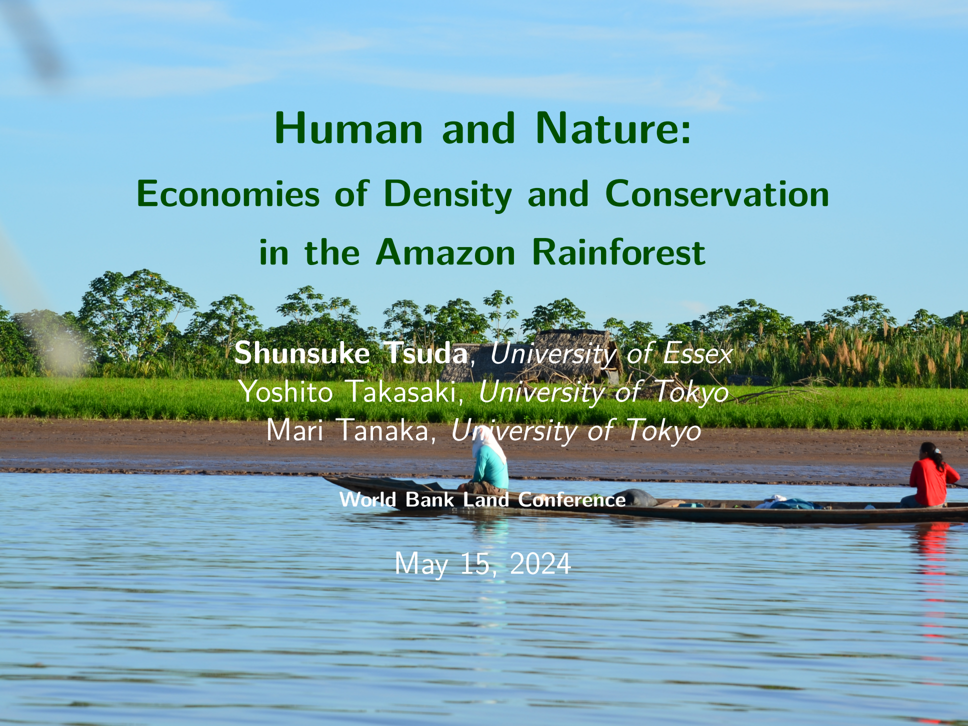

Human and Nature:

Economies of Density and Conservation in the Amazon Rainforest

Shunsuke Tsuda, *University of Essex*
Yoshito Takasaki, *University of Tokyo*
Mari Tanaka, *University of Tokyo*

World Bank Land Conference

May 15, 2024

Human-Nature Interactions across Space in Rainforests

Tropical forests:

- Home to much of the world's bio-diversity and natural resources
- Growing concerns about the role of small-scale farmers in conservation

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e.g. Sectoral reallocation: Cost of forest clearing $\uparrow \Rightarrow$ Fishing/hunting $\uparrow \Rightarrow$ Bio-diversity $\downarrow$
Spatial reallocation: Protected areas $\Rightarrow$ Resource depletion in other locations $\uparrow$

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Research question: Are there policies that improve both local populations' welfare and ecological conservation?

This Paper

Rural Agglomeration Economies and the Conservation

1. Spatial GE model with density externalities in multiple rural sectors
   - **Agglomeration**: Population density $\uparrow \Rightarrow$ Productivity $\uparrow$
   - **Congestion**: Population density $\uparrow \Rightarrow$ Productivity $\downarrow$

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- **Agglomeration in agriculture > Congestion in access to land**

  Concentration ⇒ Productivity ↑ & Deforestation *per farmer* ↓

- **Congestion with spatial spillovers in natural resource extraction**

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❸ Counterfactuals

Combining *well-targeted* place-based protection policies and transport infrastructure improves both human & ecological well-being:

- Local populations' welfare ↑
- Deforestation ↓
- Natural resource depletion ↓

Data & Facts

The Peruvian Amazon

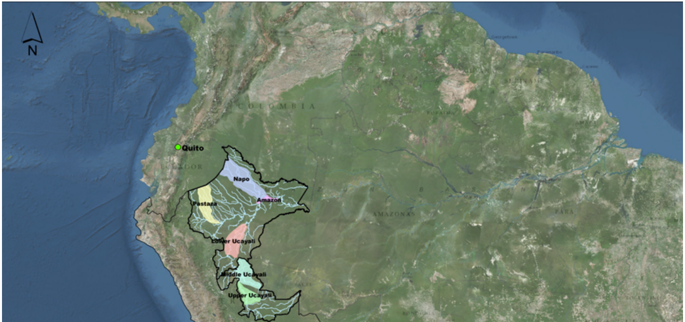
❶ Traditional ways of life in remote areas without modern technology and large-scale external investments (in contrast to the Brazilian Amazon)

⟹ Attribute resource extractions to small-scale farmers and hunter-gatherers and focus on externalities that they cause

- Primary livelihoods: agriculture (shifting cultivation), fishing, hunting, forest products
- Small-scale deforestation recently increased in the Amazon (Kalamandeen et al. 2018)

❷ River networks almost solely constitute the transportation routes

⟹ Identify key structural parameters by exploiting exogenous river shapes



Main Data Sources

1. **Peruvian Amazon Rural Livelihoods and Poverty (PARLAP)** project:
   - **Community census (CC, 2012-2014)** from rural communities ($n = 919$) in the four major river basins

     → Sectoral populations, prices, transport modes, and many others

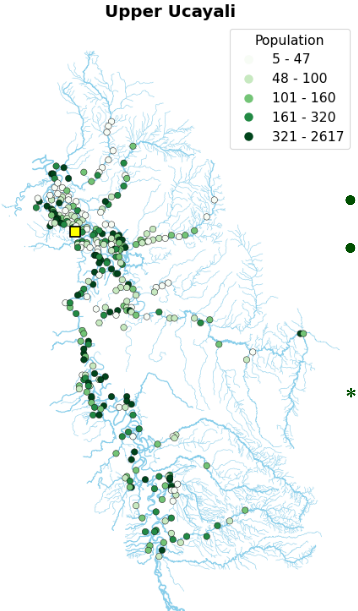
2. **Satellite images**:
   - Forest cover measures by remote sensing experts
   - Grid cell-level (1km × 1km) and community-level

3. **National censuses** by National Institute of Statistics and Informatics (INEI):
   - Peru Population and Housing Census (2007, 2017)

     → Complement population information (esp. urban populations)
   - Peruvian Agricultural Census (2012)

     → Technology use by all producers

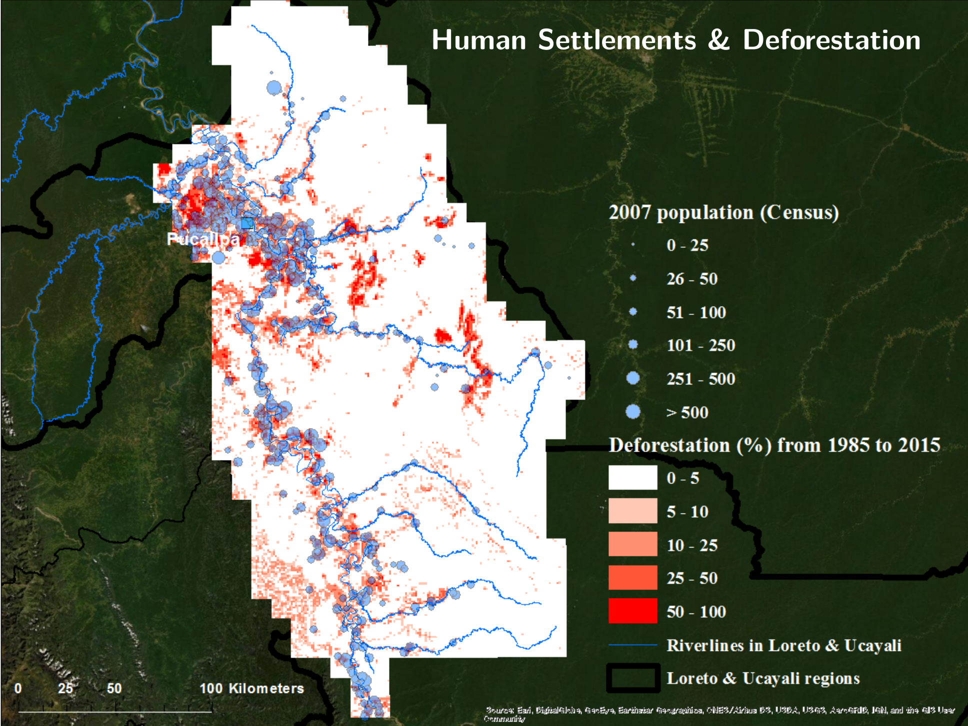
Spatial Concentration and Dispersion of Communities and Populations



