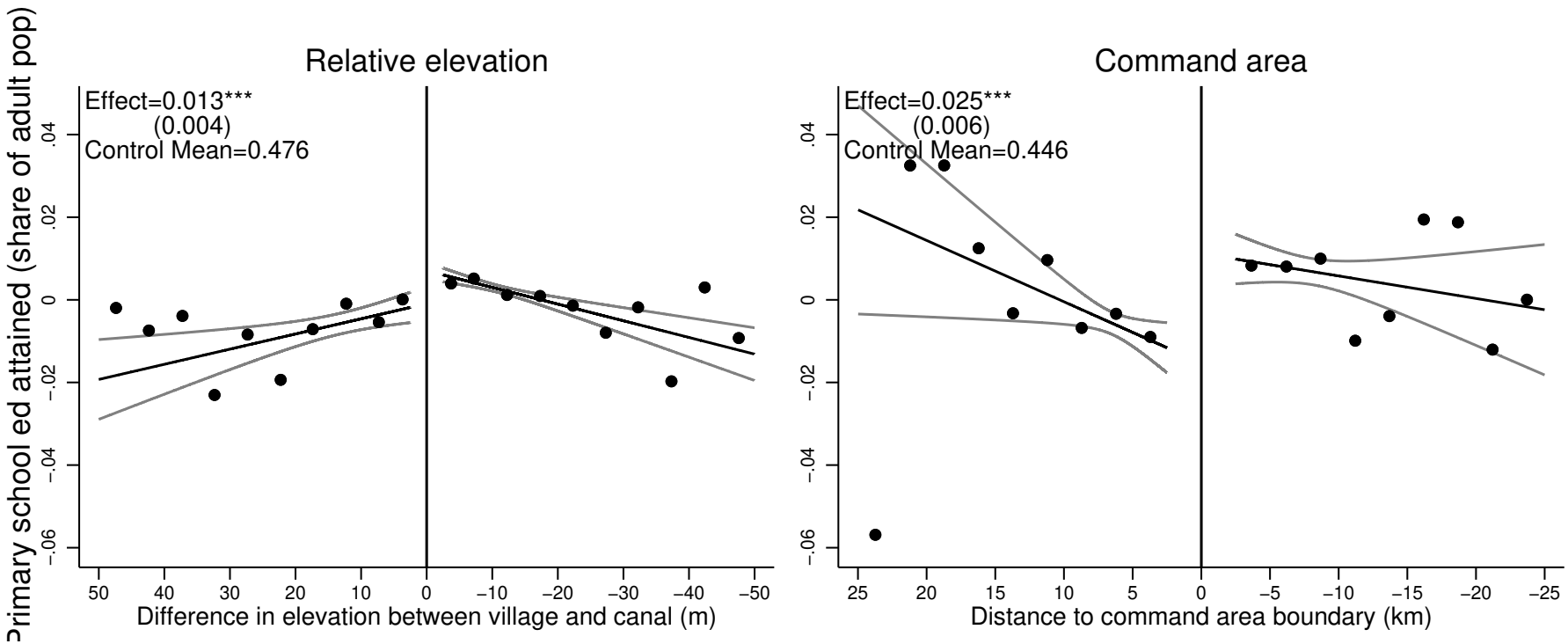
Education (primary)



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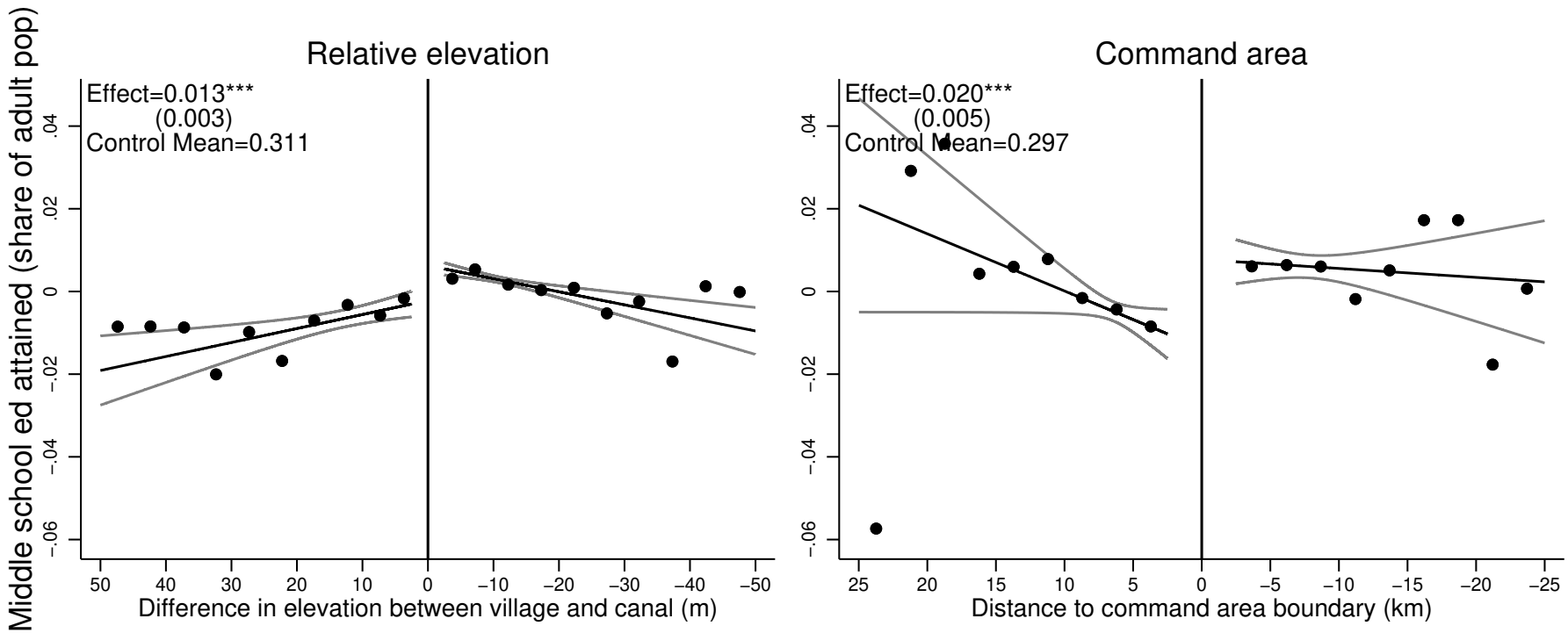
Education (middle)



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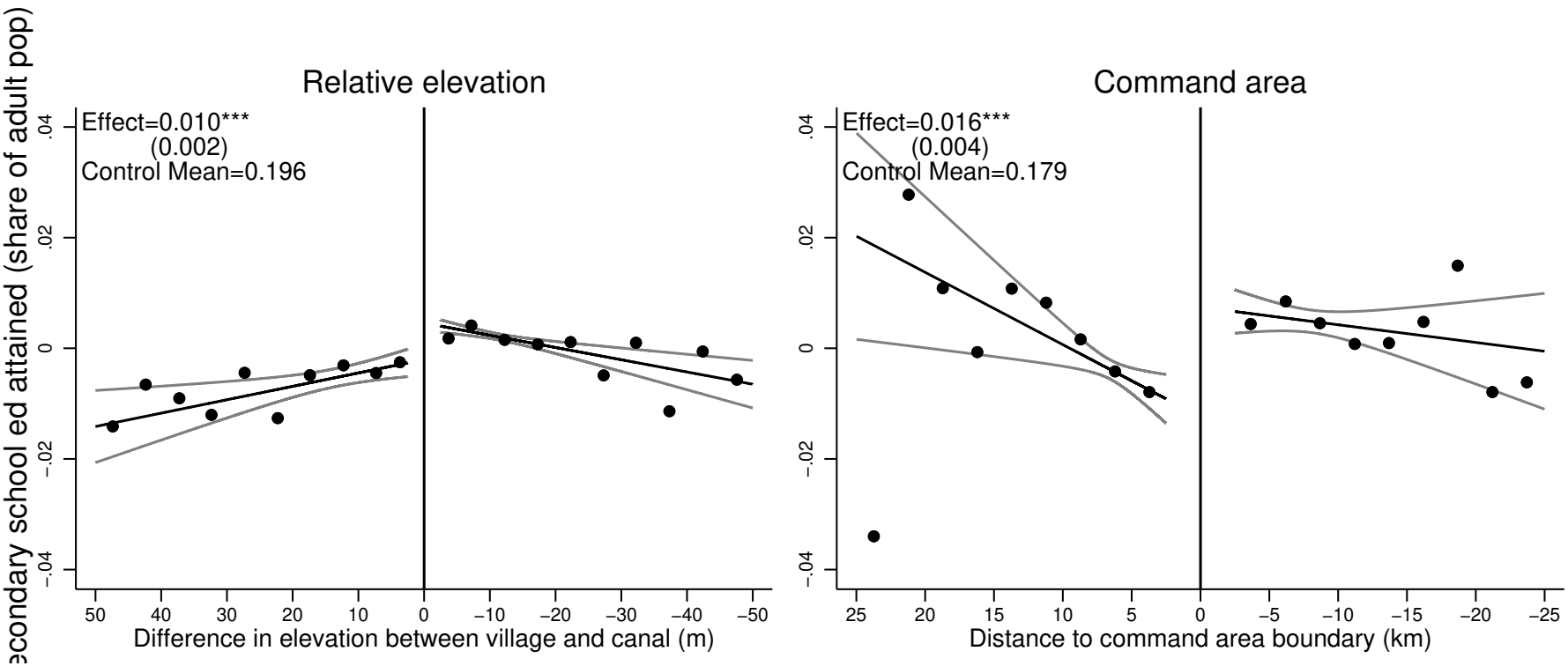
Education (secondary)



