Climate and Economics: Tropical Forests
Part IV

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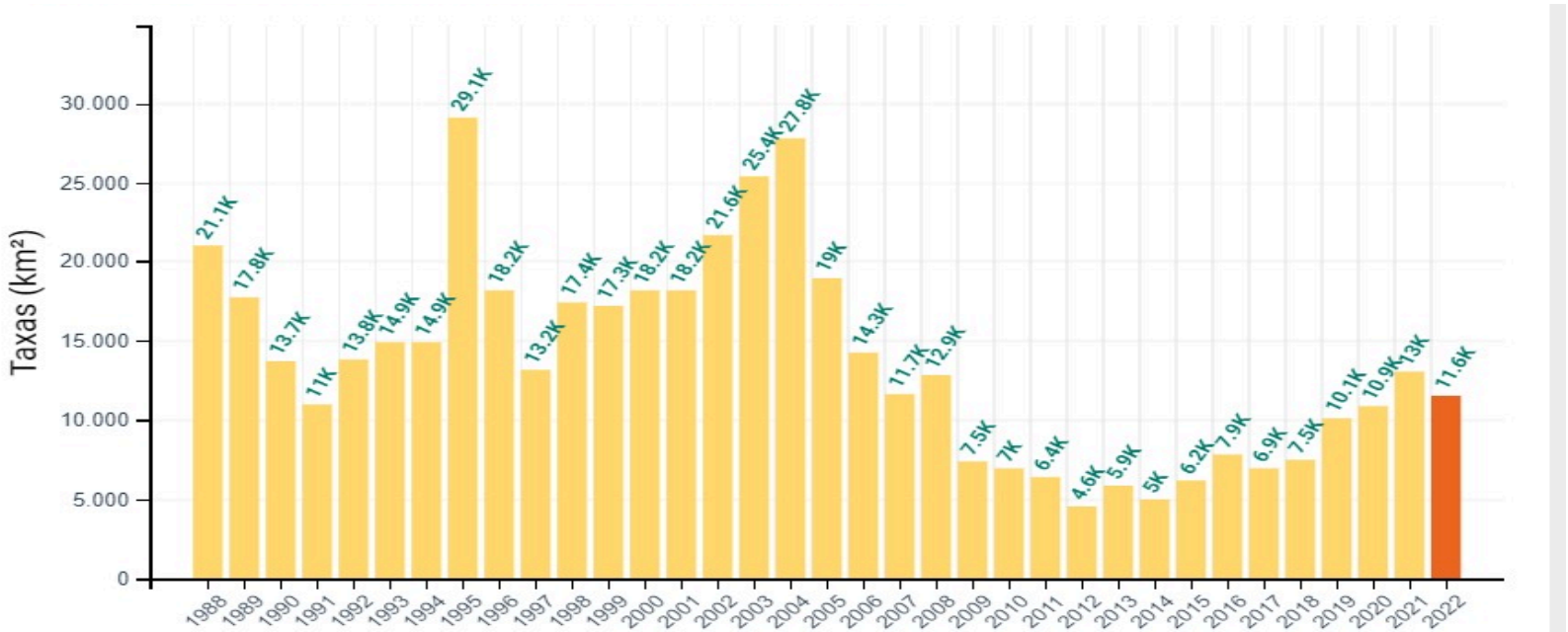
Deterring deforestation in the Brazilian Amazon.

- Bulk of tropical forests in developing countries.
- Weak institutions have long been barriers to policy implementation in developing countries.
- Assunção et al. [2023] examines the use of remote sensing technology to reduce deforestation in the Brazilian Amazon.
- Implementation in 2004 of real-time satellite based system providing daily surveillance of deforestation (DETER).
- Upon detecting change in forest-cover DETER issues an alert to environmental law-enforcement.
  - Vast majority of deforestation in Amazon biome is illegal.
- On time alert is important because upon catching violators in *flagrante delicto*, enforcers can apply instant penalties including apprehending or destroying equipment.
  - Deforestation requires machines
  - Penalize owners instead of poor workers

