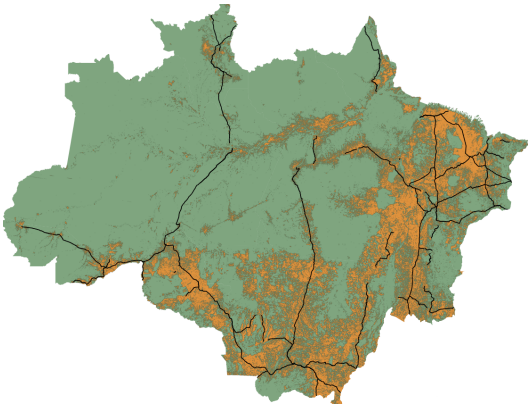
Transportation Infrastructure and Deforestation in the Amazon

Arthur Bragança (World Bank)
Rafael Araujo (FGV EESP)
Juliano Assunção (PUC-Rio & Climate Policy Initiative)

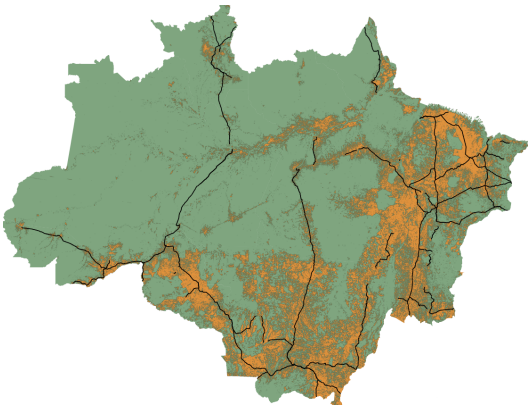
World Bank Land Conference – May 2024

Deforestation in the Amazon occurs close to transportation infrastructure



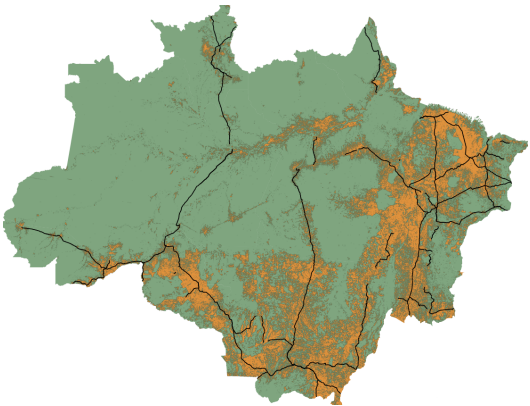
- **490,000 km^2** of native forests cleared since 1988 (INPE)
- **95%** near roads ($<$ 5.5 km) or rivers ($<$ 1km) (Barber et al. 2014)

Deforestation in the Amazon occurs close to transportation infrastructure



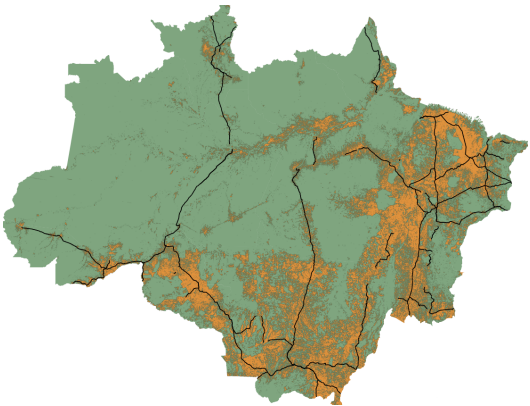
- **490,000 km^2** of native forests cleared since 1988 (INPE)
- **95%** near roads ($<$ 5.5 km) or rivers ($<$ 1km) (Barber et al. 2014)

Deforestation in the Amazon occurs close to transportation infrastructure



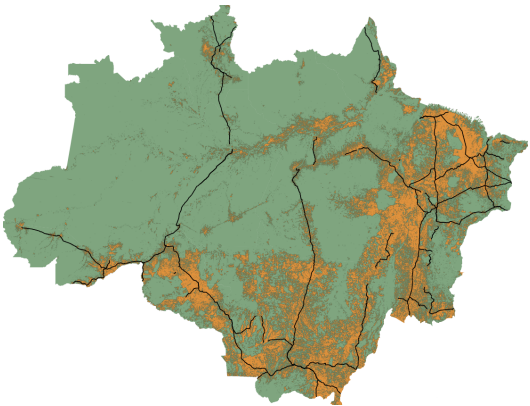
- **490,000 km^2** of native forests cleared since 1988 (INPE)
- **95%** near roads ($<$ 5.5 km) or rivers ($<$ 1km) (Barber et al. 2014)
- **Correlation $\neq$ true effect**

Deforestation in the Amazon occurs close to transportation infrastructure



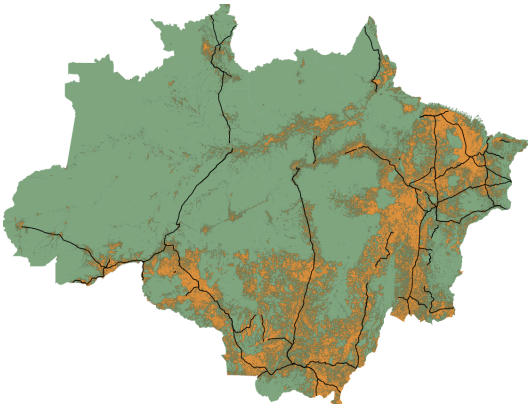
- **490,000 km^2** of native forests cleared since 1988 (INPE)
- **95%** near roads ($<$ 5.5 km) or rivers ($<$ 1km) (Barber et al. 2014)
- **A proper framework is needed**