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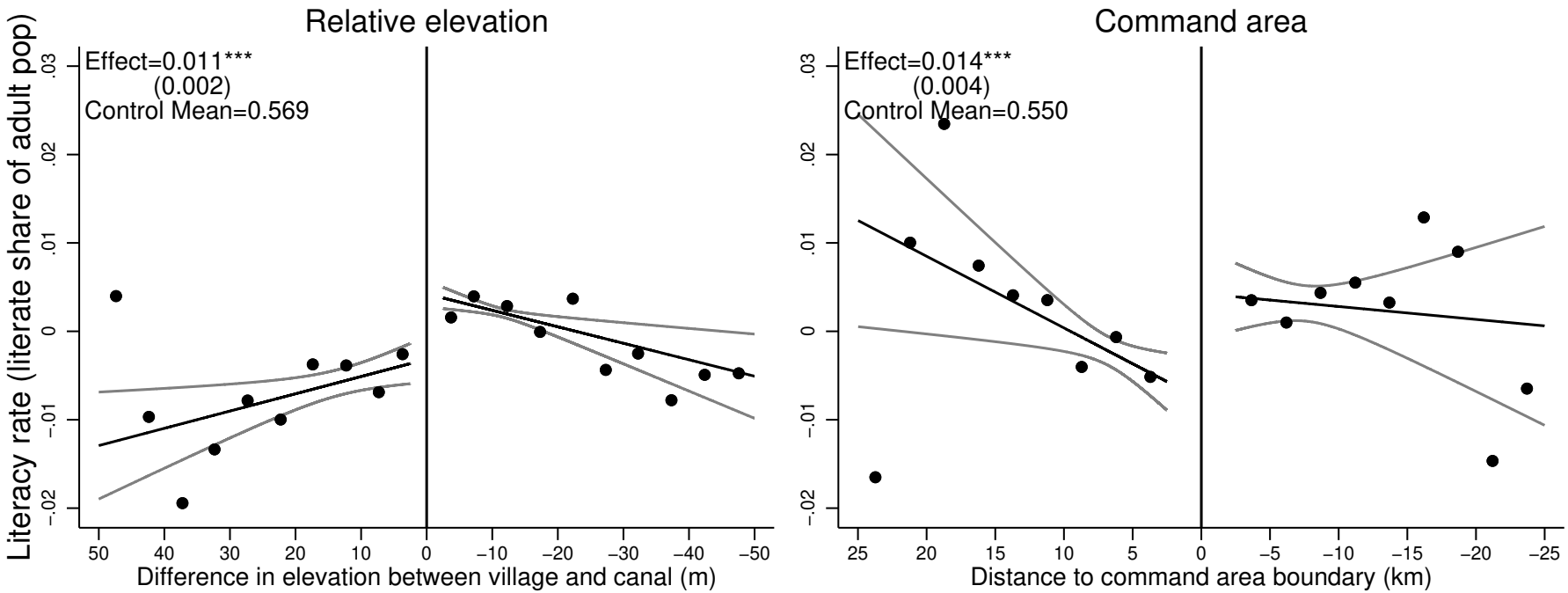
Literacy



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Main RDD Results

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.075***	0.099***	-0.011*	-0.004
	(0.008)	(0.007)	(0.007)	(0.005)
Control group mean	0.428	0.032	0.213	0.189
Observations	76,618	76,622	76,678	75,888
R^2	0.61	0.38	0.47	0.64

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of all HHs)
Below canal	0.027***	0.017*	0.071***	0.027***	0.002
	(0.006)	(0.009)	(0.012)	(0.009)	(0.002)
Control group mean	0.595	7.692	7.210	0.555	0.057
Observations	83,512	83,450	83,190	65,691	79,972
R^2	0.61	0.83	0.71	0.72	0.31

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption pc (log)
Below canal	0.154***	0.001	0.003*	-0.001	0.007
	(0.028)	(0.002)	(0.001)	(0.001)	(0.006)
Control group mean	5.239	0.090	0.059	0.020	9.743
Observations	84,763	79,291	79,291	79,291	80,677
R^2	0.42	0.26	0.19	0.28	0.52

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (literate share of pop.)
Below canal	0.013***	0.013***	0.010***	0.011***
	(0.004)	(0.003)	(0.002)	(0.002)
Control group mean	0.476	0.311	0.196	0.569
Observations	79,924	79,924	79,924	84,763
R^2	0.56	0.55	0.52	0.57

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

Back: Irrigation Back: Agricultural Back: Non-farm Back: Education

Robustness 1: All canal-area settlements

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.063***	0.090***	-0.009**	-0.008***
	(0.005)	(0.004)	(0.004)	(0.003)
Control group mean	0.431	0.048	0.212	0.177
Observations	212,351	212,385	212,480	210,636
R^2	0.64	0.44	0.48	0.56

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of households)
Below canal	0.030***	0.028***	0.053***	0.027***	0.003**
	(0.004)	(0.006)	(0.008)	(0.006)	(0.002)
Control group mean	0.569	7.706	7.255	0.571	0.050
Observations	223,974	223,982	222,107	182,016	214,645
R^2	0.59	0.80	0.72	0.73	0.34

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption per capita (log)
Below canal	0.125***	-0.002	0.001	-0.001**	0.008**
	(0.018)	(0.002)	(0.001)	(0.001)	(0.003)
Control group mean	5.231	0.092	0.059	0.020	9.721
Observations	227,183	210,412	210,412	210,412	216,408
R^2	0.48	0.25	0.19	0.23	0.53

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (share of pop.)
Below canal	0.015***	0.015***	0.012***	0.009***
	(0.002)	(0.002)	(0.001)	(0.001)
Control group mean	0.461	0.302	0.188	0.560
Observations	214,533	214,533	214,533	227,183
R^2	0.57	0.55	0.52	0.58

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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Pop increase: fertility, mortality, or migration?

- RDD shows no current evidence of fertility or mortality effects Coefplot
- Migration channel: test whether canal construction in preceding decades increases probability of being an in-migrant in 1987 data

Panel A. Migration by period of canal expansion

	Outcome: is a migrant			
Treatment period	1941-1981	1951-1981	1961-1981	1991-2021
Canal coverage gain	0.101***	0.066**	0.070**	0.027
	(0.031)	0.027)	(0.033)	(0.024)
Base year canal coverage	0.048***	0.060**	0.061**	0.030
	(0.017)	0.016)	(0.015)	(0.018)
Control group mean	0.241	0.241	0.241	0.241
Observations	624,628	624,628	624,628	624,628
R^2	0.02	0.02	0.02	0.02

Panel B. Migration by origin and destination

	Outcome: Is a migrant from a rural area		Outcome: Is a migrant from an urban area	
Sample	Rural	Urban	Rural	Urban
Canal coverage gain (1951-1981)	0.066***	0.120***	0.002	-0.023
	(0.023)	0.044)	(0.009)	(0.025)
Base year canal coverage (1951)	0.040***	0.076***	0.013	-0.003
	(0.015)	0.028)	(0.005)	(0.016)
Control group mean	0.191	0.166	0.020	0.121
Observations	419,677	206,380	419,677	206,380
R^2	0.02	0.01	0.01	0.01

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$

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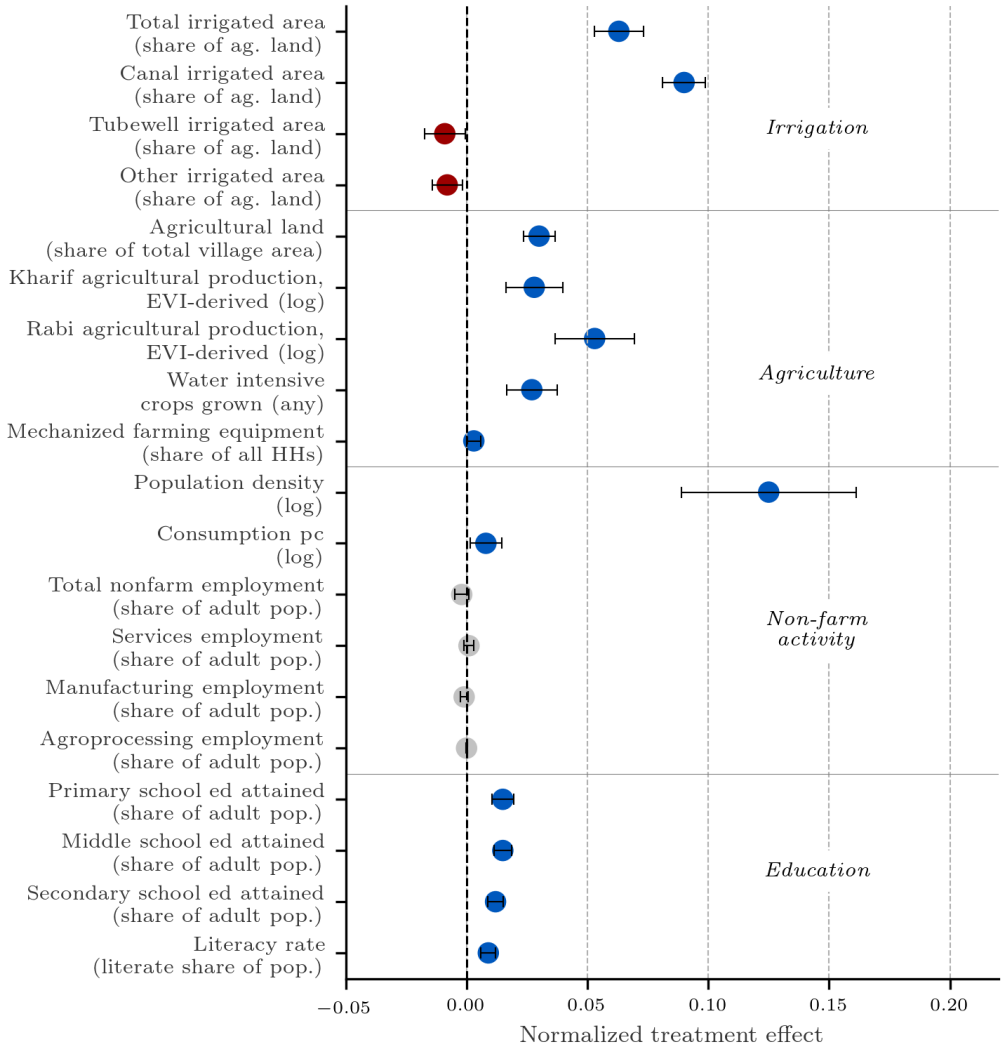
Robustness 1: All canal-area settlements



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Robustness 2: All canal-area settlements, minus donut hole

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.079***	0.111***	-0.011**	-0.009**
	(0.007)	(0.006)	(0.005)	(0.004)
Control group mean	0.412	0.035	0.199	0.183
Observations	113,428	113,475	113,545	112,057
R^2	0.59	0.39	0.48	0.63

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of households)
Below canal	0.040***	0.026***	0.066***	0.029***	0.005**
	(0.005)	(0.008)	(0.011)	(0.008)	(0.002)
Control group mean	0.554	7.704	7.228	0.561	0.048
Observations	121,955	121,924	121,525	95,430	116,883
R^2	0.59	0.81	0.69	0.74	0.31

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption per capita (log)
Below canal	0.190***	0.002	0.003***	-0.001	0.014***
	(0.025)	(0.002)	(0.001)	(0.001)	(0.005)
Control group mean	5.139	0.091	0.058	0.019	9.714
Observations	123,823	115,207	115,207	115,207	117,950
R^2	0.42	0.28	0.20	0.26	0.53

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (share of pop.)
Below canal	0.020***	0.020***	0.015***	0.013***
	(0.003)	(0.003)	(0.002)	(0.002)
Control group mean	0.455	0.296	0.184	0.556
Observations	116,821	116,821	116,821	123,823
R^2	0.58	0.57	0.53	0.59