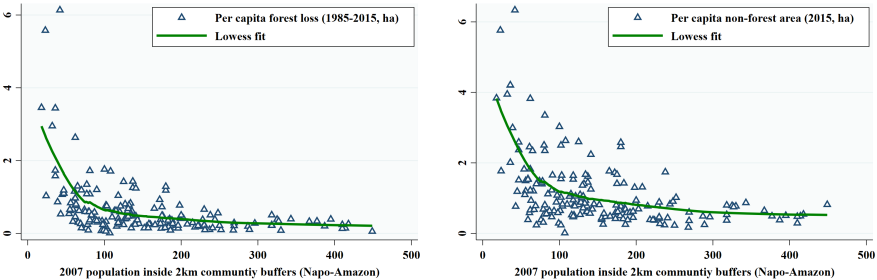
- A river basin
- The legend is based on quantiles:

  ≈ 80% of the rural communities have populations smaller than 320

* Mostly indigenous and folk populations
Colonist settlements ≈ 1.4% of communities


Human Settlements & Deforestation
Pucallpa
2007 population (Census)
0 - 25
26 - 50
51 - 100
101 - 250
251 - 500
> 500
Deforestation (%) from 1985 to 2015
0 - 5
5 - 10
10 - 25
25 - 50
50 - 100
Riverlines in Loreto & Ucayali
Loreto & Ucayali regions
0 25 50 100 Kilometers
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Negative and Convex Relationship between Population & *Per Capita* Land Footprint



Suppose, for simplicity, take this as structural, then it implies:

- Congestion force in forest clearing (without the land market)
- A mean preserving reduction in the variance of settlement size can decrease total deforestation

Dynamics?

Model

Spatial Model of Rainforest Communities

Spatial general equilibrium in a river basin with:

- Trade across multiple **rural** locations and one urban center
- Mobile population within the river basin

3 Sectors:

- Agriculture (Ag): produced in rural locations
- Natural resource extraction (Nr): produced in rural locations
- Urban good (M): produced in the urban center

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The balance b/w concentration and dispersion forces determines the equilibrium:

- Concentration forces:
    - **Agglomeration in agricultural production**
    - Higher market access
    - Proximity to an urban center
- Dispersion forces:
    - **Congestion in land access by clearing forests**
    - **Congestion in natural resource extraction**

Agriculture with Congestion & Agglomeration Externalities

Land access by forest clearing: $$L_o(j) = \underbrace{A_{o,L} N_{o,Ag}^{-\mu_L}}_{\text{productivity}} \cdot N_{o,L}(j)$$

Final output: $$Q_{o,Ag}(j) = \underbrace{z_{o,Ag}(j) N_{o,Ag}^{\mu_{Ag}}}_{\text{productivity}} \cdot N_{o,C}(j)^{\gamma} L_o(j)^{(1-\gamma)}$$

- $N_{o,L}$ & $N_{o,C}$: Employment for forest clearing & cropping
- $N_{o,Ag} = N_{o,L} + N_{o,C}$: Total employment for agriculture

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- $N_{o,L}$ & $N_{o,C}$: Employment for forest clearing & cropping
- $N_{o,Ag} = N_{o,L} + N_{o,C}$: Total employment for agriculture
- μ_L: Parameter governing **congestion forces in forest clearing** ▸ Why?
- μ_{Ag}: Parameter governing **agglomeration forces in agricultural production and marketing** (e.g. facilitating collective investments)

- $A_{o,L}$: productivity fundamentals
- $z_{o,Ag}(j)$: Fréchet shock of variety j productivity
(θ: comparative advantage; $A_{o,Ag}$: absolute advantage)

Estimation

Estimating the Model in a Sequential Procedure

Parameter	Description	Estimation strategy
δ_K	Elasticity of trade cost $(K = Ag, Nr, M)$	Commodity prices from the CC
λ_{up}, λ_{land}	Relative costs in terms of downstream river	Travel time and transport costs survey
σ	Within-sector elasticity of substitution	Expenditure information from ENAHO
$\bar{\sigma}$	Across-sector elasticity of substitution	Expenditure information from ENAHO
γ	Labor share in agricultural production	From the literature
θ	Trade elasticity	From the literature
μ_L	**Congestion in forest clearing**	Linear IV using the community-level data
μ_{Ag}	**Agglomeration in agricultural production**	Model inversion and linear IV
μ_{Nr}	**Congestion in natural resource extraction**	Model inversion and non-linear GMM
ν	**Spatial decay in natural resource access**	Model inversion and non-linear GMM
$\{A_{o,K}\}$	Absolute advantages $(K = Ag, Nr)$	Calibration
A_M	Absolute advantages in the urban sector	Calibration

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1. Obtain some parameters without solving the model ▸ Details
2. Given the parameters obtained in the previous steps, invert the model to recover wages and productivities that rationalize the observable sectoral populations as a spatial equilibrium ▸ Details
3. Employ GMM to estimate parameters governing the **density externalities** in productivities obtained in the previous step

Step 3. Density Externalities in Agriculture

- Inverted productivity composites of agriculture:

$$\tilde{A}_{o,Ag} \equiv \underbrace{A_{o,Ag} A_{o,L}^{(1-\gamma)\theta} \kappa_1^{\theta}}_{\text{fundamentals}} \cdot \underbrace{N_{o,Ag}^{\tilde{\mu}_{Ag}\theta}}_{\text{externalities}} \quad \text{where } \tilde{\mu}_{Ag} \equiv \mu_{Ag} - (1-\gamma)\mu_L$$

- Procedure:
  1. Estimate $\tilde{\mu}_{Ag}$
  2. Estimate μ_L
  3. Back out μ_{Ag}

Step 3. Agglomeration Externality in Agriculture via Linear IV

- Inverted productivity composites of agriculture:

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- Empirical specification:

$$\ln \tilde{A}_{o,Ag} = \tilde{\mu}_{Ag}\theta \ln N_{o,Ag} + X_o'\beta + \phi_B + \epsilon_{o,Ag}$$

- "River Network Access" as an IV for $\ln N_{o,Ag}$:

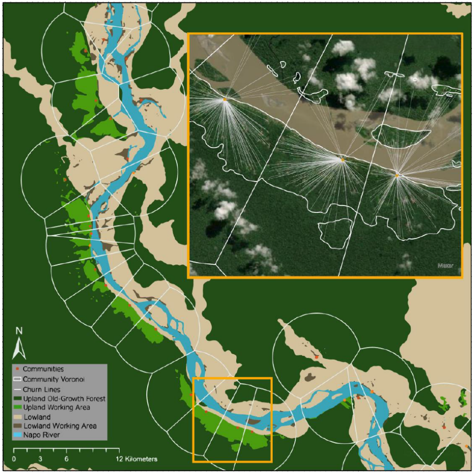
  $RNA_o \equiv \sum_{d \in RC} (\tilde{\tau}_{od})^{-\theta}$ where RC: grid cells with rivers

- Identifying assumption ▸ Intuition:

  After controlling for ▸ geographic characteristics of the own location, productivity fundamentals are uncorrelated with accessibility to other locations

- A similar strategy for estimating μ_L using the community-level land footprint from satellite images due to common residual factors

▸ Historical IV ▸ First stage ▸ Randomness



Voronoi Polygons and Land Footprint around the Census Communities

Notes: To proxy community boundaries for agricultural land use, we partition land in the study area into voronoi polygons. Within each community voronoi polygon, we detect all patches of agricultural fields and secondary forests through satellite images. We then sum them up to calculate the land footprint of each community. See Coomes et al. (2021) for more details.