Deforestation in the Amazon occurs close to transportation infrastructure



- **490,000 km^2** of native forests cleared since 1988 (INPE)
- **95%** near roads ($<$ 5.5 km) or rivers ($<$ 1km) (Barber et al. 2014)
- **A proper framework is needed**
  1. Role of **roads, railroads, waterways, ports etc.** in driving deforestation
  2. Compute **environmental cost** of individual projects

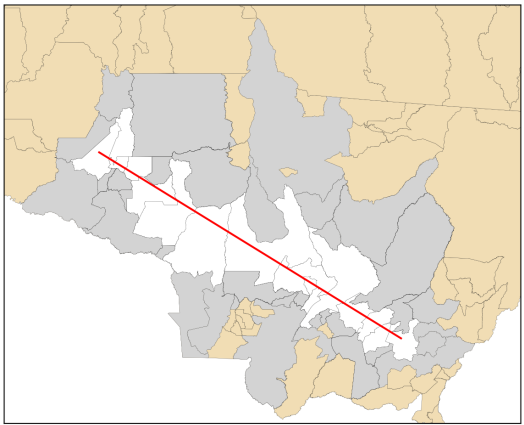
Deforestation in the Amazon occurs close to transportation infrastructure



- **490,000 km^2** of native forests cleared since 1988 (INPE)
- **95%** near roads ($<$ 5.5 km) or rivers ($<$ 1km) (Barber et al. 2014)
- **A proper framework is needed**
  1. Role of **roads, railroads, waterways, ports etc.** in driving deforestation
  2. Compute **environmental cost** of individual projects

This paper: builds a framework to measure the effects of transportation infrastructure on deforestation in the Amazon

Challenge #1: Network Effects



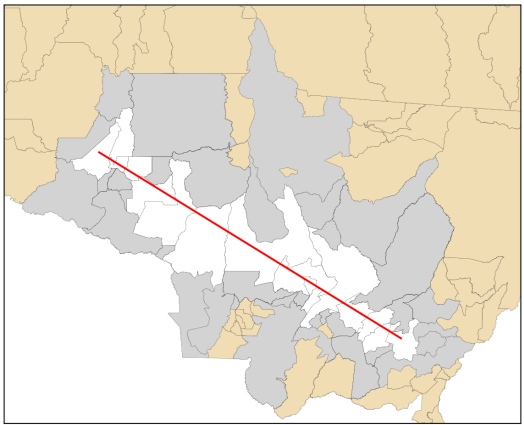
- **Transportation infrastructure:**

1. influences localities it crosses **directly**
2. influences other localities **indirectly**

- **Build inter-regional trade model:**

1. market access literature (Donaldson and Hornbeck, 2016; Donaldson, 2018)
2. two types of land: **consolidated** and **frontier**
3. log-linear relationship bt/ deforestation and market access

Challenge #1: Network Effects



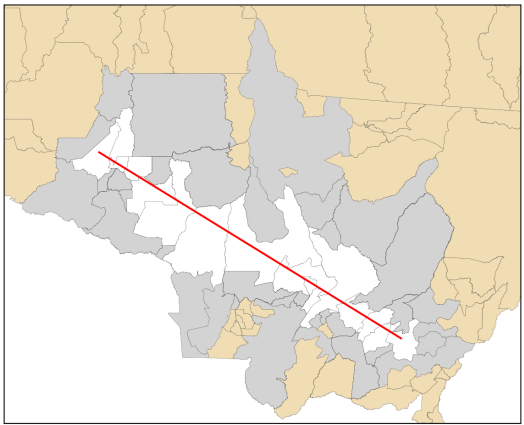
- **Transportation infrastructure:**

1. influences localities it crosses **directly**
2. influences other localities **indirectly**

- **Build inter-regional trade model:**

1. market access literature (Donaldson and Hornbeck, 2016; Donaldson, 2018)
2. two types of land: **consolidated** and **frontier**
3. log-linear relationship bt/ deforestation and market access

Challenge #1: Network Effects



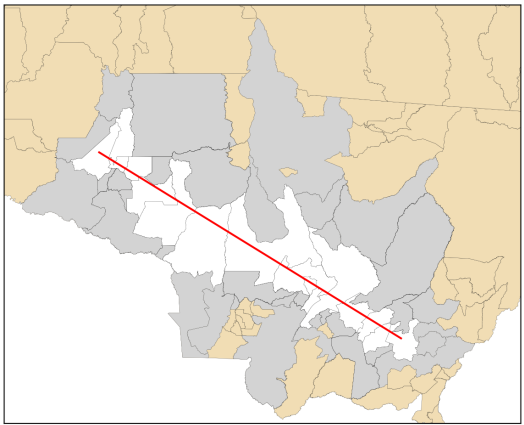
- **Transportation infrastructure:**

1. influences localities it crosses **directly**
2. influences other localities **indirectly**

- **Build inter-regional trade model:**

1. market access literature (Donaldson and Hornbeck, 2016; Donaldson, 2018)
2. two types of land: **consolidated** and **frontier**
3. log-linear relationship bt/ deforestation and market access

Challenge #1: Network Effects



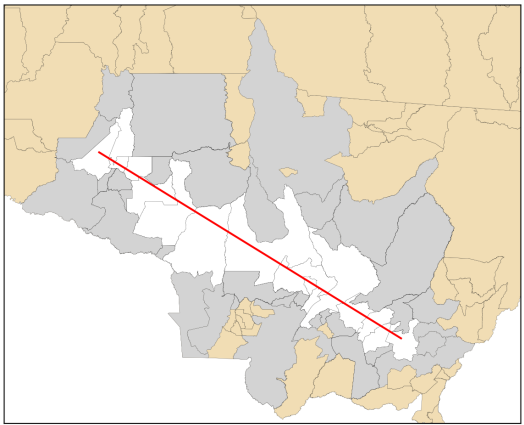
- **Transportation infrastructure:**

1. influences localities it crosses **directly**
2. influences other localities **indirectly**