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$

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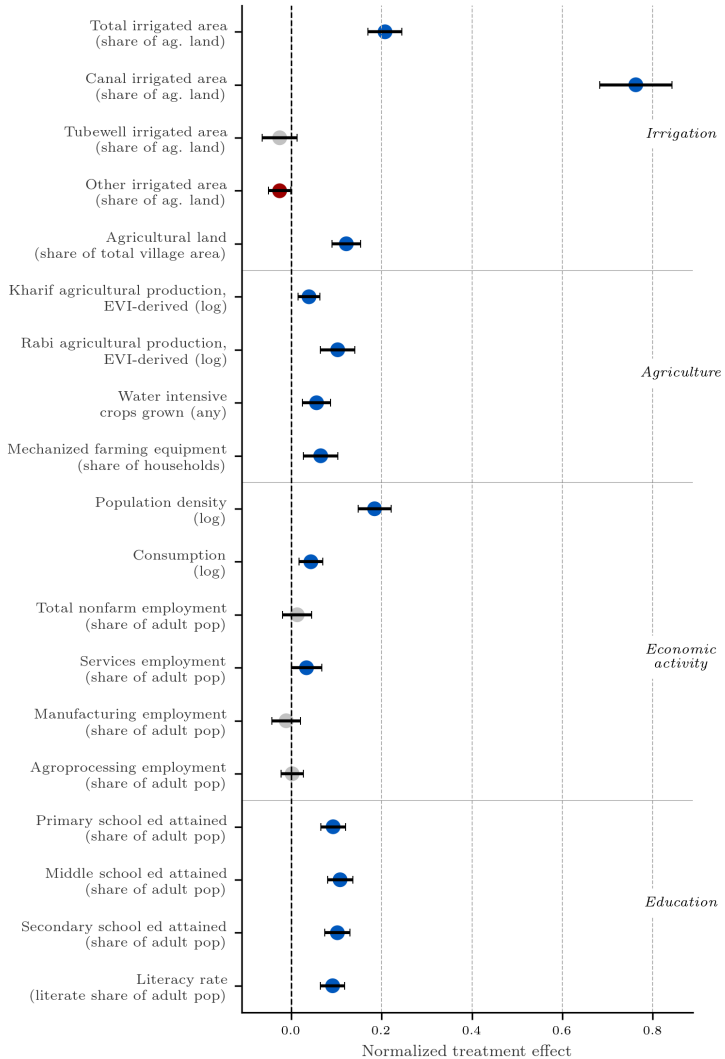
Robustness 2: All canal-area settlements, minus donut hole



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Robustness 3: Canal-area settlements balanced on ruggedness, using median settlement elevation

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.056***	0.074***	-0.008*	-0.006
	(0.006)	(0.006)	(0.004)	(0.004)
Control group mean	0.464	0.050	0.235	0.185
Observations	84,008	84,000	84,065	83,121
R^2	0.63	0.48	0.50	0.62

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of households)
Below canal	0.021***	0.029***	0.040***	0.012*	0.002
	(0.004)	(0.009)	(0.014)	(0.007)	(0.002)
Control group mean	0.626	7.700	7.262	0.567	0.059
Observations	90,993	90,908	90,547	73,006	87,321
R^2	0.61	0.82	0.72	0.73	0.35

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption per capita (log)
Below canal	0.033	-0.004*	-0.003**	-0.001*	0.008*
	(0.021)	(0.002)	(0.001)	(0.001)	(0.004)
Control group mean	5.396	0.090	0.059	0.020	9.749
Observations	92,507	86,422	86,422	86,422	88,214
R^2	0.45	0.30	0.21	0.28	0.55

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (share of pop.)
Below canal	0.008***	0.006***	0.004**	0.004**
	(0.003)	(0.002)	(0.002)	(0.002)
Control group mean	0.489	0.324	0.203	0.577
Observations	87,283	87,283	87,283	92,507
R^2	0.57	0.56	0.53	0.59

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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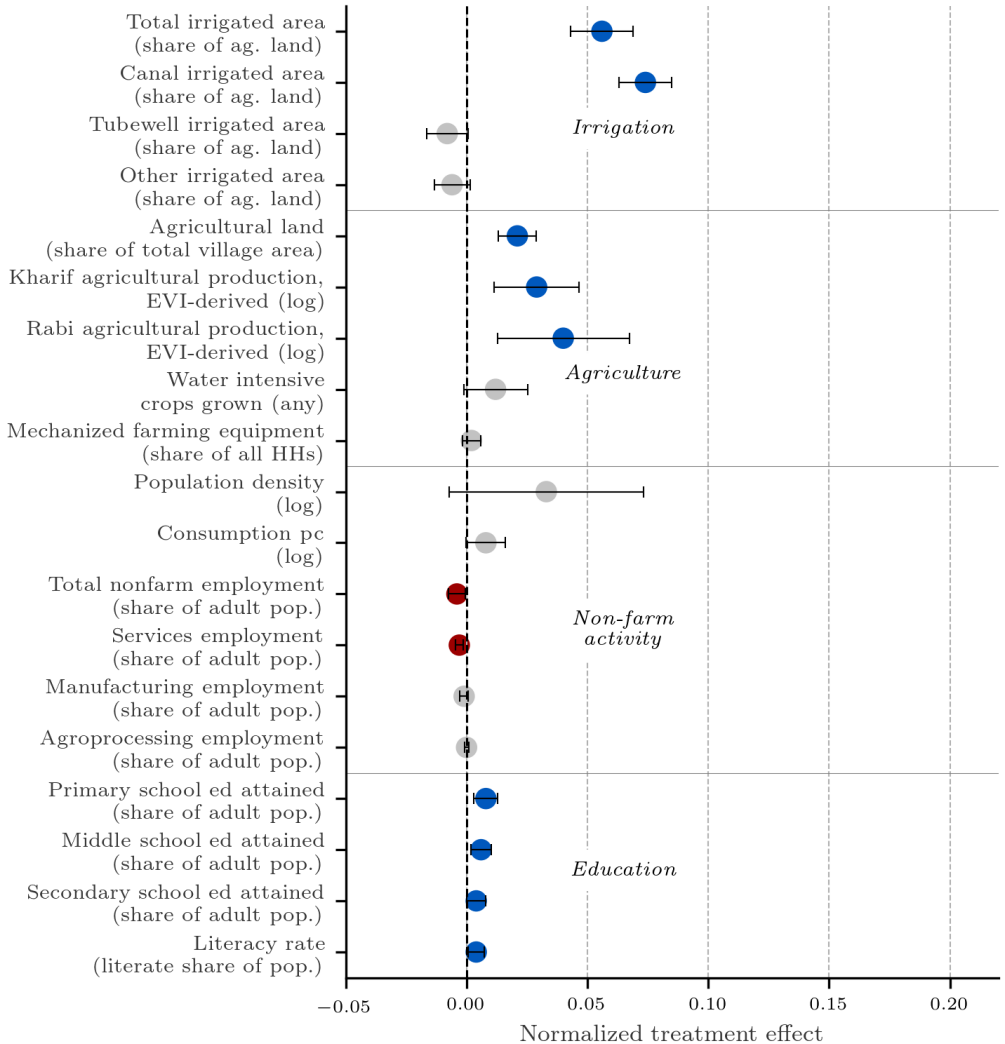
Robustness 3: Canal-area settlements balanced on ruggedness, using median settlement elevation



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Robustness 4: Canal-area settlements balanced on ruggedness, using 25th percentile settlement elevation

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.074***	0.107***	-0.017***	-0.007
	(0.007)	(0.006)	(0.005)	(0.004)
Control group mean	0.446	0.040	0.224	0.188
Observations	87,864	87,865	87,924	86,958
R^2	0.64	0.44	0.49	0.62

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of households)
Below canal	0.030***	0.037***	0.065***	0.022***	0.001
	(0.005)	(0.009)	(0.013)	(0.007)	(0.002)
Control group mean	0.614	7.693	7.241	0.556	0.058
Observations	95,055	94,990	94,711	75,928	91,121
R^2	0.61	0.82	0.72	0.71	0.33

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption per capita (log)
Below canal	0.133***	0.001	0.002	0.000	0.015***
	(0.025)	(0.002)	(0.001)	(0.001)	(0.005)
Control group mean	5.317	0.091	0.059	0.020	9.752
Observations	96,599	90,392	90,392	90,392	92,084
R^2	0.46	0.29	0.21	0.27	0.55

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (share of pop.)
Below canal	0.015***	0.013***	0.011***	0.009***
	(0.003)	(0.003)	(0.002)	(0.002)
Control group mean	0.485	0.319	0.201	0.575
Observations	91,077	91,077	91,077	96,599
R^2	0.57	0.56	0.54	0.60

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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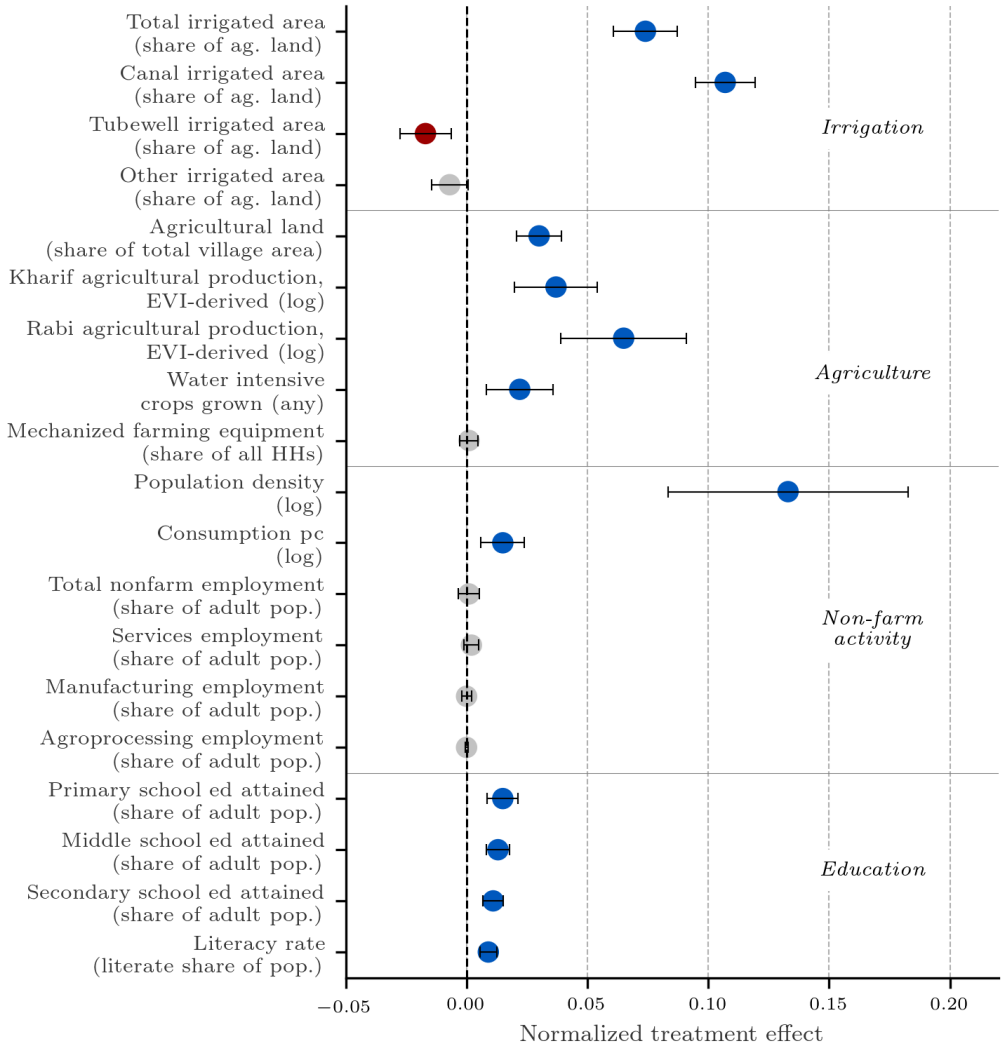
Robustness 4: Canal-area settlements balanced on ruggedness, using 25th percentile settlement elevation