Deforestation Brazilian *Legal* Amazon in Km^2

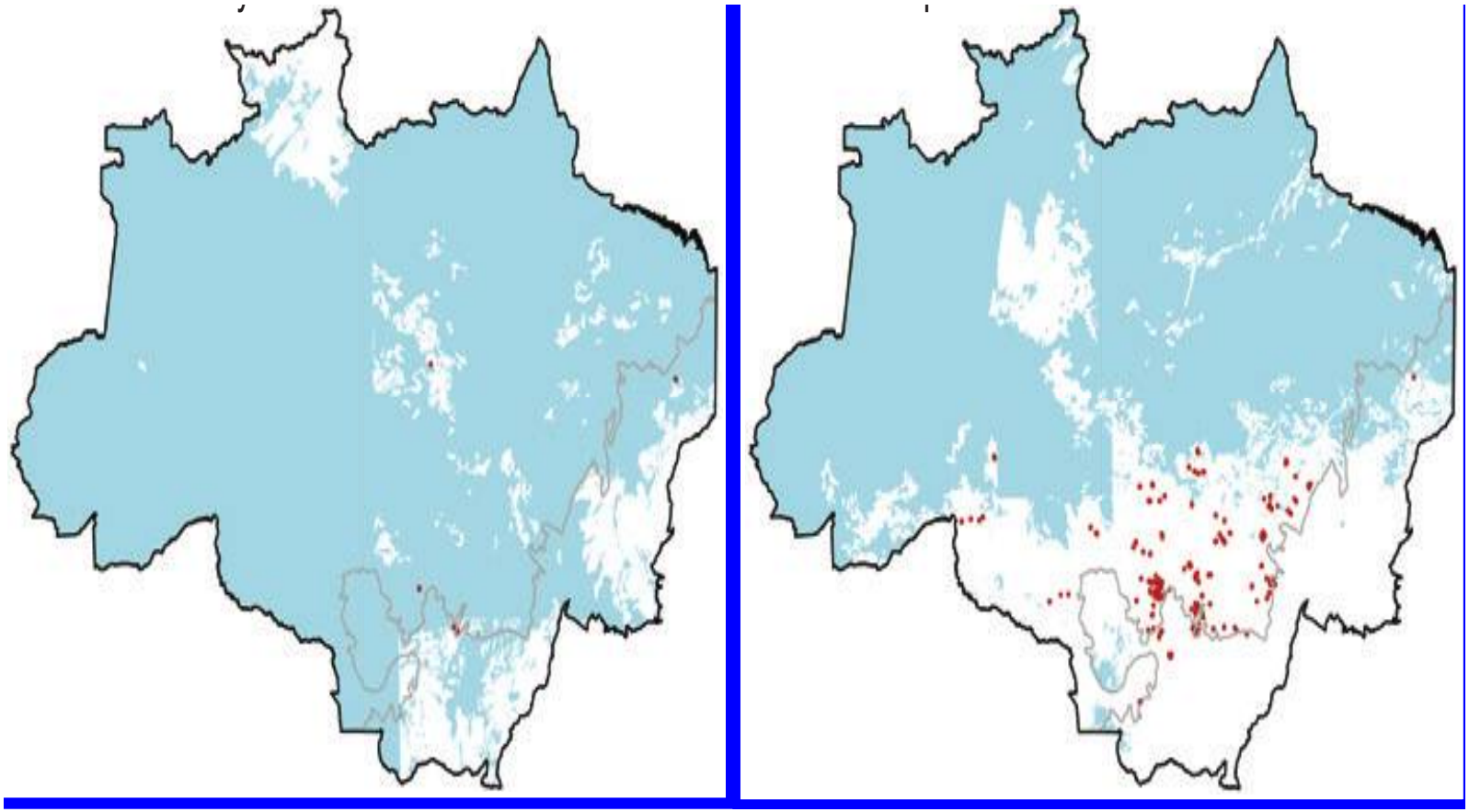


- Not exactly Amazon biome
- `https://web.archive.org/web/20230110063026/http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/rates`