- **Build inter-regional trade model:**

1. market access literature (Donaldson and Hornbeck, 2016; Donaldson, 2018)
2. two types of land: **consolidated** and **frontier**
3. log-linear relationship bt/ deforestation and market access

Challenge #1: Network Effects



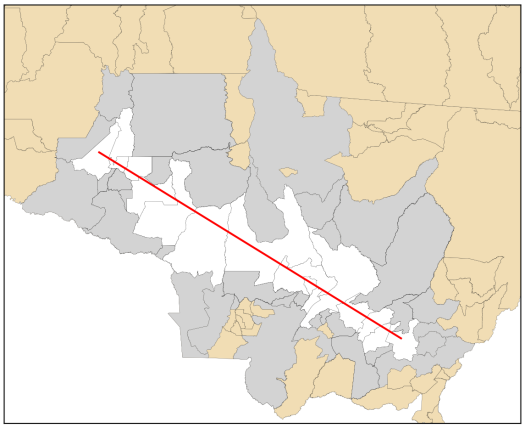
- **Transportation infrastructure:**

1. influences localities it crosses **directly**
2. influences other localities **indirectly**

- **Build inter-regional trade model:**

1. market access literature (Donaldson and Hornbeck, 2016; Donaldson, 2018)
2. two types of land: **consolidated** and **frontier**
3. log-linear relationship bt/ deforestation and market access

Challenge #1: Network Effects



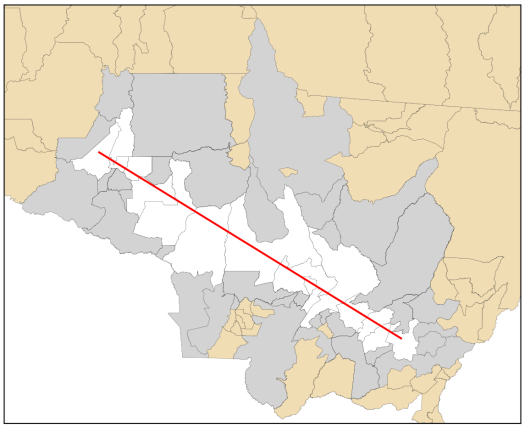
- **Transportation infrastructure:**

1. influences localities it crosses **directly**
2. influences other localities **indirectly**

- **Build inter-regional trade model:**

1. market access literature (Donaldson and Hornbeck, 2016; Donaldson, 2018)
2. two types of land: **consolidated** and **frontier**
3. log-linear relationship bt/ deforestation and market access

Challenge #1: Network Effects



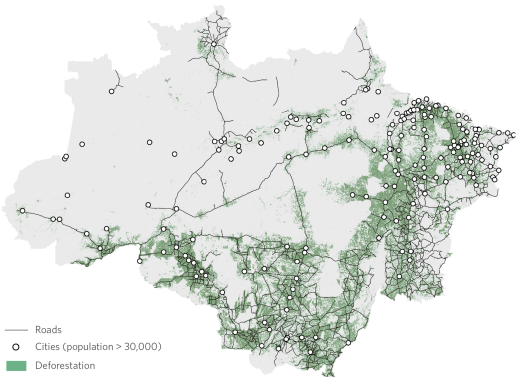
- **Transportation infrastructure:**

1. influences localities it crosses **directly**
2. influences other localities **indirectly**

- **Build inter-regional trade model:**

1. market access literature (Donaldson and Hornbeck, 2016; Donaldson, 2018)
2. two types of land: **consolidated** and **frontier**
3. log-linear relationship bt/ deforestation and market access

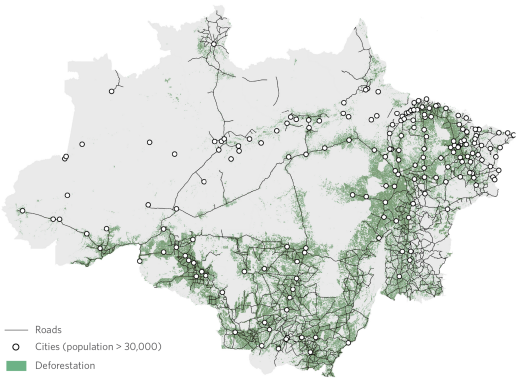
Challenge #2: Causality



- Transportation infrastructure is endogenous (e.g., close to cities)
- **Estimates model using:**

1. Pixel-level data on deforestation (1990-2019)
2. Evolution of transportation network (1980, 1990, 2000, 2010)
3. Detailed information on freights
4. IV to isolate exogenous changes in transportation costs

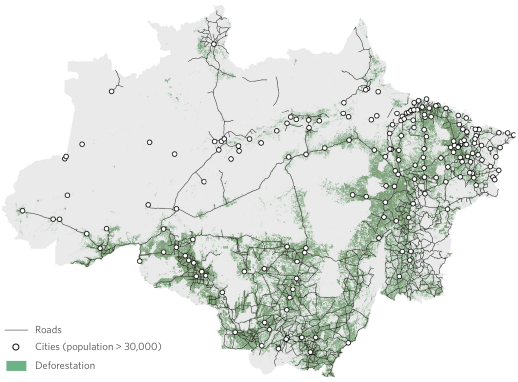
Challenge #2: Causality



- Transportation infrastructure is endogenous (e.g., close to cities)
- **Estimates model using:**