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Robustness 5: Main analysis sample, excluding villages intersected by a canal

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.054***	0.045***	0.002	0.008
	(0.008)	(0.005)	(0.007)	(0.005)
Control group mean	0.427	0.033	0.215	0.185
Observations	55,816	55,794	55,834	55,396
R^2	0.66	0.33	0.51	0.67

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of households)
Below canal	0.018***	-0.001	0.041***	0.022**	0.001
	(0.005)	(0.009)	(0.011)	(0.009)	(0.002)
Control group mean	0.593	7.714	7.220	0.541	0.055
Observations	61,614	61,583	61,441	48,857	58,801
R^2	0.62	0.83	0.73	0.74	0.31

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption per capita (log)
Below canal	0.113***	0.001	0.003*	-0.002**	0.005
	(0.026)	(0.002)	(0.002)	(0.001)	(0.006)
Control group mean	5.220	0.088	0.058	0.018	9.732
Observations	62,433	57,831	57,831	57,831	59,210
R^2	0.44	0.33	0.19	0.29	0.51

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (share of pop.)
Below canal	0.009**	0.009***	0.008***	0.009***
	(0.004)	(0.003)	(0.003)	(0.002)
Control group mean	0.472	0.308	0.193	0.566
Observations	58,762	58,762	58,762	62,433
R^2	0.56	0.55	0.52	0.57

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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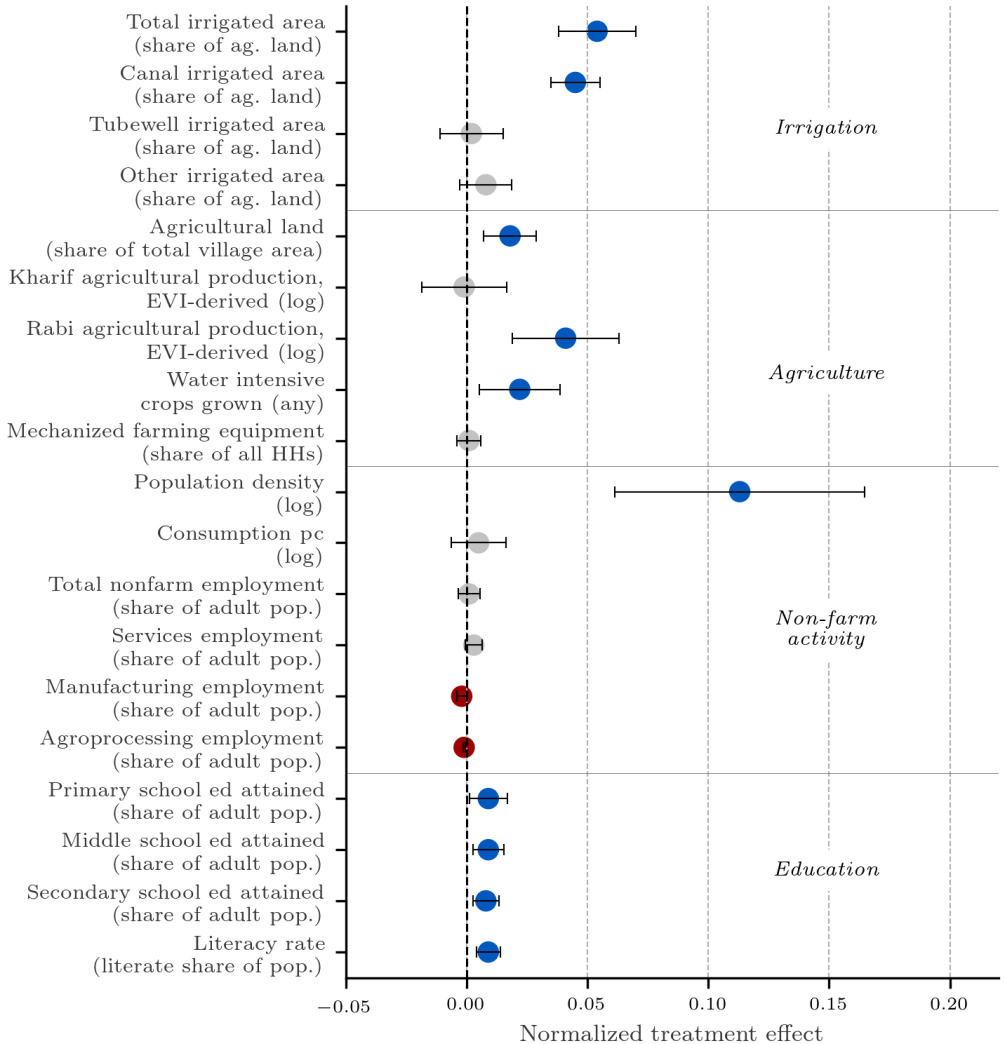
Robustness 5: Main analysis sample, excluding villages intersected by a canal



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Robustness 6: Main analysis sample, additional control for distance to canal

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.044***	0.048***	0.001	0.000
	(0.008)	(0.006)	(0.006)	(0.005)
Control group mean	0.428	0.032	0.213	0.189
Observations	76,618	76,622	76,678	75,888
R^2	0.62	0.40	0.47	0.64

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of households)
Below canal	0.018***	-0.005	0.059***	0.014	0.001
	(0.006)	(0.009)	(0.012)	(0.009)	(0.002)
Control group mean	0.595	7.692	7.210	0.555	0.057
Observations	83,512	83,450	83,190	65,691	79,972
R^2	0.61	0.83	0.71	0.72	0.31

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption per capita (log)
Below canal	0.090***	-0.001	0.002	-0.002**	0.001
	(0.028)	(0.003)	(0.002)	(0.001)	(0.006)
Control group mean	5.239	0.090	0.059	0.020	9.743
Observations	84,763	79,291	79,291	79,291	80,677
R^2	0.43	0.26	0.19	0.28	0.52

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (share of pop.)
Below canal	0.006	0.007**	0.006**	0.007***
	(0.004)	(0.003)	(0.002)	(0.002)
Control group mean	0.476	0.311	0.196	0.569
Observations	79,924	79,924	79,924	84,763
R^2	0.56	0.55	0.52	0.57

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$

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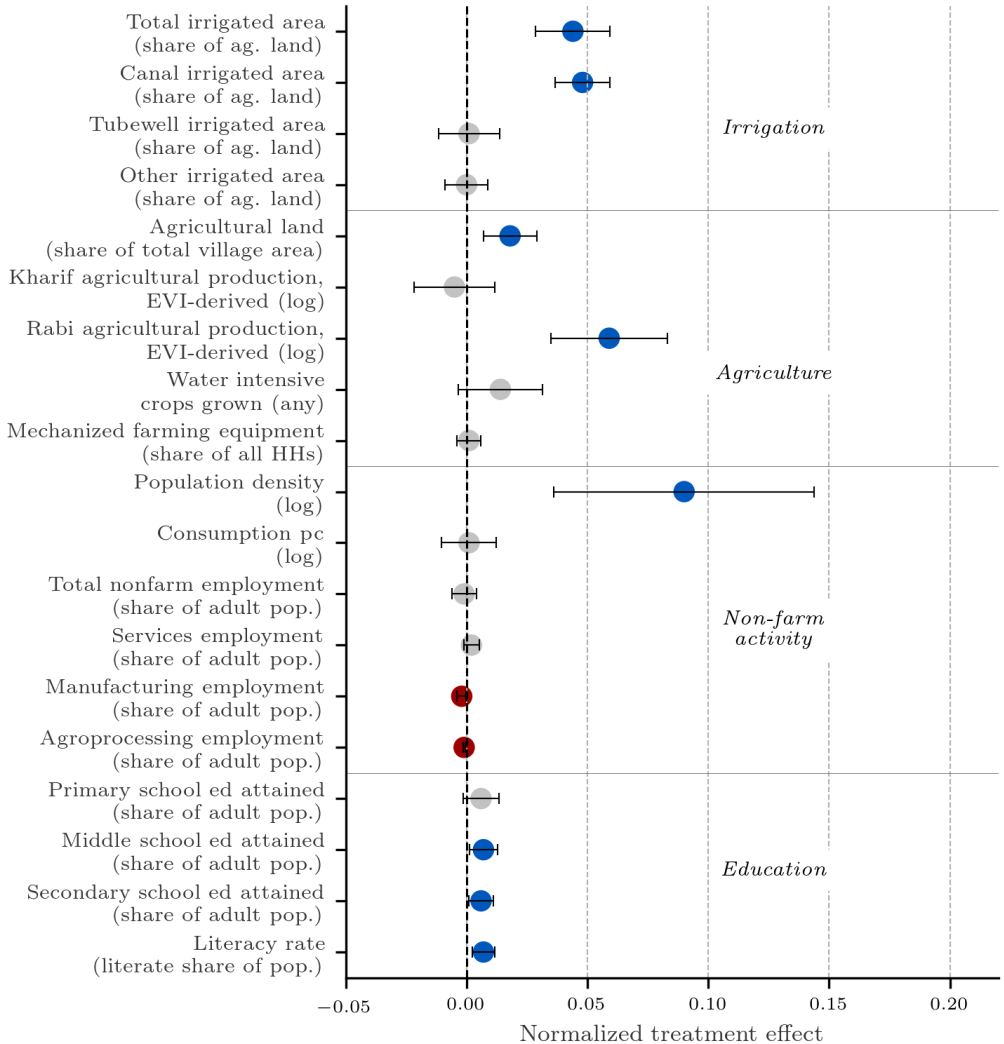
Robustness 6: Main analysis sample, additional control for distance to canal



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Robustness 7: command area boundary RD

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.117***	0.155***	-0.008	-0.019*
	(0.019)	(0.020)	(0.014)	(0.011)
Control group mean	0.469	0.047	0.285	0.148
Observations	43,172	43,134	43,167	42,695
R^2	0.72	0.50	0.55	0.50

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of households)
Below canal	0.026**	0.140***	0.061**	0.024	0.007**
	(0.012)	(0.025)	(0.031)	(0.019)	(0.004)
Control group mean	0.657	7.569	7.336	0.653	0.050
Observations	48,190	48,245	48,139	41,594	45,860
R^2	0.71	0.80	0.78	0.76	0.33

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption per capita (log)
Below canal	0.256***	0.002	0.001	0.001	0.022**
	(0.049)	(0.004)	(0.002)	(0.002)	(0.010)
Control group mean	5.763	0.084	0.058	0.020	9.707
Observations	48,809	45,004	45,004	45,004	46,130
R^2	0.61	0.33	0.23	0.34	0.56