Empirical specification: $\ln \frac{L_o}{N_{o,Ag}} = -\mu_L \ln N_{o,Ag} + X'_o\beta + \phi_B + \epsilon_{o,L}$

Step 3. Density Externalities in Rural Sectors

Parameter	Point estimate	Standard errror	Description
(A) Agriculture			
$\tilde{\mu}_{Ag}$	0.064	0.010	$= \mu_{Ag} - (1-\gamma)\mu_L$
	J test p-value $= 0.648$		
μ_L	0.522	0.094	Congestion in forest clearing
μ_{Ag}	0.273		Agglomeration in agricultural production
(B) Natural resource extraction			
μ_{Nr}	0.335	0.042	Congestion in natural resource extraction
ν	0.593	0.075	Spatial decay of congestion externality
	J test p-value $= 0.821$		

Notes: Estimates of density externalities in agriculture (panel A) are based on the linear specification using $\ln RNA_o$ and the initial community existence in 1940 as instruments. Estimates of parameters governing congestion externality in natural resource extraction (panel B) are based on the non-linear GMM using $\ln RNA_o$ and $\{\ln \sum_{d|D_{o,d}\leq x} RNA_d\}$ for $x \in \mathcal{X} = \{2, 5, 10, 25, 50, 75, 100\}$ as instruments.

(A) Agglomeration in agriculture > Congestion in access to land

- Population ↑ ⇒ Productivity ↑ & Deforestation *per farmer* ↓
- Without the agglomeration ⇒ welfare ↓ 10% & Deforestation ↑ 30%

▸ Robustness to different IVs and samples ▸ Robustness to different controls

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(B) Congestion with spatial spillovers from surrounding populations

$$Q_o^{Nr}(j) \quad = \quad z_{o,Nr}(j)\Big[\sum_{d \in \mathcal{R}} D_{od}^{-\nu} N_{d,Nr}\Big]^{-\mu_{Nr}} \cdot N_{o,Nr}(j)$$

▸ Nonlinear GMM details

Mechanisms behind the Agglomeration Externality in Agriculture

1. Economies of scale in transport technology ▸ Details
   - Endogenous transport modes (different types of boats available)
   - Endogenous transaction costs
   - Trade costs decrease with origin populations
   - Isomorphic to the original model

2. Economies of scale in agricultural intensification ▸ Details
   - Direct inputs into land and crops (insecticides, herbicides, fungicides)
   - Complementary equipment (sprayers)
   - Crop processing technology to facilitate marketing (grain mill)

Counterfactuals

Overview

1. Combining ***well-targeted*** place-based protection policies and transport infrastructure simultaneously achieves:
    - Local populations' welfare $\uparrow$
    - Deforestation $\downarrow$
    - Natural resource depletion $\downarrow$

   (while any single policy cannot)

Overview

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2. The *direction* of any environmental impact depends on *where* the place-based policy is implemented

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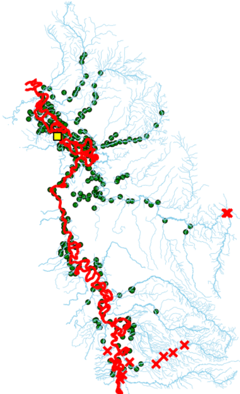
Counterfactuals	**Welfare**	**Deforestation**	**Natural resource depletion**
(A) Protection policies ‣ Details			
i. Protecting the rural frontier	−	−	−
ii. Targeting the smallest communities	−	−	+
(B) River Transport infrastructure ‣ Details			
i. Connecting hinterlands to the center	+	−	?
ii. Concentrating in the center	+	+	?
(A) i. + (B) i.	**+**	**−**	**−**

(A) Protecting the rural frontier &
(B) Transport infrastructure that connects hinterlands to the center

River basin	Welfare	Deforestation	Natural resource depletion
Napo	+1.6%	-6.7%	-0.6%
Pastaza	+1.0%	-4.7%	-0.3%
LowerUcayali	+2.1%	-1.0%	-2.4%
UpperUcayali	+1.0%	-3.1%	-0.5%



The trade-offs are relaxed by:

(A) ×: Treated areas for resettlement

i.e. Shrink the outer edge within a basin where human settlement is advancing into undeveloped areas

&

(B) **Red river lines**:

- No asymmetric transport costs
- -20% of the downstream-river-equivalent distance

(Robust across all four basins)

(A) Protecting the rural frontier &
(B) Transport infrastructure that connects hinterlands to the center

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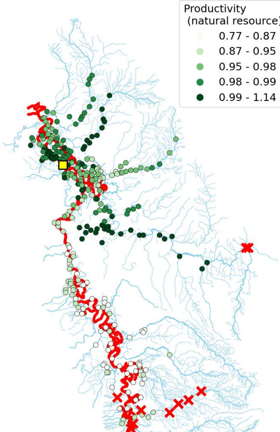

Intuition:

(A) More compact basin for human settlements

- Surrounding population density ↑ in most of populated areas
- Congestion externality with spatial spillovers ↑ & Productivity ↓ in most areas

⇒ Overall natural resource depletion ↓

Legend: values in the counterfactual relative to those in the benchmark equilibrium

(A) Protecting the rural frontier &
(B) Transport infrastructure that connects hinterlands to the center

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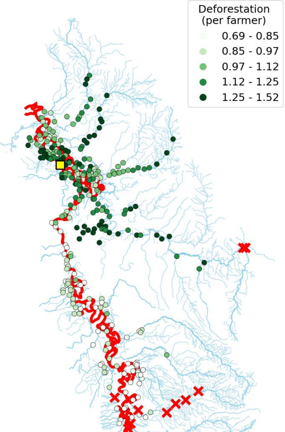

Intuition:

(B) Integrated between the center and hinterlands

- Total deforestation ↓ given the convex structure of congestion forces in access to land
- Reallocate farmers from the central to remote areas
- Settlement size variance ↓ & Agricultural productivity in remote areas ↑

Agglomeration benefits spread more evenly across the basin with more medium-sized settlements

Conclusions

- Applies a multi-sector spatial GE model to rainforest communities
- Estimates density externalities (agglomeration & congestion)

RQ. *How can we design policies that improve both local populations' welfare and ecological conservation?*

- Combination of a protection policy and transport infrastructure investments
- Policies that spread the agglomeration benefits more evenly across space and consolidate congestion forces into a more compact space are desirable to the environment

Appendix

Static vs. Dynamic Variations in Forest Cover

- Shifting cultivation with the swidden-fallow cycle:
    1. Clear primary (old-growth) forests, burn the vegetation to obtain land plots, and plant crops
    2. When plots become no longer productive, plots are left in fallow and the secondary forest regrows
    3. After several years of fallow, farmers clear such secondary forests again ($\rightarrow$ 1.)