1. Pixel-level data on deforestation (1990-2019)
2. Evolution of transportation network (1980, 1990, 2000, 2010)
3. Detailed information on freights
4. IV to isolate exogenous changes in transportation costs

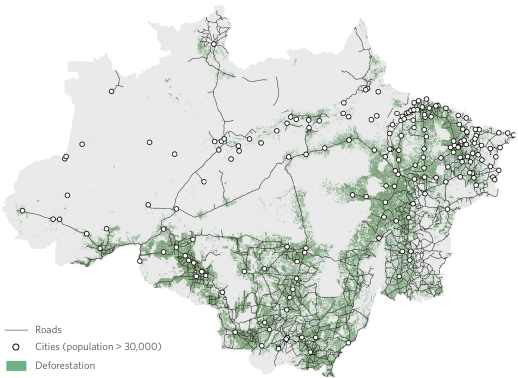
Challenge #2: Causality



- Transportation infrastructure is endogenous (e.g., close to cities)
- **Estimates model using:**

1. Pixel-level data on deforestation (1990-2019)
2. Evolution of transportation network (1980, 1990, 2000, 2010)
3. Detailed information on freights
4. IV to isolate exogenous changes in transportation costs

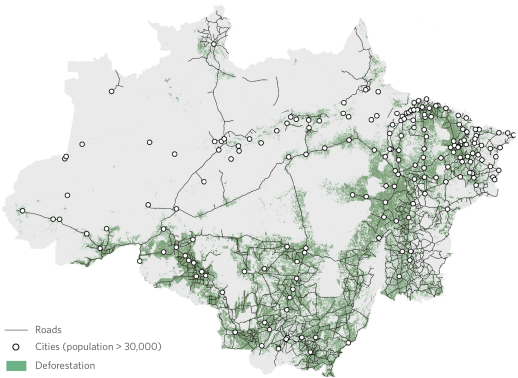
Challenge #2: Causality



- Transportation infrastructure is endogenous (e.g., close to cities)
- **Estimates model using:**

1. Pixel-level data on deforestation (1990-2019)
2. Evolution of transportation network (1980, 1990, 2000, 2010)
3. Detailed information on freights
4. IV to isolate exogenous changes in transportation costs

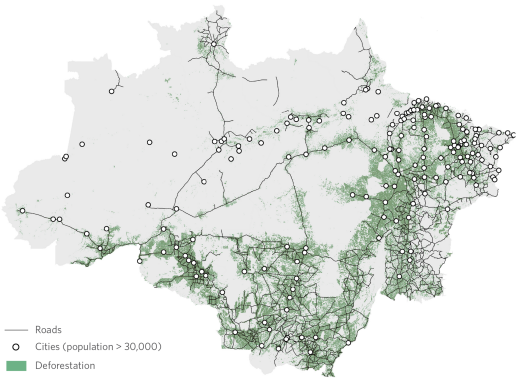
Challenge #2: Causality



- Transportation infrastructure is endogenous (e.g., close to cities)
- **Estimates model using:**

1. Pixel-level data on deforestation (1990-2019)
2. Evolution of transportation network (1980, 1990, 2000, 2010)
3. Detailed information on freights
4. IV to isolate exogenous changes in transportation costs

Challenge #2: Causality



- Transportation infrastructure is endogenous (e.g., close to cities)
- **Estimates model using:**

1. Pixel-level data on deforestation (1990-2019)
2. Evolution of transportation network (1980, 1990, 2000, 2010)
3. Detailed information on freights
4. IV to isolate exogenous changes in transportation costs

Literature

- Environmental effects of transportation infrastructure
  Chomitz and Gray (1996); Pfaff (1999); Damania et al. (2018); Asher et al. (2020)

- Drivers of deforestation in the Amazon
  Souza-Rodrigues (2018); Assunção et al. (2020); Araujo et al. (2020); Bragança and Dahis (2022)

- Deforestation control policies
  Fetzer and Marden (2017); Burgess et al. (2019); Heilmayr et al. (2020); Assunção et al. (2022); Assunção et al. (2023)

- Trade-offs between economic development and environmental protection
  Foster and Rosenzweig (2003); Copeland and Taylor (2004); Alix-Garcia et al. (2013); Damania et al. (2018); Garg and Shenoy (2021)

Model

Set up (I)

Set of regions indexed by o, two types of agents (firms/producers and workers/consumers), trade cost τ_{od} between each pair of regions o and d

Firms/producers:

- Perfectly competitive producers using Cobb-Douglas production function $MC_o(j|T) = \frac{q_o^{T\alpha} w_o^{\gamma} r_o^{1-\alpha-\gamma}}{z_o^T(j)}$

Workers/consumers:

- Supply inelastically one unit of labor (wage w^o)
- CES preferences over agricultural varieties j; buy from cheapest source $V^o = \frac{w_o}{P_o}$, in which $(P_o)^{1-\sigma} = \int_0^A p_o(j)^{1-\sigma} dj$
- Decide where to live to maximize utility; are freely mobile $V^o = V^d, \forall o, d$

Set up (II)

Capital:

- Capital is freely mobile and supplied elastically

Land:

- Two types of land: consolidated (L) and frontier (F)
  $F_o(z^C, z^F) = \exp(-(A_o^C z^{C^{-\theta}} + A_o^F z^{F^{-\theta}}))$

- Producers operate in the type of land with lower marginal cost
  $\bar{p}\left(\frac{q_o^F}{q_o^C}\right) = P\left(\frac{z_o^F(j)}{z_o^C(j)} < \left(\frac{q_o^F}{q_o^C}\right)^{\alpha}\right) = \left[1 + \frac{A_o^F}{A_o^C}\left(\frac{q_o^F}{q_o^C}\right)^{-\theta\alpha}\right]^{-1}$