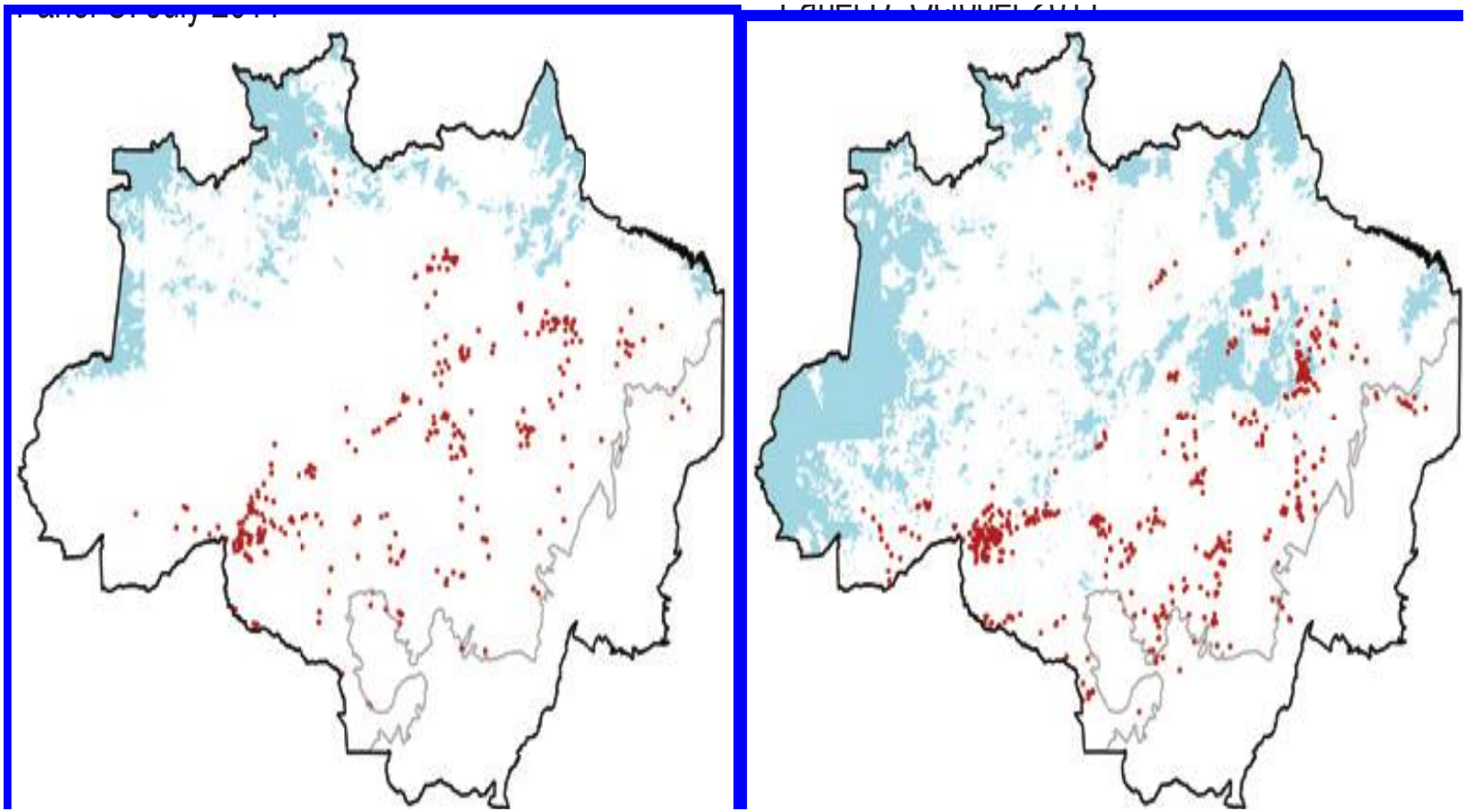
Law enforcement and illegal deforestation

- Endogeneity
  - Levitt [1997]
  - Presence of law enforcement may negatively impacts illegal forest clearing because potential offenders may fear punishment.
  - Law enforcement may be allocated partially based on the observation of clearings.
  - Only observe "'equilibrium" outcomes
- Coefficient of law enforcement on a OLS regression of change in forest cover on law enforcement plus controls cannot be interpreted as casual impact of law enforcement on forest clearing.
- Instruments.
- Assunção et al. [2023] uses cloud covers that inhibit DETER satellite detection in particular areas as instrument for law enforcement.