Static vs. Dynamic Variations in Forest Cover

- Shifting cultivation with the swidden-fallow cycle:
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  2. When plots become no longer productive, plots are left in fallow and the secondary forest regrows
  3. After several years of fallow, farmers clear such secondary forests again ($\rightarrow$ 1.)
- Although the deforested locations around the community are moving over time due to this cycle, at any given moment the stock of forest fallow and the total deforested area around the community remain relatively constant (Coomes et al. 2021)

$\Rightarrow$ The cross-sectional relationship between the settlement size and deforestation has a more significant variation, which motivates our static theoretical model

Back

Congestion Forces in Land Access

Back

- Farmers clear forests to obtain land only nearby their residential locations along the river (mean/median of land footprint depths = 1 km/0.85km)
  - High monitoring cost with weak property rights
  - High cost of carrying products from inland to the riverside
- Costs of monitoring and negotiating land allocations to farmers increase with the agricultural population

⇒ Deforested areas cannot increase proportionally to the increase in the community population size

- These costs may be small among very small communities: consistent with the convexity

Step 1. Obtaining Parameters without Solving the Model

Parameter	Description	Estimation strategy	Value
δ_{Ag}	Elasticity of trade cost	Commodity prices from the CC	0.178
δ_{Nr}	Elasticity of trade cost	Commodity prices from the CC	0.137
δ_{M}	Elasticity of trade cost	Commodity prices from the CC	0.098
λ_{up}	Relative upstream-river travel cost	Travel time and transport costs survey	1.282
λ_{land}	Relative land travel cost	Travel time and transport costs survey	36.767
σ	Within-sector elasticity of substitution	Expenditure information from ENAHO	2.401
$\bar{\sigma}$	Across-sector elasticity of substitution	Expenditure information from ENAHO	0.752
γ	Labor share in agricultural production	From the literature	0.6
θ	Trade elasticity	From the literature	7.8

▸ Back

Step 2. Model Inversion

- Observable data: sectoral populations ($\{N_{o,Ag}\}$, $\{N_{o,Nr}\}$, $\{N_{u,M}\}$)
- Use the $2|\mathcal{R}| + 1 + |\mathcal{I}|$ equations from the spatial equilibrium conditions (sectoral labor market clearing + utility equalization across space)

  with the observables

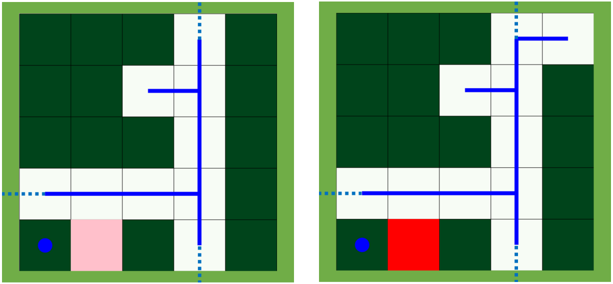
  to solve for $2|\mathcal{R}| + 1 + |\mathcal{I}|$ unknowns (productivity composites + wages): $\{\tilde{A}_{o,Ag}\}$, $\{\tilde{A}_{o,Nr}\}$, $A_{u,M}$, $\{w_o\}$

  → Use the inverted productivity composites as data in the next step

▸ Back

Intuition of Identifying the Density Externalities

$RNA_o \equiv \sum_{d \in RC} (\tilde{\tau}_{od})^{-\theta}$: River Network Access ($RC$: white cells)



RNA **at the pink cell** $<$ RNA **at the red cell**

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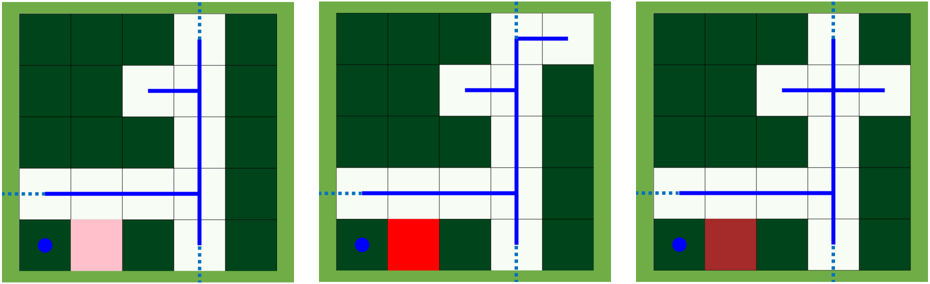
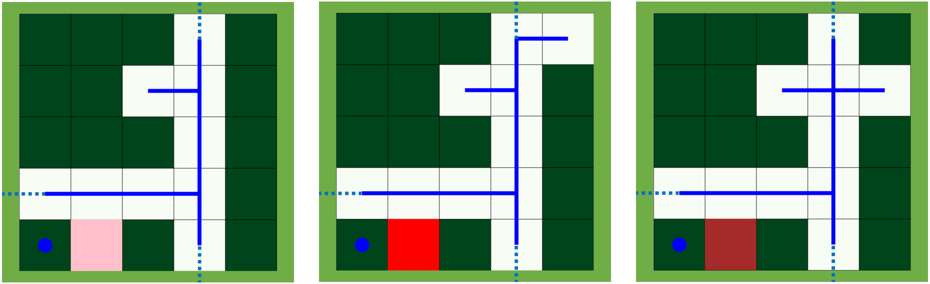


RNA **at the pink cell** $<$ RNA **at the red cell** $<$ RNA **at the brown cell**

Intuition of Identifying the Density Externalities

$RNA_o \equiv \sum_{d \in RC} (\tilde{\tau}_{od})^{-\theta}$: River Network Access ($RC$: white cells)



RNA **at the pink cell** < RNA **at the red cell** < RNA **at the brown cell**

- **Independence**: Given the same observable agricultural conditions (river proximity, water areas, soil conditions, etc), unobservable productivity fundamentals are uncorrelated with the variation in RNA *that stems from exogenous river shapes in locations far away from the own location*
- **Exclusion**: RNA (as a market potential shifter) affects productivity only through its effect on employment and thus through externalities that arise

Back

Geographic Controls

- River cell dummy
- Distance to the river point and its square
- Interaction between the above two
- River confluences
- Elevation
- Flood experience
- Geology measures
- Water (main and non-main) areas
- Distance to the urban center

Back

Historical IV

IV: Community existence in its current location by 1940

- The primary reason for early settlement was the opportunity to extract natural resource products
- The Amazon Rubber Boom:
  - Began the late 19th century, but collapsed around 1940
  - Significantly impacted initial settlements (Barham et al. 1996; Coomes 1995)

⇒ The locations of communities established before 1940 were likely to be determined primarily by natural resource endowments, not by advantages in agricultural productivity

Back

Table: River Networks, Initial Communities, and Current Populations

	$\log(N_{o,Ag})$			Community existence (1940)	
	(1)	(2)	(3)	(4)	(5)
$\log(RNA_o)$	0.758***		0.711***	-0.0145	0.0699
	(0.223)		(0.218)	(0.0254)	(0.0726)
Community existence (1940)		0.740***	0.730***		
		(0.0983)	(0.0980)		
Basin FE	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	No	Yes
Mean (Dep. var.)	4.322	4.322	4.322	0.194	0.194
SD (Dep. var.)	1.192	1.192	1.192	0.395	0.395
R^2	0.154	0.195	0.206	0.094	0.117
Observations	893	893	893	904	899

Notes: Robust standard errors in parentheses. The sample includes 1 square km grid cells that have positive populations. Geographical controls include a dummy of high river orders (4 and 5), distance to the urban center, distance to the river, squared distance to the river, interaction terms of these two variables with a river cell dummy, elevation, river confluences, flood vulnerability, geology measures, and open water access measures.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

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(A) River Network Access

	(1) Water share: non-main channel	(2) River confluence: 1st×2nd or 2nd×3rd	(3) River confluence: 3rd×4th	(4) Flood vulnerability	(5) Pleistocene soil share	(6) Tertiary soil share
$\log(RNA_o)$	0.00751	0.0470	-0.0743	-0.217	-0.0444	-0.0498
	(0.0161)	(0.0470)	(0.0618)	(0.307)	(0.0362)	(0.0474)
Mean (Dep. var.)	0.030	0.077	0.083	1.606	0.021	0.211
SD (Dep. var.)	0.087	0.266	0.277	1.606	0.115	0.344
R^2	0.068	0.095	0.137	0.130	0.057	0.735
Observations	899	899	899	899	899	899