- Supply of consolidated land is fixed, supply of frontier land is positively sloped
  $L_o^C = \bar{L}_o^C$ and $q_o^F = B_o\left(L_o^F\right)^{\eta}$

Solving the model

- Prices and bilateral trade as functions of measures of market access ▸ Prices and Exports
  Eaton and Kortum (2002); Redding and Venables (2004)

- Single measure of market access (fixed point) ▸ Market Access
  Donaldson and Hornbeck (2016)

- Market clearing conditions:
  - Total output equals to exports to all locations
    $Y_o = \sum_d X_{od}$
  - Workers are indifferent across locations
    $V^o = V^d, \forall o, d$
  - Rents across different types of land
    $\bar{p}_o q_o^F L_o^F = (1 - \bar{p}_o) q_o^C L_o^C$

Deforestation and market access in equilibrium

$$(\eta + 1 + \eta\theta\alpha) \log L_o^F = \log \frac{x A_o^F}{B_o \rho^\gamma \bar{U}^{\gamma\theta}} + (1 + \gamma) \log MA_o$$

Sufficient statistic

- The ratio between $(1 + \gamma)$ and $(\eta + 1 + \eta\theta\alpha)$ is a sufficient statistic for the effects of transportation infrastructure on deforestation

- Possible to perform counterfactuals (e.g., predict effects of individual projects) using this sufficient statistic

Data

Connecting model and data

- First-order approximation of market access (Donaldson and Hornbeck, 2016)

$$MA_o \cong \sum_d \tau_{od}^{-\theta} N_d$$

- Empirical model

$$\log y_{o,t} = \alpha + \beta \log MA_{o,t_I} + \phi_t X_o + \gamma_o + \gamma_{s,t} + \epsilon_{o,t}$$

- Data for the period 1990-2019

  $y_{o,t}$ is cumulative deforestation in the decade (1990-1999, 2000-2009, 2010-2019)

  MA_{o,t_I} is initial market access in the decade (1990, 2000, 2010)

Deforestation

Mapbiomas (LANDSAT data)

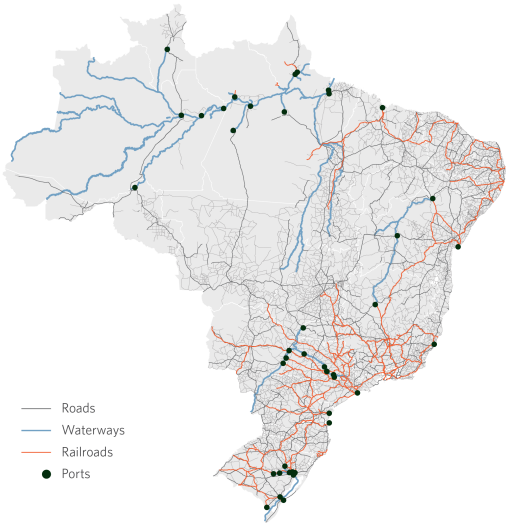
- Classifies land-use at 30-meters pixels: forest, pasture, crop

Measuring deforestation

- Select pixels that were initially classified as forest
- **Deforestation (pixel-level):** first year in which pixel was classified as non-forest
- **Deforestation (municipality-level):** total area of pixels deforested in each municipality-decade pair

Transportation Network

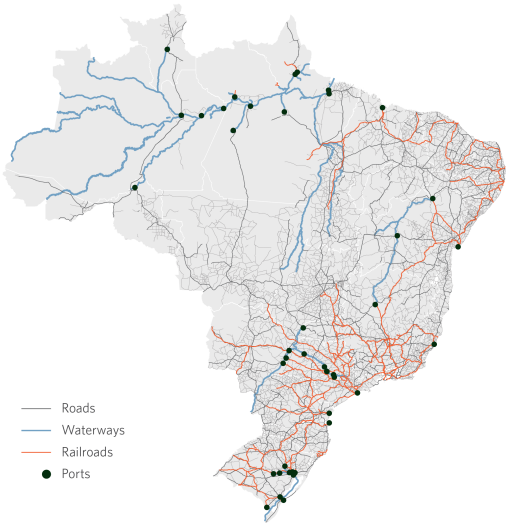
Figure 1. Network of Transports in Brazil



- Decennial geo-referenced information on the road network (1980-2010, Ministry of Infrastructure
- Decennial geo-referenced information on the rail network (1980-2010, ANTT)
  Hand-coded rail stations operating in each period
- Geo-referenced information on navigable rivers (ANTAQ)
  Hand-coded river ports operating in each period

Transportation Network

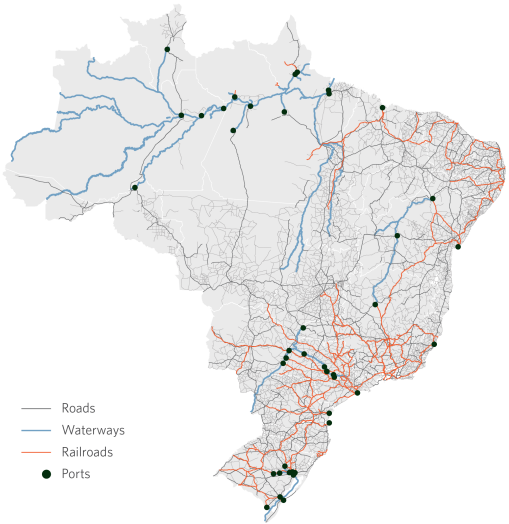
Figure 1. Network of Transports in Brazil