Clouds and Deter alerts (January *vs* April 2011)



Clouds and Deter alerts (July *vs* October 2011)



Empirical strategy I

- Law enforcement measured by yearly total deforestation-related fines applied by IBAMA in municipality.
  - Upon verifying deforestation Ibama may apply other penalties but always issues a fine
  - Ibama produces public data on fines that contains date, municipality, and fine type of infraction, what allows to identify deforestation-related fines.
  - https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php (raw data received May 2016).
- Deforestation measured by PRODES a system that started in 1988 , which uses a better (and more expensive) satellite system, and chooses the best pictures from the yearly Amazon dry season for each area.
  - PRODES uses optical images from Landsat satellites

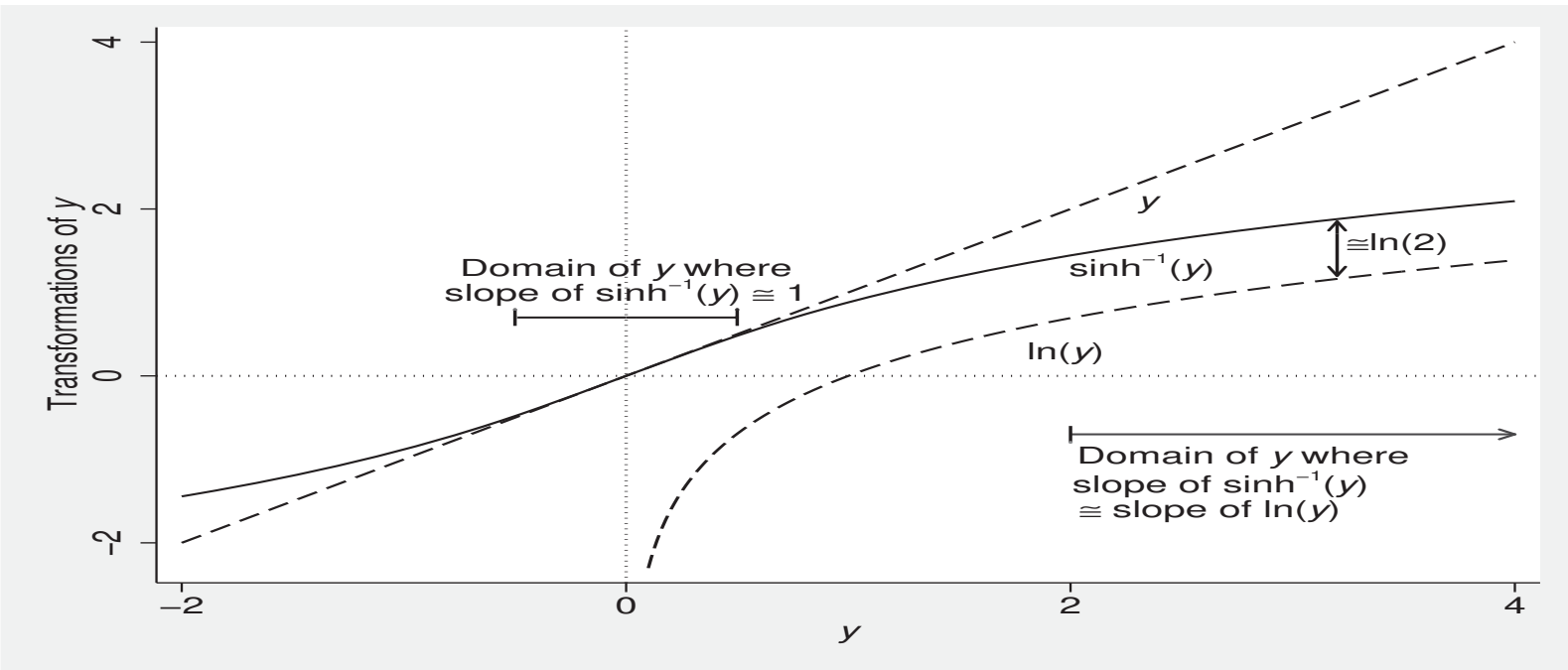
Empirical strategy II

- PRODES produces a yearly measure of deforestation change for 30m pixels. PRODES counts pixels that are near totally deforested. Once area counted as deforested it is considered deforested forever.
- Does not account for reforestation or deforestation of reforested areas.