(B) Early human settlements

	(1) Water share: main channel	(2) Water share: non-main channel	(3) Flood vulnerability	(4) Floodplain soil share	(5) Pleistocene soil share	(6) Tertiary soil share
Community existence (1940)	0.0263	-0.00352	0.218	0.00191	0.00777	-0.0108
	(0.0193)	(0.00698)	(0.142)	(0.0268)	(0.0122)	(0.0257)
Mean (Dep. var.)	0.109	0.030	1.606	0.584	0.021	0.211
SD (Dep. var.)	0.203	0.087	1.606	0.359	0.115	0.344
R^2	0.162	0.038	0.116	0.250	0.030	0.243
Observations	899	899	899	899	899	899
Basin FE	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Robust standard errors in parentheses. The sample includes 1 square km grid cells that have positive populations. In panel (A), geographical controls include a dummy of high river orders (4 and 5), distance to the urban center, distance to the river, squared distance to the river, interaction terms of these two variables with a river cell dummy, elevation, water share of main channel rivers, and floodplain soil share. In panel (B), geographical controls include a dummy of high river orders (4 and 5), distance to the urban center, distance to the river, squared distance to the river, interaction terms of these two variables with a river cell dummy, elevation, and river confluences.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

▸ Back

Step 3. Congestion in Natural Resource Extraction with Spatial Spillovers via Non-Linear GMM

- Inverted productivity composites of natural resource extraction:

$$\tilde{A}_{o,Nr} \equiv \underbrace{A_{o,Nr}}_{\text{fundamentals}} \cdot \underbrace{[\sum_d D_{od}^{-\nu} N_{d,Nr}]^{-\mu_{Nr}\theta}}_{\text{externalities}}$$

- Moment conditions:

$$\mathbb{E}[\epsilon_{o,Nr} \ln RNA_o] = 0 \quad \text{and} \quad \mathbb{E}[\epsilon_{o,Nr} \ln(\sum_{d|D_{o,d} \leq x} RNA_d)] = 0, \; x \in \mathcal{X}$$

  - $\epsilon_{o,Nr}$: the residual variation in $\ln A_{o,Nr}$ (productivity fundamentals)
  - $\mathcal{X} = \{2, 5, 10, 25, 50, 75, 100\,(\text{km})\}$
  - Similar to the identification strategy by Ahlfeldt et al. (2015)

- Estimate ν & μ_{Nr} by the two-step nonlinear GMM

Across-sector externality? Back

Across-Sector Externality?

- There may exist the across-sector externality——the effect of clearing forests for agriculture on the productivity of natural resource extraction
- We are not incorporating it. 3 comments:

1. The spatial extent of these sectors' activities is distinct:
   - Deforestation for agricultural land is distributed along the rivers: mean, median, max (land footprint depths) = 1 km, 0.85km, 5.5 km
   - Natural resources are also extracted in deep inland areas away from the river
2. Natural resource endowments are not significantly correlated with the community-level land footprint Table
3. This model choice does not affect the inversion problem, but affects outcomes in counterfactual policy simulations:
   - We investigate policies that reduce total deforestation in a river basin
   - We can interpret these policies' welfare effects as lower bounds

Back (Model) Back (Estimation)

Table: Natural Resource Endowments, Calibrated Productivity, and Community Land Footprint

(A)	Number of species found around a community				
	(1)	(2)	(3)	(4)	(5)
	Total	Fish	Timber	NTFP	Game
$\log(\tilde{A}_{o,Nr})$ (calibrated)	0.206***	0.0220	0.386***	0.0488**	0.380***
	(0.0306)	(0.0334)	(0.0407)	(0.0204)	(0.0437)
Mean (Dep. var.)	2.025	3.161	1.788	0.552	1.958
SD (Dep. var.)	1.145	1.163	1.676	0.893	1.636
R^2	0.059	0.150	0.126	0.349	0.213
Observations	909	909	909	909	909
(B)	Number of species found around a community				
	(1)	(2)	(3)	(4)	(5)
	Total	Fish	Timber	NTFP	Game
log (land footprint)	0.0171	-0.0653*	-0.0209	0.0126	0.0752
	(0.0381)	(0.0383)	(0.0533)	(0.0245)	(0.0478)
Mean (Dep. var.)	2.021	3.147	1.796	0.555	1.956
SD (Dep. var.)	1.147	1.183	1.677	0.894	1.637
R^2	0.014	0.163	0.059	0.336	0.146
Observations	906	906	906	906	906
(C)	Number of species found around a community				
	(1)	(2)	(3)	(4)	(5)
	Total	Fish	Timber	NTFP	Game
log (depth of land footprint)	0.0458	-0.0358	-0.135*	-0.0248	0.0911
	(0.0587)	(0.0541)	(0.0771)	(0.0342)	(0.0728)
Mean (Dep. var.)	2.070	3.168	1.873	0.550	1.964
SD (Dep. var.)	1.141	1.159	1.676	0.885	1.626
R^2	0.026	0.170	0.059	0.364	0.146
Observations	811	811	811	811	811
Basin FE	Yes	Yes	Yes	Yes	Yes
Geographic controls	No	No	No	No	No

Notes: Robust standard errors in parentheses. The unit of anaylysis is a community in the PARLAP Community Census (CC) in 2014. In panel (B), the land footprint represents the community-level land footprint within a voronoi polygon around the settlement, detected in satellite images. In panel (C), the land footprint depth represents the distance from the river to the furthest inland point in the community-level land footprint.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

▸ Back

Table: Agglomeration Externality in Agriculture

	The calibrated value of $\log(\tilde{A}_{o,Ag})$							
	All locations				$N_o < 1000$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\log(N_{o,Ag})$	0.676***	0.440**	0.514***	0.501***	0.735***	0.384**	0.509***	0.464***
	(0.0207)	(0.171)	(0.0809)	(0.0790)	(0.0196)	(0.169)	(0.124)	(0.109)
Basin FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
IV: RNA	No	Yes	No	Yes	No	Yes	No	Yes
IV: Historical	No	No	Yes	Yes	No	No	Yes	Yes
Mean (Dep. var.)	-0.096	-0.096	-0.096	-0.096	-0.172	-0.172	-0.172	-0.172
SD (Dep. var.)	4.578	4.578	4.578	4.578	4.614	4.614	4.614	4.614
First stage *F*-stat		11.502	56.653	31.005		15.298	35.632	22.822
Hansen's *J* test *p*-value				0.648				0.472
Observations	893	893	893	893	852	852	852	852

Notes: Robust standard errors in parentheses. The sample includes 1 square km grid cells that have positive populations. We use $\log(RNA_o)$ (IV: RNA) and the initial community existence in 1940 (IV: Historical) as instruments for $\log(N_{o,Ag})$. Geographical controls include a dummy of high river orders (4 and 5), distance to the urban center, distance to the river, squared distance to the river, interaction terms of these two variables with a river cell dummy, elevation, river confluences, flood vulnerability, geology measures, and open water access measures.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

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Table: Agglomeration Externality in Agriculture