- Decennial geo-referenced information on the road network (1980-2010, Ministry of Infrastructure
- Decennial geo-referenced information on the rail network (1980-2010, ANTT)
  Hand-coded rail stations operating in each period
- Geo-referenced information on navigable rivers (ANTAQ)
  Hand-coded river ports operating in each period

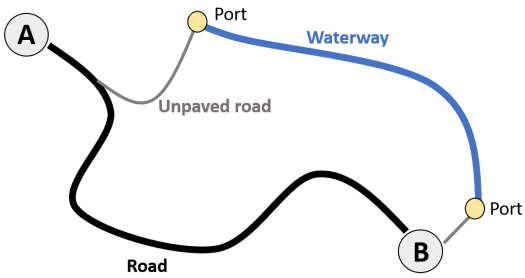
Transportation Network

Figure 1. Network of Transports in Brazil



- Decennial geo-referenced information on the road network (1980-2010, Ministry of Infrastructure
- Decennial geo-referenced information on the rail network (1980-2010, ANTT)
  Hand-coded rail stations operating in each period
- Geo-referenced information on navigable rivers (ANTAQ)
  Hand-coded river ports operating in each period

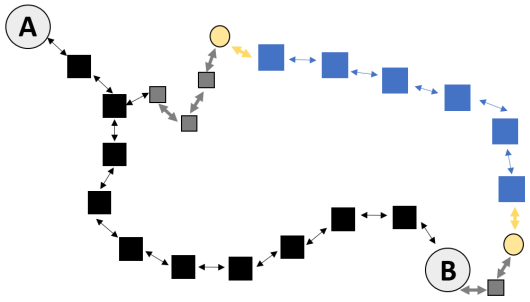
Transportation Costs



- Convert transportation network into **graph**
  multi-modal, restricted access, trans-shipment costs
- Assign **cost** of traversing each pixel as in Araujo et al. (2020)
- Compute **(unit-free) transportation costs** between locations using Dijkstra (1959)'s algorithm
- Use freight information to obtain iceberg costs

$$cost_{odt} = \alpha + \beta cost\_graph_{odt} + \epsilon_{odt}$$

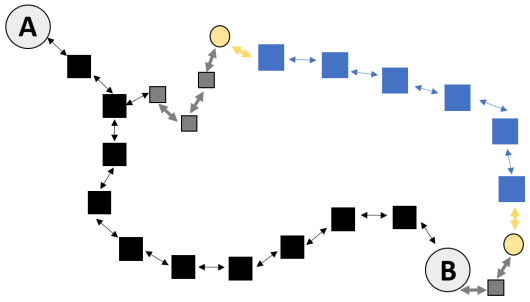
Transportation Costs



- Convert transportation network into **graph** multi-modal, restricted access, trans-shipment costs
- Assign **cost** of traversing each pixel as in Araujo et al. (2020)
- Compute **(unit-free) transportation costs** between locations using Dijkstra (1959)'s algorithm
- Use freight information to obtain iceberg costs

$$cost_{odt} = \alpha + \beta cost\_graph_{odt} + \epsilon_{odt}$$

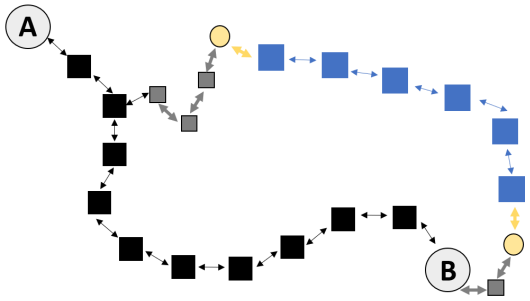
Transportation Costs



- Convert transportation network into **graph**
  multi-modal, restricted access, trans-shipment costs
- Assign **cost** of traversing each pixel as in Araujo et al. (2020)
- Compute **(unit-free) transportation costs** between locations using Dijkstra (1959)'s algorithm
- Use freight information to obtain iceberg costs

$$cost_{odt} = \alpha + \beta cost\_graph_{odt} + \epsilon_{odt}$$

Transportation Costs

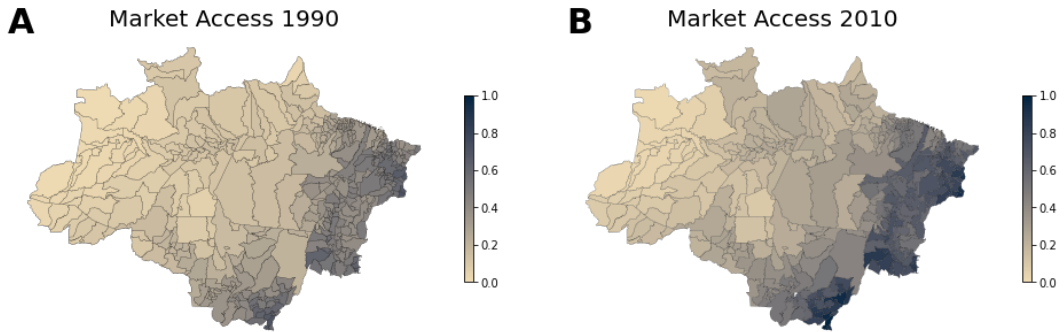


- Convert transportation network into **graph**
  multi-modal, restricted access, trans-shipment costs
- Assign **cost** of traversing each pixel as in Araujo et al. (2020)
- Compute **(unit-free) transportation costs** between locations using Dijkstra (1959)'s algorithm
- Use freight information to obtain iceberg costs

$$cost_{odt} = \alpha + \beta cost\_graph_{odt} + \epsilon_{odt}$$

Market Access

Combine τ_{odt} with data on population N_{dt} and trade elasticity ($\theta = 8.2$) to compute market access