Empirical strategy III

- To reduce influence of large municipalities transform PRODES total increment in deforestation by using the transformation

$$\sinh^{-1}(y) = \ln\left(y + \sqrt{y^2 + 1}\right)$$



Empirical strategy IV

- Cloud cover measured using DETER.
- DETER uses optical images from MODIS sensor on the Terra Satellite
  - Resolution of 250 meters.
  - Daily visits of all areas
- Law enforcement gets high frequency info on deforestation but public data on cloud-cover is monthly.
- Variable $Cloudc_{i,t}$ is yearly average of monthly ratios of area covered by clouds to municipal area.
- Panel of observations over municipalities i and PRODES year t, August $(t-1)$ to July (t), for $t = 2006 \ldots 2016$.
- OLS regression

$$Deforest_{i,t} = \tilde{\beta} LE_{i,t-1} + \sum_{k} [\tilde{\gamma}_k Control_{i,t,k}] + \tilde{\alpha}_i + \tilde{\phi}_t + \tilde{\epsilon}_{i,t} \qquad (1)$$

Empirical strategy V

- Controls include, agricultural prices at municipality, precipitation and temperature at municipality, and PRODES satellite blocked areas.
- But coefficient $\tilde{\beta}$ is affected by presence of reverse causality.
- Instead, first-stage regression

$$LE_{i,t} = \beta Cloudc_{i,t} + \sum_{k} [\gamma_k Xi, t, k] + \alpha_i + \phi_t + \epsilon_{i,t} \qquad (2)$$

- $X_{i,t}$ municipality-level controls that include precipitation, temperature, and PRODES blocked areas.
- α municipality f.e., ϕ year f.e.
- SE clustered at municipality (521) and micro-region (81)-year two-way clustering.
- Clustering is to allow for heteroskedascity between error terms when computing standard errors.

Empirical strategy VI

- Two way clustering allows for heteroskedasticity and autocorrelation.
- β significantly $\neq 0$, (relevance).
- To use *Cloudc* as an instrument for *LE* need to argue that it is uncorrelated with the residuals in the OLS (1) . (exclusion)
- Threats to exclusion restriction
  - $Cloudc_{i,t}$ correlated with omitted geographical variables that correlate with forest clearings.
  - Addressed by controlling for rainfall and temperature which could be causes of cloud cover, and may correlate with deforestation via *e.g.*, ecological effect of forest loss.
  - $Cloudc_{i,t}$ may be correlated with measure of deforestation
  - Addressed by using PRODES and a control for PRODES blocked areas.

Empirical strategy VII

- Second-stage (IV) regression:

$$Dforestat_{i,t} = \delta Cloudc_{i,t-1} + \sum_{k} [\theta_k X_{i,t,k}] + \psi_i + \lambda_t + \xi_{i,t} \qquad (3)$$

- Use of $Cloudc_{i,t-1}$ based on literature starting with (Levitt [1997]) that documents lagged response of illegal activity to enhanced enforcement.
- $X_{i,t,k}$ include in addition to those in equation (2), agriculture commodity prices.
- Robustness exercises include controls for conservation policy controls.

2SLS, second stage and OLS: Cloud coverage and law enforcement

TABLE 2—IV REGRESSIONS: LAW ENFORCEMENT AND DEFORESTATION

Panel A. 2SLS, second-stage results and OLS

Depvar:	IHS(deforest) 2SLS (1)	ln(deforest) 2SLS (2)	deforest/muni area 2SLS (3)	deforest/mean 2SLS (4)	IHS(deforest) OLS (5)
Enforcement, $t-1$	−0.0503	−0.0743	−0.0244	−0.0452	0.0002
	(0.0235)	(0.0399)	(0.0123)	(0.0243)	(0.0006)
FE: municipality and year	Yes	Yes	Yes	Yes	Yes
Controls: full	Yes	Yes	Yes	Yes	Yes
Observations	5,210	5,210	5,210	5,210	5,210
Municipalities	521	521	521	521	521