	The calibrated value of $\log(\tilde{A}_{o,Ag})$						
	IV						OLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\log(N_{o,Ag})$	0.434***	0.519***	0.519***	0.521***	0.509***	0.501***	0.676***
	(0.0920)	(0.0789)	(0.0788)	(0.0789)	(0.0789)	(0.0790)	(0.0207)
log (Elevation)		2.341***	2.354***	2.324***	2.360***	2.397***	2.252***
		(0.171)	(0.175)	(0.179)	(0.176)	(0.177)	(0.176)
River confluence (1st×2nd or 2nd×3rd)			0.0155	0.0186	0.0206	0.0309	0.0180
			(0.0958)	(0.0964)	(0.0982)	(0.0995)	(0.0969)
River confluence (3rd×4th)			-0.0356	-0.0339	-0.0246	-0.0266	0.0173
			(0.0724)	(0.0723)	(0.0730)	(0.0733)	(0.0618)
Flood vulnerability (1-4)				-0.0115	-0.00947	-0.0123	-0.0154
				(0.0136)	(0.0137)	(0.0137)	(0.0130)
Water share: non-main channel					0.0806	0.123	-0.00146
					(0.238)	(0.238)	(0.203)
Water share: main channel					0.161	0.185	0.189
					(0.122)	(0.121)	(0.120)
Floodplain soil share						0.127**	0.126**
						(0.0625)	(0.0575)
Pleistocene soil share						0.175	0.333
						(0.222)	(0.227)
Basin FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mean (Dep. var.)	-0.094	-0.096	-0.096	-0.096	-0.096	-0.096	-0.096
SD (Dep. var.)	4.576	4.578	4.578	4.578	4.578	4.578	4.578
First stage *F*-stat	28.030	29.419	29.974	29.634	30.770	31.005	
Observations	894	893	893	893	893	893	893

Notes: Robust standard errors in parentheses. The sample includes 1 square km grid cells that have positive populations. We use $\log(RNA_o)$ and the initial community existence in 1940 as instruments for $\log(N_{o,Ag})$. Other controls include distance to the urban center, distance to the river, squared distance to the river, and interaction terms of these two variables with a river cell dummy.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Back

Table: Density Externality in Forest Clearing

	log (per capita land footprint)					
	All locations		$N_o < 1000$		$N_o < 500$	
	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV
$\log(N_{o,Ag})$	-0.650***	-0.522***	-0.654***	-0.552***	-0.674***	-0.545***
	(0.0307)	(0.0940)	(0.0323)	(0.109)	(0.0346)	(0.123)
Basin FE	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes
Mean (Dep. var.)	0.929	0.929	0.956	0.956	0.981	0.981
SD (Dep. var.)	1.231	1.231	1.218	1.218	1.223	1.223
First stage *F*-stat		34.198		28.141		23.709
Hansen's *J* test *p*-value		0.987		0.896		0.969
Observations	895	895	878	878	847	847

Notes: Robust standard errors in parentheses. The unit of anaylysis is a community in the PARLAP Community Census (CC) in 2014. We use $\log(RNA_o)$ and the initial community existence in 1940 as instruments for $\log(N_{o,Ag})$. Geographical controls include a dummy of high river orders (4 and 5), distance to the urban center, distance to the river, squared distance to the river, interaction terms of these two variables with a river cell dummy, elevation, river confluence, flood vulnerability, geology measures, and open water access measures for a grid cell where each census community belongs.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

▸ Back

Table: Congestion Externality in Natural Resource Extraction with Spatial Spillovers

	The calibrated value of $\log(\tilde{A}_{o,Nr})$									
	IV									OLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$\log(N_{o,Nr})$	-2.127**	-1.385	-0.879	-0.581	0.0960	0.278	0.573***	0.634***	0.606***	0.950***
	(1.075)	(0.939)	(0.688)	(0.558)	(0.322)	(0.280)	(0.208)	(0.179)	(0.184)	(0.0516)
$\log(\sum_{d\|D_{o,d}\leq 2km} N_{d,Nr})$		-0.573*	-0.0343	0.0235	-0.0745	-0.0705	-0.0648	-0.0745	-0.0856	-0.0663
		(0.331)	(0.282)	(0.236)	(0.143)	(0.122)	(0.0883)	(0.0822)	(0.0838)	(0.0611)
$\log(\sum_{d\|D_{o,d}\leq 5km} N_{d,Nr})$			-0.596***	-0.286	-0.138	-0.130	-0.120*	-0.111*	-0.112*	-0.132***
			(0.189)	(0.183)	(0.106)	(0.0888)	(0.0637)	(0.0597)	(0.0613)	(0.0425)
$\log(\sum_{d\|D_{o,d}\leq 10km} N_{d,Nr})$				-0.337**	0.0345	0.0364	0.0579	0.0425	0.0322	0.0140
				(0.141)	(0.107)	(0.0885)	(0.0625)	(0.0596)	(0.0639)	(0.0378)
$\log(\sum_{d\|D_{o,d}\leq 25km} N_{d,Nr})$					-0.470***	-0.357***	-0.327***	-0.294***	-0.285***	-0.165***
					(0.0918)	(0.0837)	(0.0584)	(0.0560)	(0.0571)	(0.0283)
$\log(\sum_{d\|D_{o,d}\leq 50km} N_{d,Nr})$						-0.195***	-0.0318	-0.0548	-0.0480	-0.0619**
						(0.0610)	(0.0581)	(0.0526)	(0.0548)	(0.0242)
$\log(\sum_{d\|D_{o,d}\leq 75km} N_{d,Nr})$							-0.280***	-0.0758	-0.0407	-0.0989***
							(0.0779)	(0.125)	(0.142)	(0.0352)
$\log(\sum_{d\|D_{o,d}\leq 100km} N_{d,Nr})$								-0.258*	-0.439*	-0.263***
								(0.141)	(0.231)	(0.0498)
$\log(\sum_{d\|D_{o,d}\leq 150km} N_{d,Nr})$									0.187	0.0970*
									(0.171)	(0.0567)
Basin FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mean (Dep. Var.)	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337
SD (Dep. Var.)	2.862	2.862	2.862	2.862	2.862	2.862	2.862	2.862	2.862	2.862
Observations	894	894	894	894	894	894	894	894	894	894

Notes: Robust standard errors in parentheses. The sample includes 1 square km grid cells that have positive populations. We use $\ln RNA_o$ and $\{\ln \sum_{d|D_{o,d}\leq x} RNA_d\}$ for $x \in \mathcal{X}$ as instruments when endogenous variables include $\log(N_{o,Nr})$ and $\{\ln \sum_{d|D_{o,d}\leq x} N_{d,Nr}\}$ for $x \in \mathcal{X}$. Geographical controls include a dummy of high river orders (4 and 5), distance to the river, squared distance to the river, interaction terms of these two variables with a river cell dummy, elevation, river confluence, flood vulnerability, geology measures, and open water access measures.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Back

Economies of Scale in Transport Technology

- Consider an alternative model without the agglomeration externality in the production function but with **endogenous trade costs**:

$$\tilde{\tau}_{od,Ag} = N_{o,Ag}^{-\boldsymbol{\mu}_{\mathbf{Ag}}} \tau_{od,Ag}$$

- This model is **isomorphic to the original model**
- The trade cost can be decreasing in the origin population possibly because:
  - Large commercial boats ('lancha') are more likely to stop by
  - Collective investment in motor boats ('rapido')
  - The average transport cost charged is decreasing in the amount of products traded

Transport Modes in the Peruvian Amazon

Canue

Lancha

Peque-peque (most widely available)

Rapido (express motor boat)

Table: Community Population and Availability of Transport Modes

	Availability of Transport Modes in a Community							
	Lancha		Colectivo		Rapido		Peque-peque	
	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV	(7) OLS	(8) IV
$\log(N_{o,Ag})$	0.0469***	0.144***	0.0478***	0.0280	0.0522***	0.0566*	-0.00528	0.00418
	(0.0111)	(0.0430)	(0.0115)	(0.0383)	(0.0108)	(0.0292)	(0.00576)	(0.0156)
Basin FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mean (Dep. var.)	0.492	0.492	0.386	0.386	0.110	0.110	0.972	0.972
SD (Dep. var.)	0.500	0.500	0.487	0.487	0.314	0.314	0.164	0.164
First stage *F*-stat		24.84462		24.84462		24.84462		24.84462
Observations	906	906	906	906	906	906	906	906