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (share of pop.)
Below canal	0.022***	0.021***	0.020***	0.019***
	(0.008)	(0.006)	(0.004)	(0.005)
Control group mean	0.446	0.297	0.179	0.550
Observations	45,848	45,848	45,848	48,809
R^2	0.65	0.61	0.56	0.68

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$

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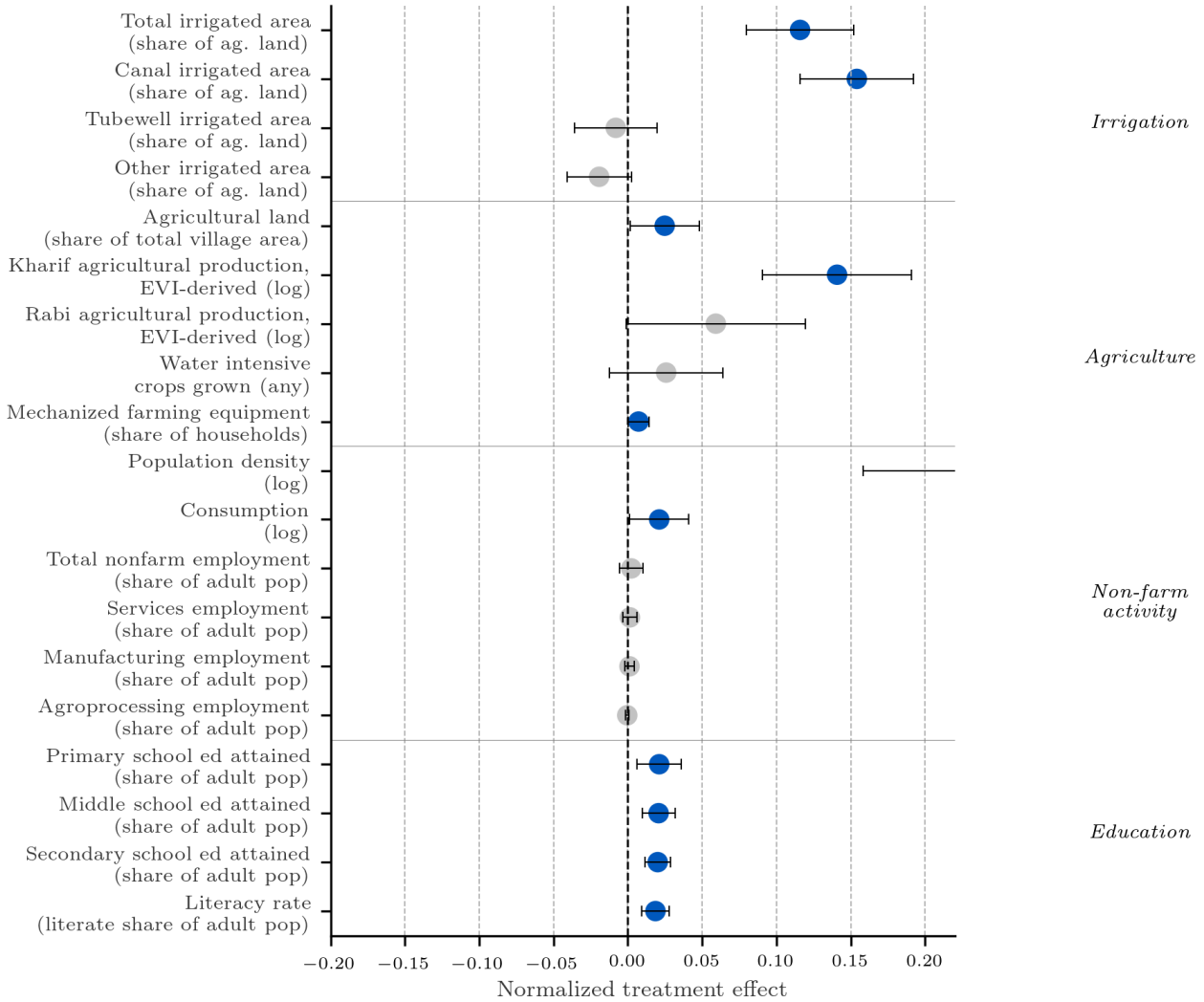
Robustness 7: command area boundary RD



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Robustness 8: long straight canals only

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below canal	0.095***	0.115***	-0.024	0.005
	(0.023)	(0.018)	(0.022)	(0.011)
Control group mean	0.428	0.032	0.213	0.189
Observations	12,178	12,177	12,183	12,132
R^2	0.70	0.45	0.52	0.48

Panel B. Agriculture outcomes

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of households)
Below canal	0.033**	0.022	0.077*	0.067**	-0.002
	(0.017)	(0.030)	(0.039)	(0.026)	(0.006)
Control group mean	0.595	7.692	7.210	0.555	0.057
Observations	13,906	13,899	13,854	12,004	13,285
R^2	0.68	0.80	0.78	0.77	0.31

Panel C. Non-farm outcomes

	Population density (log)	Total emp. (share of adult pop.)	Services emp. (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption per capita (log)
Below canal	0.232***	0.006	0.010*	-0.001	0.000
	(0.083)	(0.008)	(0.005)	(0.003)	(0.017)
Control group mean	5.239	0.090	0.059	0.020	9.743
Observations	14,147	13,104	13,104	13,104	13,390
R^2	0.53	0.20	0.18	0.26	0.52

Panel D. Education outcomes

	At least primary (share of adult pop.)	At least middle (share of adult pop.)	At least secondary (share of adult pop.)	Literacy (share of pop.)
Below canal	0.017	0.025***	0.021***	0.026***
	(0.012)	(0.009)	(0.007)	(0.008)
Control group mean	0.476	0.311	0.196	0.569
Observations	13,279	13,279	13,279	14,147
R^2	0.54	0.55	0.54	0.52

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$

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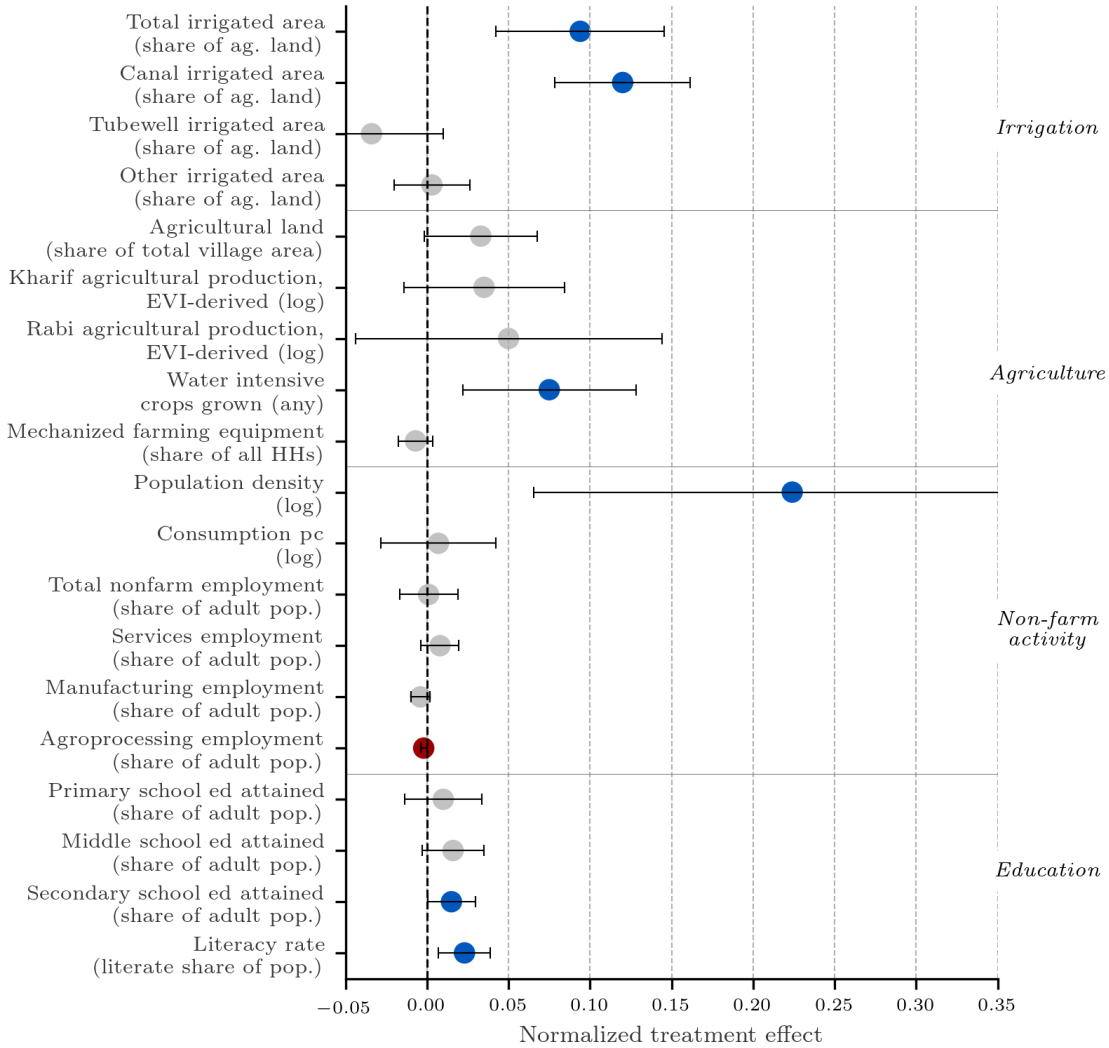
Robustness 8: long straight canals only