- Estimate in specification (1) implies that on average, increasing monitoring law enforcement by 50% yields 25% decrease in deforestation.
- Computation of elasticity as derived in Bellemare and Wichman [2020]

2SLS first stage: Cloud coverage and law enforcement

Panel B. 2SLS, first-stage results

	Depvar: enforcement 2SLS
DETER cloud coverage	−9.6628 (3.0394)
Precipitation	−0.0004 (0.0003)
Temperature	−0.5530 (1.5160)
PRODES cloud coverage	0.0002 (0.0001)
PRODES nonobservable	0.0029 (0.0026)
First-stage *F*-statistic	10.11
FE: municipality and year	Yes
Controls: agricultural prices	Yes
Observations	5,210
Municipalities	521

- First stage $F > 10$ means instrument strength not a cause for concern [Stock et al., 2002]

Cost effectiveness I

- Total budget for Ibama and Inpe amounted to $6.85 billion.
  - This uses 2011 budgets multiplied by the number of years (10).
  - Ibama and Inpe have many other tasks, so surely this exaggerates costs.
    - Ibama in charge of environmental impact evaluation and licensing in Brazil.
- Two counterfactual- exercises concerning deforestation in 2007-2016 using specification (3).
  1. No monitoring or low enforcement. Set $LE = 0$.
  2. No new satellite system: Set $LE =$ average 2002-2004 (pre-DETER)
- Both scenarios yield substantial increase in deforestation.
- Actual deforestation in period was 69,500 km^2.
- Scenario 1 implies Amazon would have seen 338,000 km^2 of cleared areas an increase of almost 400%.
- Scenario 2 implies 279,000 km^2 of cleared areas.

Cost effectiveness II

- Based on scenario 1 this would have implied extra emission of almost 10 gigatons of CO_2. Thus the cost corresponds to \$.69/ton.
- Based on scenario 2 cost =\$.89 /ton
- Deterrence of deforestation at scale and with punishment is very cheap.

Calculating impact of counterfactual law enforcement I

- Let $y_{i,t}$ denote normalized deforestation and rewrite the benchmark specification (equation (3)) as:

$$y_{i,t} = \delta LE_{i,t-1} + \sum_k \theta_k X_{i,t,k} + \psi_i + \lambda_t + \xi_{i,t} \tag{4}$$

- In a counterfactual scenario of law enforcement :

$$\begin{aligned}
\mathbb{E}[y_{i,t|sim} - y_{i,t}] &= \hat{\delta} LE_{i,t-1|sim} + \sum_k \hat{\theta}_k X_{i,t,k} + \hat{\psi}_i + \hat{\lambda}_t \\
&\quad - \left[\hat{\delta} LE_{i,t-1} + \sum_k \hat{\theta}_k X_{i,t,k} + \hat{\psi}_i + \hat{\lambda}_t \right] \\
&= \hat{\delta} \left(LE_{i,t-1|sim} - LE_{i,t-1} \right)
\end{aligned}$$

Calculating impact of counterfactual law enforcement II

- For the linear transformation in which annual municipal deforestation ($def_{i,t}$) is divided by a municipality-specific constant (μ_i), this difference is given by:

$$\mathbb{E}\left[\frac{def_{i,t}}{\mu_i}|_{sim} - \frac{def_{i,t}}{\mu_i}\right] = \hat{\delta}\left(LE_{i,t-1|sim} - LE_{i,t-1}\right)$$

$$\implies \mathbb{E}\left[\frac{def_{i,t|sim} - def_{i,t}}{\mu_i}\right] = \hat{\delta}\left(LE_{i,t-1|sim} - LE_{i,t-1}\right)$$

$$\implies \mathbb{E}\left[def_{i,t|sim} - def_{i,t}\right] = \mu_i\hat{\delta}\left(LE_{i,t-1|sim} - LE_{i,t-1}\right)$$