Results

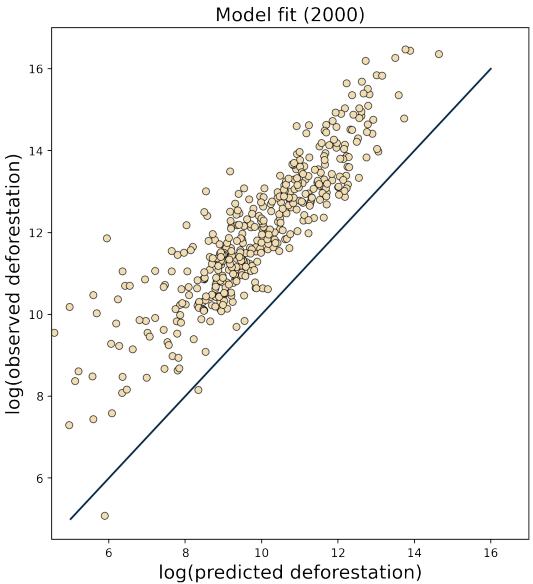
Market Access and Deforestation

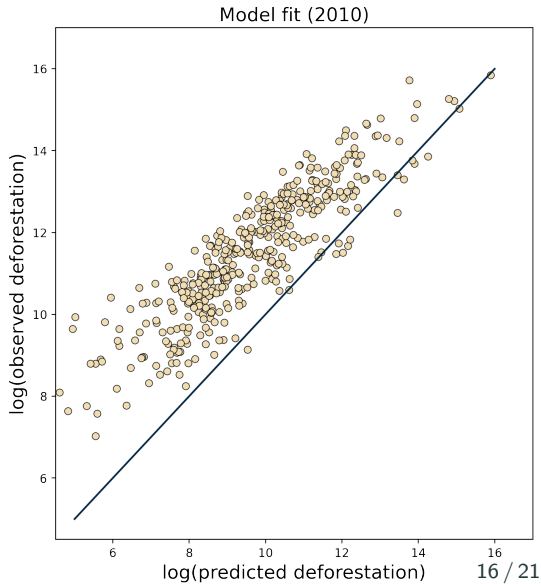
$$\log y_{o,t} = \alpha + \beta \log MA_{o,t_I} + \phi_t X_o + \gamma_o + \gamma_{s,t} + \epsilon_{o,t}$$

	log (Deforestation)					
log(Market Access)	0.45***	0.51***	0.47***	0.47***	0.52***	0.49***
	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)
R^2 (within)	0.16	0.16	0.17	0.16	0.16	0.17
Observations	1,278	1,278	1,278	1,278	1,278	1,278
	First stage: log(Market Access)					
log(Market Access, $\bar{d} = 400$km)				0.95***	0.95***	0.95***
				(0.002)	(0.002)	(0.002)
F Statistic				87,994	94,216	94,346
Observations				1,278	1,278	1278

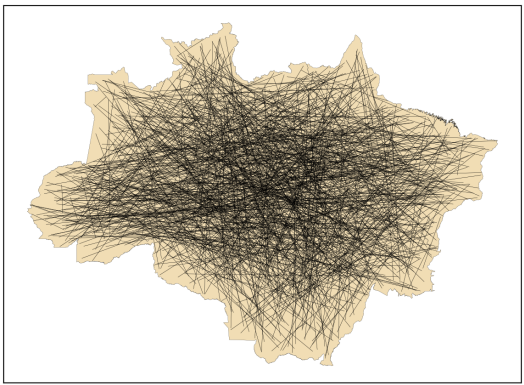
▸ Instruments ▸ Trade Elasticity ▸ Controls ▸ Weights ▸ Domestic Market Access

Model predicts deforestation remarkably well



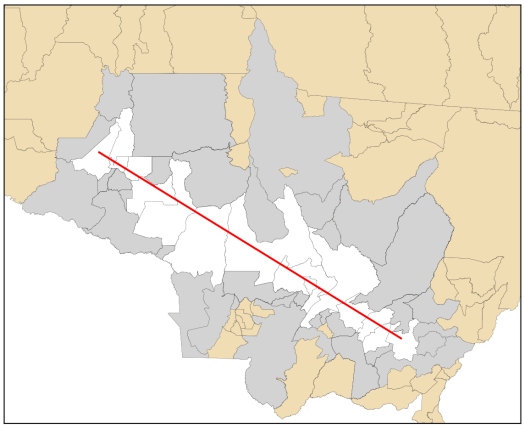


Indirect effects are important!



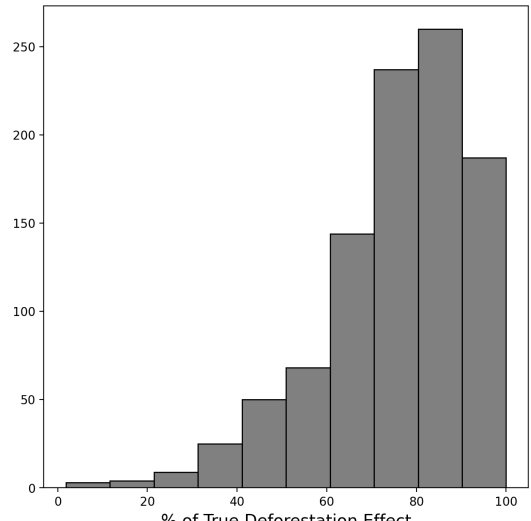
- Simulate 1,000 random roads + simulate its effects on deforestation
- Simulate effects using DID design (Asher et al., 2020)
- DID underestimate effects by 25%

Indirect effects are important!