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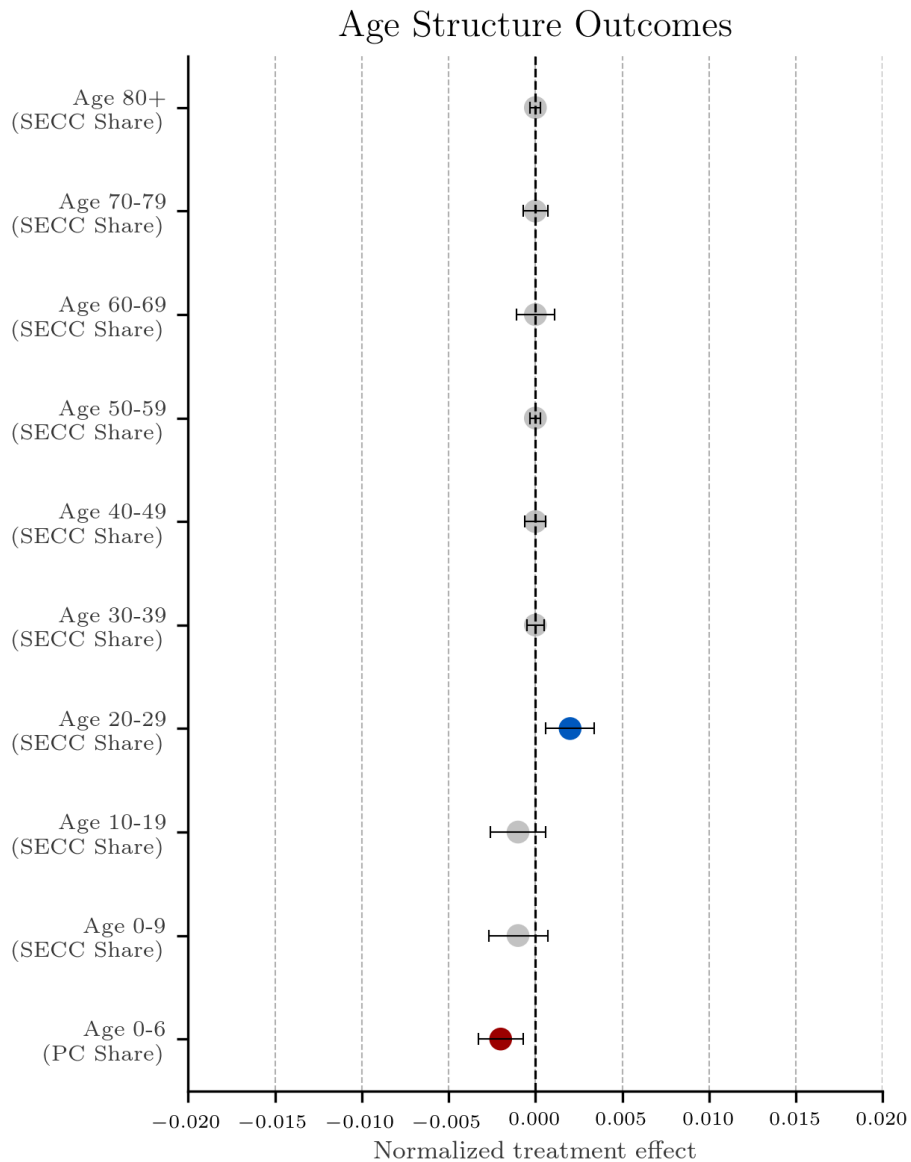
Fertility



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Results by land ownership

Panel A. Land ownership overview

	Land-owning HHs (share of all HHs)	Avg. size of land holdings (log hectares, all HHs)	Avg. size of land holdings (log hectares, land-owning HHs)
Below canal	-0.027***	-0.055***	0.006
	(0.005)	(0.019)	(0.014)
Control group mean	0.534	0.745	1.525
Observations	79,972	77,756	77,723
R^2	0.46	0.46	0.50

Panel B. Consumption distribution

	Consumption pc		Consumption pc (log, land-owning HHs)			
	(log, landless HHs)	(log, land-owning HHs)	1^{st} quartile	2^{nd} quartile	3^{rd} quartile	4^{th} quartile
Below canal	0.002	0.021***	0.000	0.015**	0.019***	0.029***
	(0.006)	(0.006)	(0.008)	(0.007)	(0.007)	(0.007)
Control group mean	9.603	9.812	9.737	9.763	9.810	9.904
Observations	77,791	77,720	67,968	71,126	71,860	69,404
R^2	0.46	0.55	0.45	0.46	0.45	0.41

Panel C. Education attainment

	At least primary, share of		At least middle, share of		At least secondary, share of	
	landless pop.	land-owning pop.	landless pop.	land-owning pop.	landless pop.	land-owning pop.
Below canal	0.011***	0.022***	0.011***	0.023***	0.007***	0.019***
	(0.004)	(0.004)	(0.003)	(0.004)	(0.002)	(0.003)
Control group mean	0.431	0.515	0.268	0.351	0.160	0.231
Observations	77,638	78,018	77,638	78,018	77,638	78,018
R^2	0.46	0.59	0.45	0.57	0.41	0.54

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$

Results: Spillovers in irrigation and agriculture outcomes

Panel A. Irrigation outcomes

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Below-canal settlements	0.046***	0.083***	-0.009	-0.017**
(0-10km)	(0.013)	(0.010)	(0.008)	(0.008)
Distant settlements	-0.009	-0.005	-0.007	0.003
(15-50km)	(0.007)	(0.004)	(0.006)	(0.005)
Control group mean	0.450	0.068	0.212	0.177
Observations	76,014	76,196	76,185	75,569
R^2	0.62	0.17	0.42	0.79

Panel B. Agriculture outcomes

Settlement type	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of all HHs)
Below-canal settlements	0.020***	0.015	0.055***	0.005	0.007***
(0-10km)	(0.007)	(0.011)	(0.020)	(0.012)	(0.002)
Distant settlements	0.004	-0.003	0.028	-0.043**	0.000
(15-50km)	(0.007)	(0.009)	(0.018)	(0.017)	(0.002)
Control group mean	0.572	7.821	7.337	0.659	0.038
Observations	84,682	84,654	84,467	63,937	80,887
R^2	0.56	0.87	0.58	0.71	0.32

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Results: Spillovers in non-agricultural outcomes

Panel C. Non-farm outcomes

Settlement type	Population density (log)	Total emp (share of adult pop.)	Services emp (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption pc (log, all HHs)
Below-canal settlements	0.160***	0.001	0.002	0.000	0.024***
(0-10km)	(0.028)	(0.002)	(0.001)	(0.001)	(0.006)
Distant settlements	-0.052**	0.001	-0.001	0.001	-0.003
(15-50km)	(0.024)	(0.003)	(0.001)	(0.002)	(0.007)
Control group mean	5.634	0.083	0.053	0.021	9.637
Observations	85,762	78,572	78,572	78,572	81,351
R^2	0.27	0.14	0.09	0.22	0.43

Panel D. Outcomes disaggregated by land ownership

Settlement type	Consumption pc (log, landless HHs)	Consumption pc (log, land-owning HHs)	Middle school ed. (share of landless pop.)	Middle school ed. (share of land-owning pop.)
Below-canal settlements	0.008*	0.023***	0.011***	0.023***
(0-10km)	(0.004)	(0.006)	(0.003)	(0.005)
Distant settlements	0.009	-0.008	0.001	-0.004
(15-50km)	(0.008)	(0.009)	(0.004)	(0.006)
Control group mean	9.502	9.739	0.256	0.359
Observations	78,325	78,683	78,142	78,852
R^2	0.36	0.43	0.44	0.54

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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Spillover Robustness: Entropy Balance, Irrigation

	Total irrigated area (share of ag. land)	Canal irrigated area (share of ag. land)	Tubewell irrigated area (share of ag. land)	Other irrigated area (share of ag. land)
Panel A. Entropy balance, 0-10km above-canal settlements, no outliers dropped				
Below-canal settlements	0.057***	0.086***	-0.003	-0.014*
(0-10km)	(0.015)	(0.011)	(0.007)	(0.008)
Distant settlements	-0.012*	-0.004	-0.004	-0.004
(15-50km)	(0.007)	(0.003)	(0.006)	(0.005)
Control group mean	0.465	0.071	0.216	0.185
Observations	103,844	104,060	104,034	103,279
R^2	0.60	0.18	0.39	0.76
Panel B. Entropy balance, 0-10km above-canal settlements, 5% outliers dropped				
Below-canal settlements	0.054***	0.094***	-0.003	-0.024***
(0-10km)	(0.016)	(0.014)	(0.010)	(0.008)
Distant settlements	-0.010	-0.007	-0.009	0.005
(15-50km)	(0.008)	(0.005)	(0.007)	(0.005)
Control group mean	0.437	0.066	0.212	0.167
Observations	55,491	55,667	55,653	55,130
R^2	0.63	0.18	0.44	0.78
Panel C. Entropy balance, 0-5km above-canal settlements, 2.5% outliers dropped				
Below-canal settlements	0.050***	0.075***	-0.005	-0.011
(0-10km)	(0.016)	(0.011)	(0.010)	(0.010)
Distant settlements	-0.017	-0.007	-0.012	0.003
(15-50km)	(0.011)	(0.005)	(0.009)	(0.007)
Control group mean	0.450	0.086	0.200	0.170
Observations	35,878	35,957	35,937	35,722
R^2	0.59	0.19	0.40	0.76
Panel D. Entropy balance, 0-20km above-canal settlements, 2.5% outliers dropped				
Below-canal settlements	0.044***	0.086***	-0.006	-0.027***
(0-10km)	(0.014)	(0.011)	(0.007)	(0.007)
Distant settlements	-0.024**	-0.005	-0.015**	-0.005
(25-50km)	(0.010)	(0.005)	(0.007)	(0.008)
Control group mean	0.454	0.071	0.211	0.178
Observations	59,036	59,121	59,163	58,617
R^2	0.66	0.22	0.43	0.78

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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Spillover Robustness: Entropy Balance, Agriculture

	Agricultural land (share of village area)	Kharif (monsoon) ag. prod (log)	Rabi (winter) ag. prod (log)	Water intensive crops (any)	Mechanized farm equip. (share of all HHs)
Panel A. Entropy balance, 0-10km above-canal settlements, no outliers dropped					
Below-canal settlements	0.017***	-0.003	0.059***	0.030*	0.002
(0-10km)	(0.006)	(0.013)	(0.020)	(0.016)	(0.002)
Distant settlements	0.003	0.007	0.024	-0.025	0.002
(15-50km)	(0.007)	(0.012)	(0.016)	(0.016)	(0.002)
Control group mean	0.574	7.755	7.331	0.680	0.043
Observations	114,967	115,148	114,879	88,268	110,421
R^2	0.54	0.84	0.59	0.66	0.30
Panel B. Entropy balance, 0-10km above-canal settlements, 5% outliers dropped					
Below-canal settlements	0.024***	0.026**	0.033	-0.011	0.002
(0-10km)	(0.009)	(0.012)	(0.024)	(0.014)	(0.003)
Distant settlements	-0.001	-0.004	0.030	-0.030	-0.003
(15-50km)	(0.008)	(0.010)	(0.021)	(0.020)	(0.002)
Control group mean	0.574	7.857	7.358	0.633	0.036
Observations	61,979	61,968	61,857	45,927	58,985
R^2	0.55	0.89	0.60	0.73	0.31
Panel C. Entropy balance, 0-5km above-canal settlements, 2.5% outliers dropped					
Below-canal settlements	0.018**	0.012	0.089***	0.021	0.004
(0-10km)	(0.008)	(0.013)	(0.020)	(0.016)	(0.003)
Distant settlements	0.012	-0.019	0.067**	-0.077***	0.000
(15-50km)	(0.010)	(0.026)	(0.031)	(0.026)	(0.003)
Control group mean	0.544	7.818	7.332	0.629	0.042
Observations	40,977	40,955	40,830	30,508	39,107
R^2	0.55	0.89	0.59	0.71	0.34
Panel D. Entropy balance, 0-20km above-canal settlements, 2.5% outliers dropped					
Below-canal settlements	0.018***	0.014	0.058**	0.027*	0.000
(0-10km)	(0.007)	(0.013)	(0.026)	(0.014)	(0.003)
Distant settlements	-0.007	-0.011	0.033	-0.033	-0.004*
(25-50km)	(0.008)	(0.014)	(0.025)	(0.025)	(0.002)
Control group mean	0.567	7.805	7.309	0.667	0.039
Observations	66,683	66,641	66,450	50,242	63,589
R^2	0.59	0.87	0.55	0.66	0.35