Notes: Robust standard errors in parentheses. The unit of anaylysis is a community in the PARLAP Community Census (CC) in 2014. We use $\log(RNA_o)$ and the initial community existence in 1940 as instruments for $\log(N_{o,Ag})$. Geographical controls include a dummy of high river orders (4 and 5), distance to the urban center, distance to the river, squared distance to the river, interaction terms of these two variables with a river cell dummy, elevation, river confluence, flood vulnerability, geology measures, and open water access measures for a grid cell where each census community belongs.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

- The data supports the fact that ‘peque-peque’ is most widely available
- Significant scale effects on the availability of ‘lancha’ and ‘rapido’
- Consistent results for the frequency of transport modes available and other proxies of transaction costs as well

Back

Economies of Scale in Agricultural Intensification

- Test this using producer-level information from the Agricultural Census
- Modern technologies are limited: each of 24 listed modern technologies (except for boat) is used by <10% of agricultural producers
- Significant scale effects on:
    - direct inputs into land and crops (insecticides, herbicides, fungicides)
    - complementary equipment (sprayers)
    - crop processing technology to facilitate marketing (grain mill)

Table: Community Population and Modern Technology Use

(A) Basic infrastructure						
	(1)	(2)	(3)	(4)	(5)	(6)
	Irrigation	Certified seed	Crops have been certified organic	Electricity for agricultural work	Animals for agricultural work	Tractors for agricultural work
$\log(N_{o,Ag})$	-0.00329*	-0.000857	0.0000692	-0.000688	0.00315	0.000476
	(0.00180)	(0.00430)	(0.000584)	(0.000863)	(0.00206)	(0.000811)
Mean (Dep. var.)	0.013	0.064	0.001	0.003	0.010	0.002
SD (Dep. var.)	0.112	0.245	0.037	0.054	0.098	0.044
First stage F-stat	1649.082	1649.082	1649.082	1649.082	1649.082	1649.082
Observations	25827	25827	25827	25827	25827	25827
(B) Inputs into land and crops						
	(1)	(2)	(3)	(4)	(5)	(6)
	Guano/manure/ compost	Chemical fertilizers	Insecticides	Herbicides	Fungicides	Biologic control
$\log(N_{o,Ag})$	0.000807	0.00265**	0.0228***	0.0314***	0.0118***	-0.00239
	(0.00111)	(0.00115)	(0.00353)	(0.00371)	(0.00219)	(0.00239)
Mean (Dep. var.)	0.005	0.004	0.040	0.051	0.012	0.020
SD (Dep. var.)	0.069	0.063	0.197	0.221	0.111	0.140
First stage F-stat	1649.082	1649.082	1649.082	1649.082	1649.082	1649.082
Observations	25827	25827	25827	25827	25827	25827
(C) Animal, electrical, or mechanical energy						
	(1)	(2)	(3)	(4)	(5)	(6)
	Iron plow of animal traction	Wooden plow of animal traction	Harvester	Foot plow	Motorized sprayer	Manual sprayer
$\log(N_{o,Ag})$	-0.000796	-0.000223	-0.000229	-0.000806	0.00197**	0.0214***
	(0.000523)	(0.000311)	(0.000282)	(0.000556)	(0.000815)	(0.00401)
Mean (Dep. var.)	0.001	0.000	0.001	0.001	0.002	0.062
SD (Dep. var.)	0.035	0.022	0.025	0.035	0.043	0.241
First stage F-stat	1649.082	1649.082	1649.082	1649.082	1649.082	1649.082
Observations	25827	25827	25827	25827	25827	25827
(D) Electrical or mechanical energy						
	(1)	(2)	(3)	(4)	(5)	(6)
	Grain mill	Grass chopper	Thresher	Electric generator	Wheel tractor	Boat/canue/ speedboat
$\log(N_{o,Ag})$	0.00696***	0.000462	-0.00102	-0.0103***	0.000932	-0.0187**
	(0.00194)	(0.000448)	(0.000674)	(0.00323)	(0.000590)	(0.00746)
Mean (Dep. var.)	0.013	0.001	0.004	0.036	0.001	0.618
SD (Dep. var.)	0.111	0.025	0.061	0.186	0.030	0.486
First stage F-stat	1649.082	1649.082	1649.082	1649.082	1649.082	1649.082
Observations	25827	25827	25827	25827	25827	25827
Basin FE	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Robust standard errors in parentheses. The unit of anaylysis is a household in the 2012 Peruvian Agricultural Census. We use $\log(RNA_o)$ and the initial community existence in 1940 as instruments for $\log(N_{o,Ag})$. Geographical controls include a dummy of high river orders (4 and 5), distance to the urban center, distance to the river, squared distance to the river, interaction terms of these two variables with a river cell dummy, elevation, river confluence, flood vulnerability, geology measures, and open water access measures for a grid cell where each census community belongs.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

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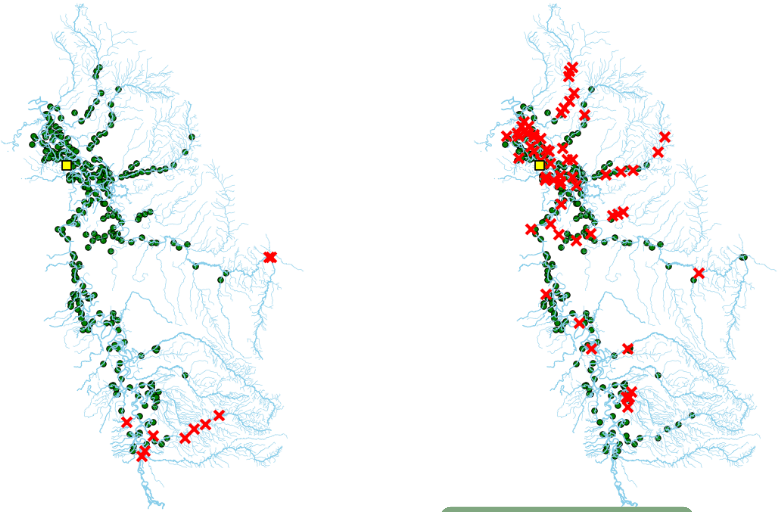
Spatial Targeting Matters: Protection Policies

(A) Protecting the rural frontier (B) Small communities not allowed



×: Protected areas for resettlement

▸ Community formation patterns

Spatial Targeting Matters: Protection Policies

Basin	Welfare	**Deforestation**	**Natural resource depletion**
(A) Protecting the rural frontier			
Napo	-0.2%	-5.2%	-0.3%
UpperUcayali	-0.2%	-2.0%	-0.8%
(B) Not allowing for small communities			
Napo	-0.3%	-13.1%	+0.2%
UpperUcayali	-0.1%	-7.3%	+0.5%

- Both policies treat 2.5% of the total rural population in the basin

(B) $\Rightarrow$ **natural resource depletion** $\uparrow$

- Protected areas are dispersed
- Congestion from surrounding populations not much affected

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- Both policies treat 2.5% of the total rural population in the basin

(B) ⇒ **natural resource depletion ↑**

- Protected areas are dispersed
- Congestion from surrounding populations not much affected

(B) ⇒ **deforestation ↓ more** by concentrating the land footprint in much fewer spots (rather than having many small communities)

★ Policymaker's trade-off between mitigating different environmental costs

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The comparison between resettlement policies illustrates the planner's ecological trade-off

Basin	Welfare	**Deforestation**	**Natural resource depletion**
(A) Protected areas: controlling rural frontier expansion			
Napo	-0.2%	**-5%**	**-0.3%**
UpperUcayali	-0.2%	**-2%**	**-0.8%**
(B) Not allowing for small communities			
Napo	-0.3%	**-12.5%**	**+0.2%**
UpperUcayali	-0.1%	**-6.9%**	**+0.5%**