Robustness Checks

- Checking if pre-DETER differences drive results
  1. 2003 deforestation stock
  2. 2003 increase in deforestation
  3. 2002-2004 average municipal fines
- Coefficient on $Cloudc_{i,t-1}$ in second stage specifications remain statistically significant and first-stage coefficient of $Cloudc_{i,t}$ keeps sign, significance and instrument strength.
- Sample restricted to municipalities in which forest/municipal area in 2003 above median
- Control for conservation policies implemented alongside DETER: extension of protected areas, priority municipalities.
- Alternative weather controls (NOAA) instead of benchmark from [Matsuura and Willmott, 2018a,b]

Placebo I - Changing timing of *Cloudc* I

TABLE 4—REDUCED-FORM SPECIFICATIONS AND PLACEBO CHECKS: CLOUD COVERAGE AND DEFORESTATION

	Depvar: IHS(deforest)			
	(1)	(2)	(3)	(4)
DETER cloud coverage, $t-1$	0.4863			0.5313
	(0.1729)			(0.1891)
DETER cloud coverage, t		−0.1783		−0.0181
		(0.1696)		(0.1824)
DETER cloud coverage, $t+1$			−0.2111	−0.2291
			(0.1944)	(0.1878)
FE: muni. and year	Yes	Yes	Yes	Yes
Controls: full	Yes	Yes	Yes	Yes
R^2	0.8702	0.8699	0.8676	0.8703
Observations	5,210	5,210	4,689	4,689
Municipalities	521	521	521	521

Placebo II - Could cover before DETER I

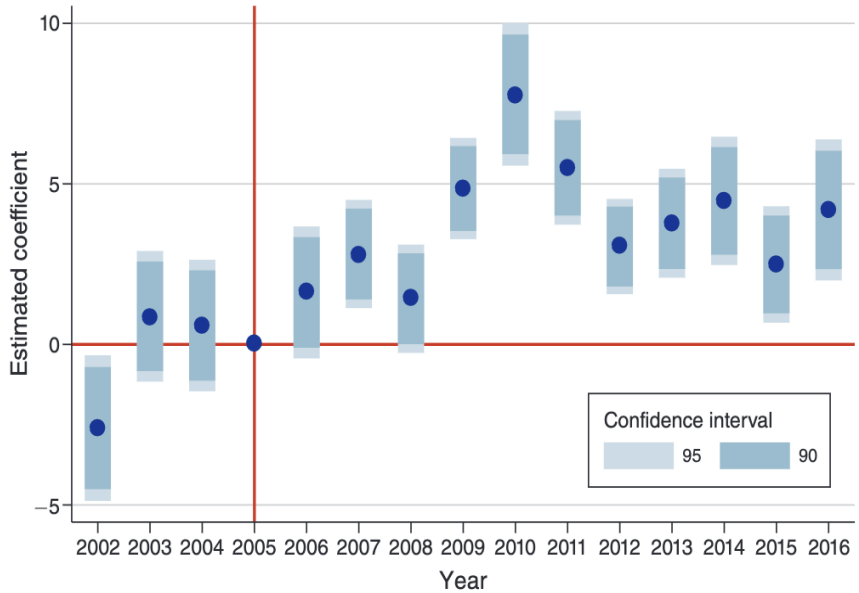


FIGURE 3. PLACEBO CHECK: CLOUD COVERAGE AND DEFORESTATION BEFORE AND AFTER REMOTE MONITORING

- Use cloud-cover from NASA's Earth Data Giovanni platform.
  - Correlation of .63 with DETER cloud cover.
- Regression as in specification (1) of previous table but adding interaction between year dummies and cloud-cover.

Summary of Results

- Estimated coefficient $\tilde{\beta}$ of OLS not significantly different from 0, suggesting law enforcement does not affect deforestation. Because of reverse causality, expect OLS upward biased.
- Estimated β in first-stage regression significantly negative.
- Elasticity of deforestation with respect to law enforcement (proxied by Cloudc) is .53 for the average municipality.
- Empirical evidence that environmental law enforcement effectively curbed tropical deforestation in 2006-2016.
- Counterfactuals show that if implemented at scale protecting forests is cheap.

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