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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Spillover Robustness: Entropy Balance, Non-farm

	Population density (log)	Total emp (share of adult pop.)	Services emp (share of adult pop.)	Manuf. emp (share of adult pop.)	Consumption pc (log, all HHs)
Panel A. Entropy balance, 0-10km above-canal settlements, no outliers dropped					
Below-canal settlements	0.191***	0.002	0.003**	0.000	0.021***
(0-10km)	(0.024)	(0.002)	(0.001)	(0.001)	(0.005)
Distant settlements	-0.034	0.001	0.000	0.001	0.005
(15-50km)	(0.029)	(0.002)	(0.001)	(0.001)	(0.008)
Control group mean	5.665	0.088	0.057	0.021	9.653
Observations	116,773	107,081	107,081	107,081	111,140
R^2	0.32	0.12	0.10	0.18	0.41
Panel B. Entropy balance, 0-10km above-canal settlements, 5% outliers dropped					
Below-canal settlements	0.181***	0.001	0.002	0.001	0.024***
(0-10km)	(0.034)	(0.002)	(0.001)	(0.001)	(0.007)
Distant settlements	-0.056*	0.002	0.001	0.001	-0.003
(15-50km)	(0.029)	(0.004)	(0.001)	(0.002)	(0.009)
Control group mean	5.604	0.080	0.051	0.020	9.625
Observations	62,712	57,153	57,153	57,153	59,287
R^2	0.26	0.16	0.08	0.26	0.38
Panel C. Entropy balance, 0-5km above-canal settlements, 2.5% outliers dropped					
Below-canal settlements	0.160***	0.001	0.003*	0.000	0.028***
(0-10km)	(0.032)	(0.003)	(0.002)	(0.001)	(0.009)
Distant settlements	-0.042	0.007	0.001	0.002	-0.009
(15-50km)	(0.042)	(0.006)	(0.002)	(0.003)	(0.013)
Control group mean	5.515	0.094	0.055	0.023	9.640
Observations	41,450	38,045	38,045	38,045	39,321
R^2	0.24	0.18	0.09	0.25	0.41
Panel D. Entropy balance, 0-20km above-canal settlements, 2.5% outliers dropped					
Below-canal settlements	0.157***	0.002	0.002	0.001	0.022***
(0-10km)	(0.029)	(0.003)	(0.002)	(0.001)	(0.007)
Distant settlements	-0.041	-0.001	0.001	-0.001	-0.001
(25-50km)	(0.031)	(0.003)	(0.002)	(0.002)	(0.008)
Control group mean	5.620	0.079	0.052	0.019	9.646
Observations	67,473	62,127	62,127	62,127	63,954
R^2	0.29	0.15	0.10	0.22	0.44

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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Spillover Robustness: Entropy Balance, Landownership

	Consumption pc (log, landless HHs)	Consumption pc (log) (log, land-owning HHs)	Middle school ed. (share of landless pop.)	Middle school ed. (share of land-owning pop.)
Panel A. Entropy balance, 0-10km above-canal settlements, no outliers dropped				
Below-canal settlements	0.005	0.021***	0.012***	0.025***
(0-10km)	(0.005)	(0.006)	(0.003)	(0.005)
Distant settlements	0.012*	0.004	0.000	-0.004
(15-50km)	(0.007)	(0.009)	(0.004)	(0.005)
Control group mean	9.523	9.752	0.258	0.363
Observations	107,339	106,445	107,114	106,826
R^2	0.37	0.40	0.43	0.52
Panel B. Entropy balance, 0-10km above-canal settlements, 5% outliers dropped				
Below-canal settlements	0.006	0.024***	0.015***	0.031***
(0-10km)	(0.005)	(0.006)	(0.003)	(0.005)
Distant settlements	0.012	-0.007	-0.002	-0.006
(15-50km)	(0.009)	(0.010)	(0.005)	(0.006)
Control group mean	9.487	9.730	0.250	0.353
Observations	56,837	57,490	56,689	57,611
R^2	0.35	0.41	0.45	0.53
Panel C. Entropy balance, 0-5km above-canal settlements, 2.5% outliers dropped				
Below-canal settlements	0.006	0.026***	0.012***	0.027***
(0-10km)	(0.007)	(0.010)	(0.003)	(0.005)
Distant settlements	0.001	-0.025*	0.000	-0.006
(15-50km)	(0.014)	(0.015)	(0.007)	(0.009)
Control group mean	9.506	9.739	0.252	0.349
Observations	37,872	38,061	37,782	38,151
R^2	0.37	0.40	0.42	0.54
Panel D. Entropy balance, 0-20km above-canal settlements, 2.5% outliers dropped				
Below-canal settlements	0.012*	0.025***	0.015***	0.026***
(0-10km)	(0.007)	(0.008)	(0.004)	(0.005)
Distant settlements	0.009	-0.005	0.001	-0.005
(25-50km)	(0.009)	(0.010)	(0.005)	(0.006)
Control group mean	9.514	9.742	0.259	0.361
Observations	61,456	61,808	61,320	61,979
R^2	0.38	0.43	0.42	0.53

$^{*}p < 0.10,^{**}p < 0.05,^{***}p < 0.01$

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Town Robustness

	Population (log)		Town Existence (pop. 5,000)	
*Panel A. Add State * Year Fixed Effects*				
Command area in town catchment area *(binary treatment)*	0.077***		0.031***	
	(0.028)		(0.013)	
Share of town catchment area in command area *(continuous treatment)*		0.234***		0.091***
		(0.041)		(0.018)
Observations	302691	64260	302691	64260
R^2		0.840		0.720
Panel B. Drop Years After 1990				
Command area in town catchment area *(binary treatment)*	0.096***		0.025*	
	(0.038)		(0.016)	
Share of town catchment area in command area *(continuous treatment)*		0.248***		0.070***
		(0.056)		(0.024)
Observations	231436	52080	231436	52080
R^2		0.830		0.700
Panel C. Define Catchment Area as 10 km Radius				
Command area in town catchment area *(binary treatment)*	0.101***		0.029**	
	(0.032)		(0.014)	
Share of town catchment area in command area *(continuous treatment)*		0.250***		0.083***
		(0.038)		(0.017)
Observations	301519	49464	301519	49464
R^2		0.830		0.700
Panel D. Define Catchment Area as 30 km Radius				
Command area in town catchment area *(binary treatment)*	0.107***		0.028**	
	(0.030)		(0.014)	
Share of town catchment area in command area *(continuous treatment)*		0.289***		0.076***
		(0.047)		(0.018)
Observations	301966	74244	301966	74244
R^2		0.830		0.700

$^{*}p < 0.10, ^{**}p < 0.05, ^{***}p < 0.01$

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Measuring agricultural productivity

- No below-district data on agricultural productivity in India, but satellites see all with very high resolution
- Vegetation Index - either NDVI or EVI
  - Widely used proxy for agricultural productivity
  - MODIS sensor, 250m resolution
- We could use mean, max, and delta (difference between late growing season max and early growing season average). We need to test:
  - How much does the growing season change from year-to-year?
  - How much does the growing season vary spatially in one year?
  - How much does the growing season vary by crop?
- Validation: use Cost of Cultivation data to ensure that our NDVI/EVI measure is able to estimate Kharif and Rabi yields

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Cost of cultivation data validation

- Cost of Cultivation Data
  - Farmers from 2,073 villages surveyed about cultivation for the season, including yields for each crop at the plot level
  - Data collected in 3 rounds: 2008-11, 2011-14, and 2014-17
- We select the log of the delta EVI measure
  - No meaningful difference between EVI and NDVI
  - The delta measure subtracts out non-crop biomass and does a better job estimating yields than the seasonal mean
  - We do a fairly good job estimating yields with district and year fixed effects, meaning we are capturing local spatial variability in the yield data with this EVI measure

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EVI/NDVI definitions

We use the following definitions for the mean/max/delta of EVI/NDVI measure to test which best approximates yields.

Season	Max (full season)	Mean (early season)
Kharif	Late May - Early October	Late May - Early October OR June
Rabi	Late December - Late March (~12/19-4/06)	November
Zaid	March - June	March - June

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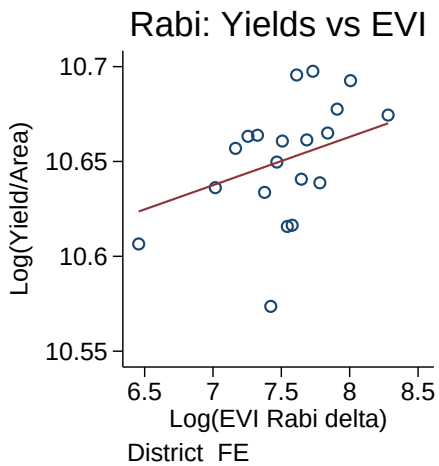
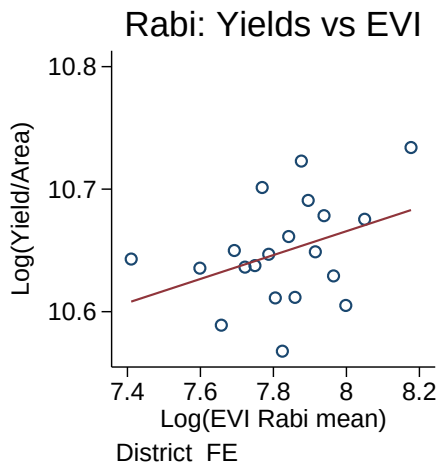
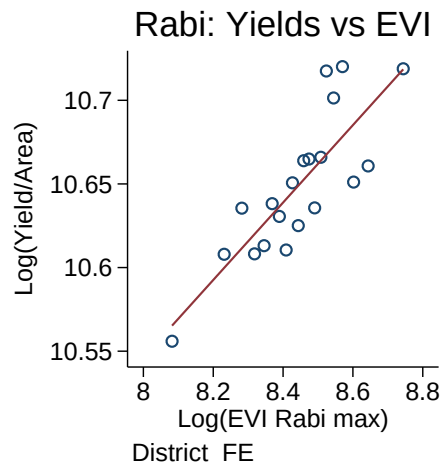
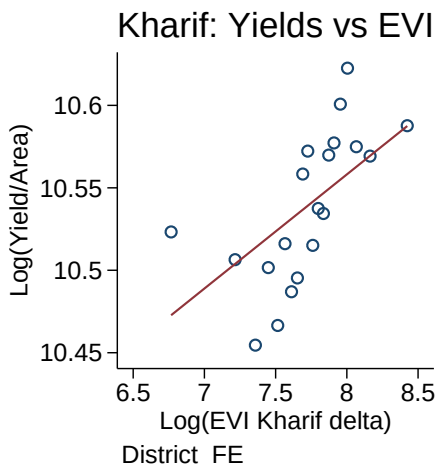
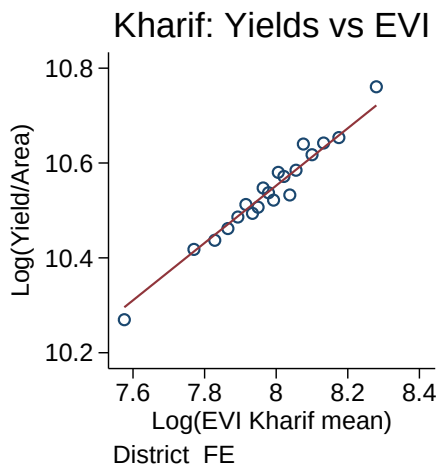
Binscatters with district FE