(A)⇒ **natural resource depletion** ↓ but with a smaller deforestation impact

- Overall scope of natural resource extraction activities is narrowed
- Surrounding populations ↑ in most of populated areas
- Productivity ↓ due to the congestion externality with spatial spillovers

▸ Maps

(B)⇒ **reduces deforestation the most** but **natural resource depletion** ↑

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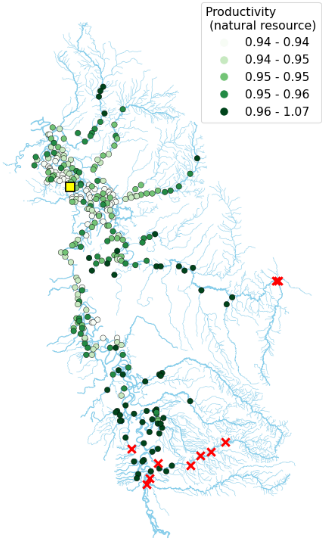
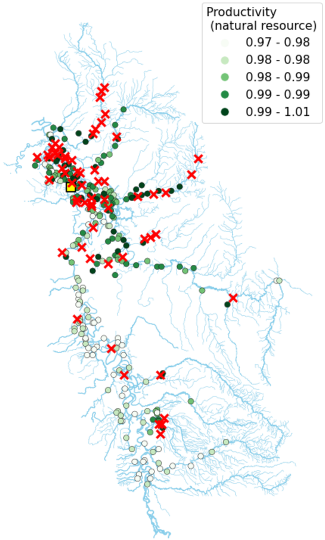
(A) Protected areas by rural frontier



(B) Small communities not allowed



Legend: values in the counterfactual scenario relative to those in the benchmark equilibrium

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Improving River Transport Infrastructure: Overview

- **High trade costs**:
  - Asymmetric transport costs due to river orientations
  - Seasonality of transport costs due to water level fluctuations
  - Slow speed of river boats
- **Transport infrastructure investments**:
  - Better quality boats
  - River dredging

    Amazon Waterway Project: Government scheme with Chinese investment to deepen and widen the central parts of rivers to allow larger ships to travel

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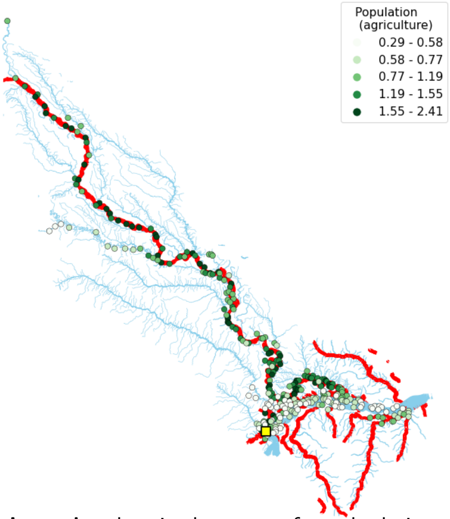
    Amazon Waterway Project: Government scheme with Chinese investment to deepen and widen the central parts of rivers to allow larger ships to travel
- Replace the **downstream-river-equivalent distance** with:

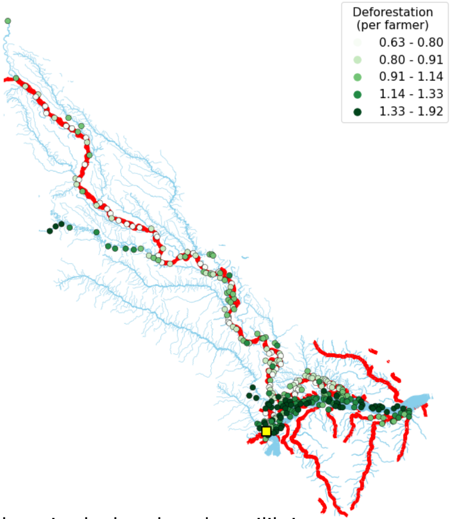
$$D_{od} = D_{od,initial,down} + \lambda_{up} D_{od,initial,up} + \lambda_{land} D_{od,land} + \lambda_{upgraded} D_{od,upgraded}$$

where $\lambda_{upgraded} = 0.8$ & symmetric transport cost in the "upgraded" part

Connecting Hinterlands to the Central Area of Basin ⇒

- **Spatial reallocation of farmers toward remote areas**
- **Deforestation per farmer ↓ in remote areas**





Legend: values in the counterfactual relative to those in the benchmark equilibrium
Red lines: transport infrastructure improvement

Connecting Hinterlands to the Central Area of a Basin ⇒

- **Welfare ↑**
- **Deforestation ↓**
- **Natural resource depletion (↓)?**

Basin	Welfare	Deforestation	Natural resource depletion
Napo	+1.8%	-1.1%	-0.3%
UpperUcayali	+1.2%	-1.1%	+0.3%

- **The agglomeration benefits spread more evenly across the basin with more moderate-sized settlements**
- Transport infrastructure that integrates hinterlands

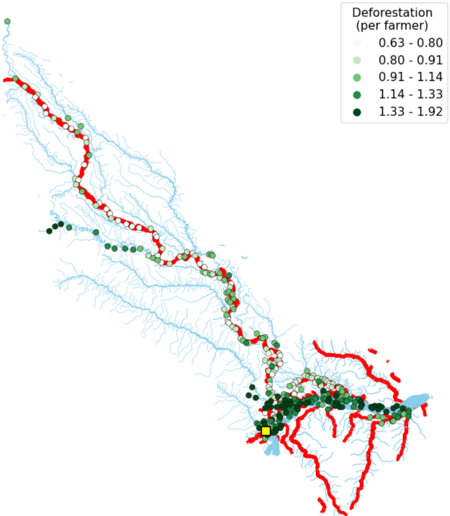
⇒ Reallocate farmers from the central area to remote areas

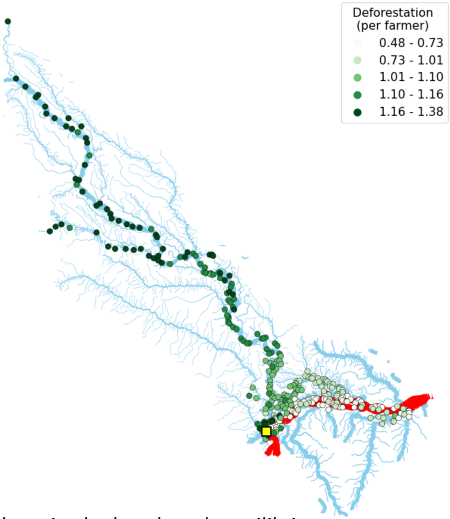
⇒ Settlement size variance ↓ & Agricultural productivity in remote areas ↑

⇒ Total deforestation ↓ given the structure of congestion forces in access to land (negative and convex between ag population and per-farmer deforestation)

* The overall impact on natural resource depletion is unclear through GE effects

Connecting Hinterlands to the Central Area of Basin (left) vs. Concentrating the Infrastructure Investment in the Center (right)





Legend: values in the counterfactual relative to those in the benchmark equilibrium
Red lines: transport infrastructure improvement

Direction of deforestation impacts depends on where transport infrastructure is improved

Basin	Welfare	Deforestation	Natural resource depletion
(A) Transport infrastructure improved by connecting hinterlands to the center			
Napo	+1.8%	**-1.1%**	-0.3%
(B) Transport infrastructure improved by concentrating investments in the center			
Napo	+1.0%	**+6.0%**	-0.4%

Improving the infrastructure only in densely populated areas $\Rightarrow$ Deforestation $\uparrow$

- The population is more concentrated in the central area of the basin
- At the same time, **much smaller communities with much higher deforestation *per farmer* in hinterlands**

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