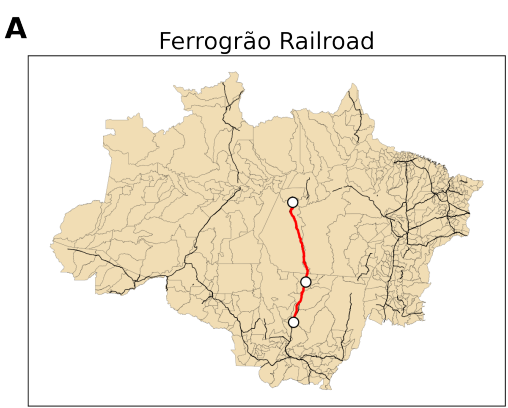
- Simulate 1,000 random roads + simulate its effects on deforestation
- Simulate effects using DID design (Asher et al., 2020)
- DID underestimate effects by 25%

Indirect effects are important!



- Simulate 1,000 random roads + simulate its effects on deforestation
- Simulate effects using DID design (Asher et al., 2020)
- DID underestimate effects by 25%

Ferrogrão railroad



More in the paper

- Elasticity of land supply
  - 1.20-1.36 for frontier land ($\approx$ (Gouel and Laborde, 2018; Pellegrina and Sotelo, 2021; Dominguez-Iino, 2021))
  - 0.17-0.26 overall ($>$ Roberts and Schlenker (2013))

- Extensions
  - Dynamics, multiple sectors, correlated shocks $\rightarrow$ possibly stronger effects

- Importance of heterogeneity in land types
  - Model with one type of land does not predict heterogeneous responses across municipalities ▸ Model w/ one type of land
  - 5$\times$ more deforestation for *Ferrogrão* railroad

Conclusion

Conclusion

Recap:

- Inter-regional trade model connecting deforestation and market access
- $\uparrow$ market access, $\uparrow$ deforestation (elasticity ≈ 0.5)
- Predicts deforestation well, indirect effects are important
- Framework for evaluating the effects of individual projects

Implications:

1. Transportation infrastructure is major driver of deforestation in the Amazon
2. Interaction between types of land key to understand land use dynamics in the region
3. Investments in transportation infrastructure have effects beyond their immediate surroundings
    - Project selection, licensing procedures etc. should consider this explicitly

THANKS!

https://arthurbraganca7.github.io/

aamorimbraganca@worldbank.org

Robustness: Other Instruments

	$d = 400$km	Out-of-state	Fixed pop.	Dom. market
	log (Deforestation)			
log(Market Access)	0.49***	0.48***	0.46***	0.52***
	(0.13)	(0.13)	(0.13)	(0.14)
Observations	1,278	1,278	1,278	1,278
	First stage: log(Market Access)			
log(Alt. Market Access)	0.95***	0.95***	1.00***	0.88***
	(0.01)	(0.01)	(0.01)	(0.01)
F Statistic	94,346	132,155	54,860	2,815
Observations	1,278	1,278	1,278	1,278

Back

Robustness: Controls for Local Infrastructure

	log (Deforestation)					
log(Market Access)	0.47***	0.5***	0.47***	0.47***	0.49***	0.46***
	(0.13)	(0.13)	(0.14)	(0.13)	(0.13)	(0.13)
Observations	1,278	1,278	1,278	1,278	1,278	1,278
	First stage: log(Market Access)					
log(Market Access, $\bar{d} = 400$km)	0.95***	0.95***	0.95***	0.95***	0.95***	0.95***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
F Statistic	99,956	103,394	102,706	98,707	102,782	102,116

Back

Robustness: Trade Elasticity

	log (Deforestation)					
log(Market Access)	0.47***	0.5***	0.47***	0.47***	0.49***	0.46***
	(0.13)	(0.13)	(0.14)	(0.13)	(0.13)	(0.13)
Observations	1,278	1,278	1,278	1,278	1,278	1,278
	First stage: log(Market Access)					
log(Market Access, $\bar{d} = 400$km)	0.95***	0.95***	0.95***	0.95***	0.95***	0.95***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
F Statistic	99,956	103,394	102,706	98,707	102,782	102,116

Back

Robustness: Domestic Market Access

	log (Deforestation)			
log(Market Access)	0.43***	0.49***	0.45***	0.46***
	(0.11)	(0.12)	(0.12)	(0.12)
$R^2(within)$	0.16	0.16	0.17	0.17
Observations	1,278	1,278	1,278	1,278
	First stage: log(Market Access)			
log(Market Access, $d = 400$km)				0.90***
				(0.004)
F Statistic				22,078
Observations				1,278

Back

Robustness: Weights

	area	$\sqrt{area}$	None	None
log(Market Access)	0.47***	0.60***	0.86***	0.69***
	(0.13)	(0.16)	(0.20)	(0.22)
Area $\times$ log(Market Access)				0.01**
				(0.006)
$R^2(within)$	0.17	0.17	0.17	0.17
Observations	1,278	1,278	1,278	1,278

Back

Robustness: One type of land

	log (Deforestation)					
log(Market Access)	0.17***	0.19***	0.18***	0.17***	0.19***	0.18***
	(0.06)	(0.06)	(0.05)	(0.06)	(0.06)	(0.06)
	First stage: log(Market Access)					
log(Market Access, $d = 400$km)				0.96***	0.96***	0.96***
				(0.002)	(0.002)	(0.002)
F Statistic				128,250	130,266	131,612
Observations	1,278	1,278	1,278	1,278	1,278	1278

Back