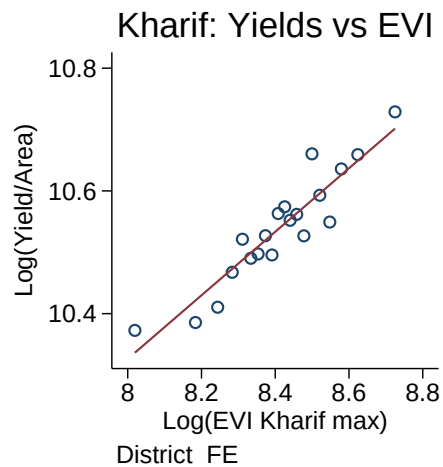












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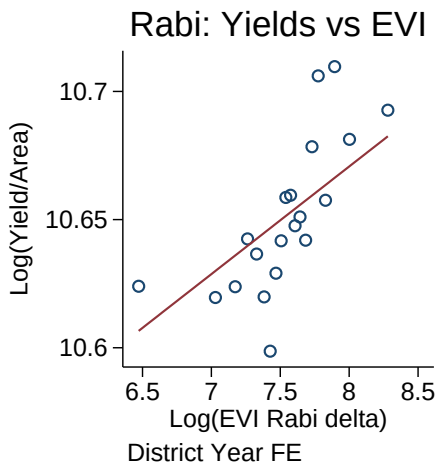
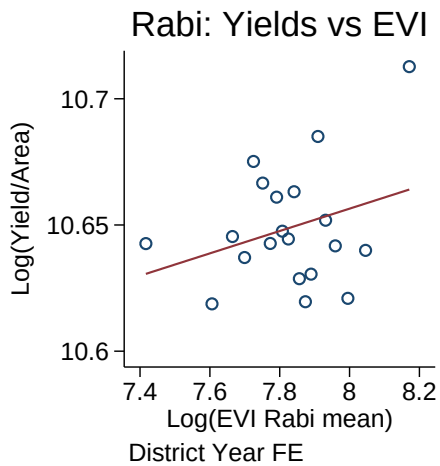
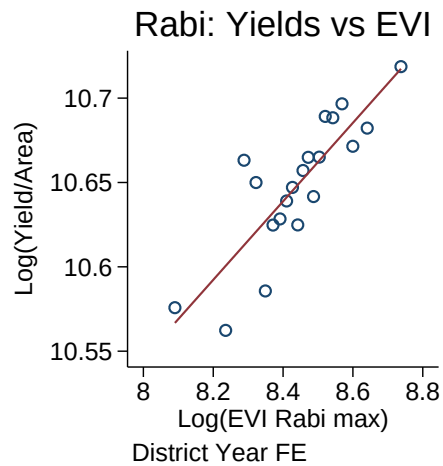
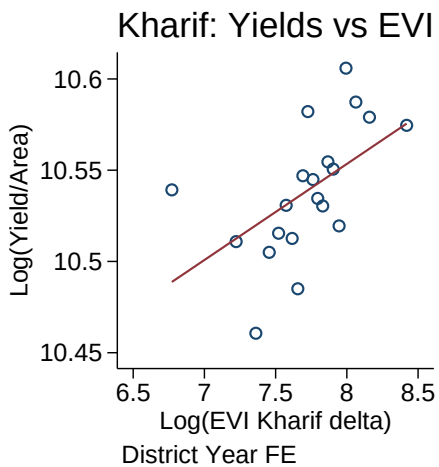
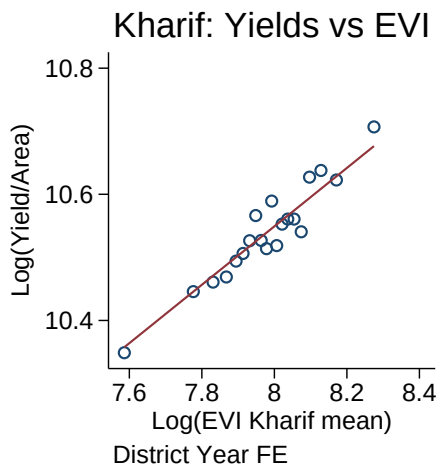
Binscatters with district year FE

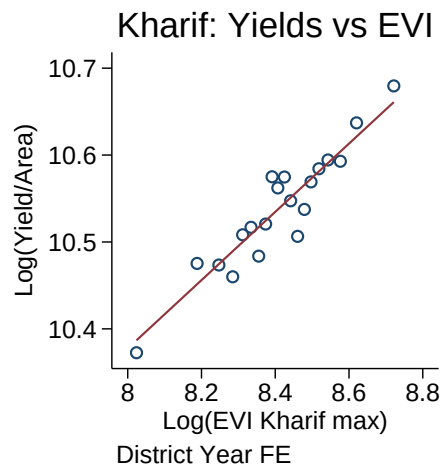












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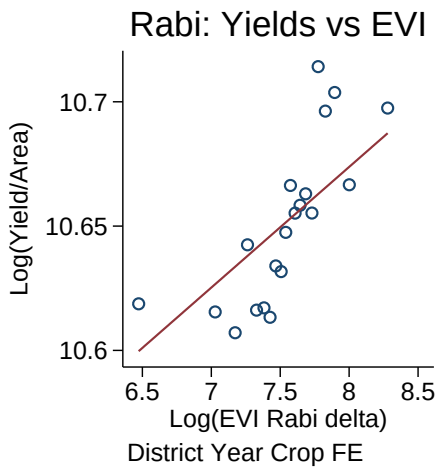
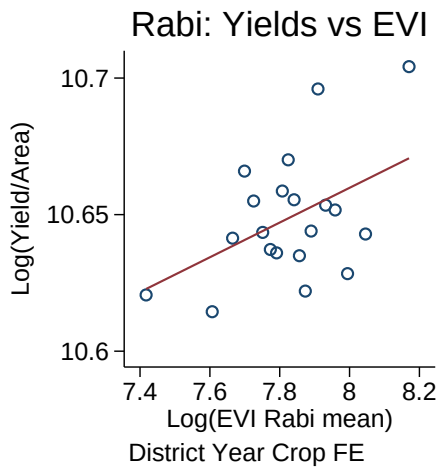
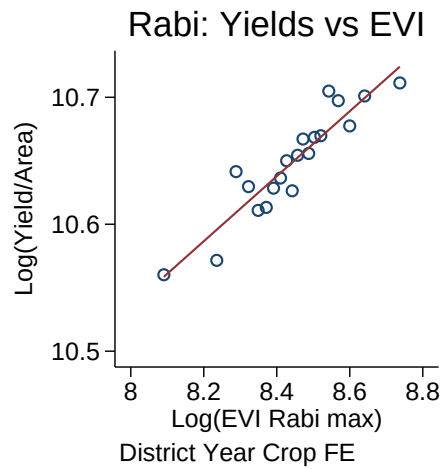
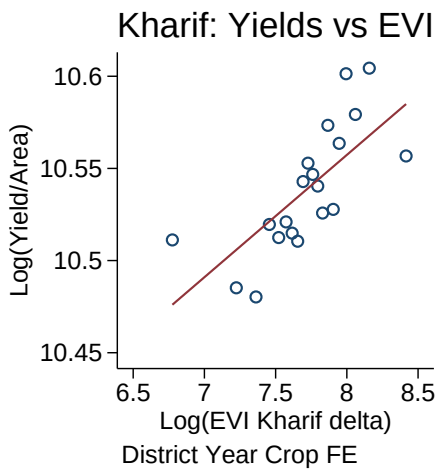
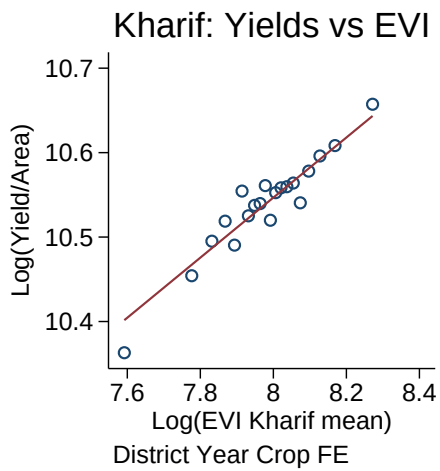
Binscatters with district, crop, year FE

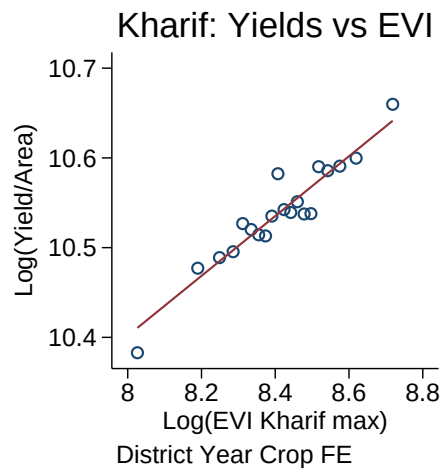












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Correlation between cost of cultivation yields and EVI

Fixed effects for the year and district and crop

	(1) Ln(Yield/Area)	(2) Ln(Yield/Area)	(3) Ln(Yield/Area)	(4) Ln(Yield/Area)	(5) Ln(Yield/Area)	(6) Ln(Yield/Area)
Ln(EVI Delta Kharif)	0.0664***					
	(0.0124)					
Ln(EVI Mean Kharif)		0.356***				
		(0.0297)				
Ln(EVI Max Kharif)			0.333***			
			(0.0283)			
Ln(EVI Delta Rabi)				0.0485***		
				(0.00989)		
Ln(EVI Mean Rabi)					0.0636**	
					(0.0229)	
Ln(EVI Max Rabi)						0.256***
						(0.0263)
Constant	10.03***	7.702***	7.735***	10.29***	10.15***	8.488***
	(0.0955)	(0.237)	(0.238)	(0.0746)	(0.179)	(0.223)
Dist_FE	Yes	Yes	Yes	Yes	Yes	Yes
Year_FE	Yes	Yes	Yes	Yes	Yes	Yes
Crop_FE	Yes	Yes	Yes	Yes	Yes	Yes

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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Measuring consumption

- Earnings/consumption unavailable except in district-identified sample surveys
- SECC data has only assets, censored earnings for highest earning member
- Solution: small area estimation (Elbers, Lanjouw and Lanjouw, 2003)
  - Predict consumption using regression coefficients from another detailed dataset that contains all variables (IHDS-II)
- Less variance because no error term but highly correlated with other measures of productivity (Asher et al, 2020)
- Outcome of interest: mean predicted consumption per capita by community (SC, Muslim, and Other)

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