Local incentives and national tax evasion:
The response of illegal mining to a tax reform in Colombia

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Quantil

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How does evasion respond to the revenue allocation?

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- However, tax revenue sources unchanged.
- How does tax evasion respond to the revenue allocation among municipalities?
- Does illegal activity have additional effects besides lost tax revenue?

Evasion is observable in the case of illegal mining

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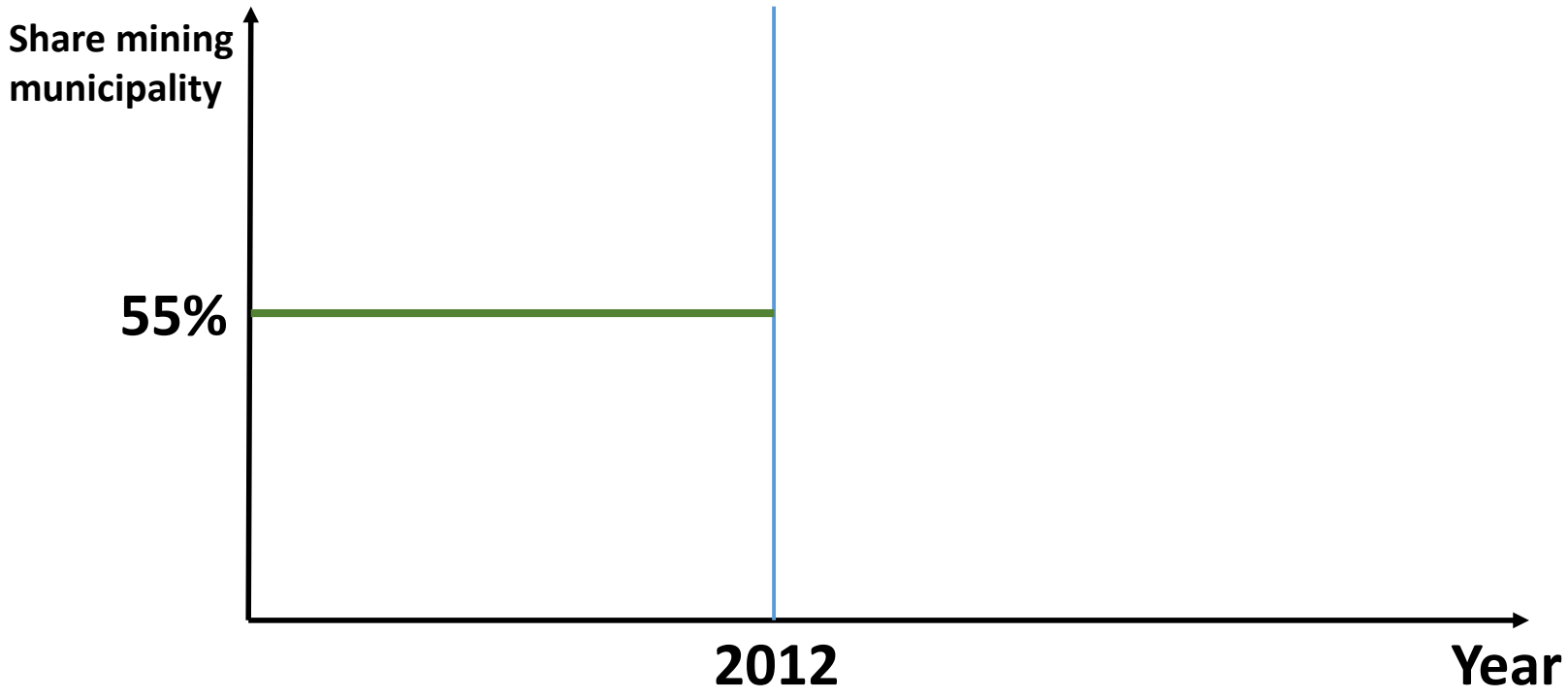
Google Maps Remedios, Antioquia

Reform reduced revenue share for mining municipalities



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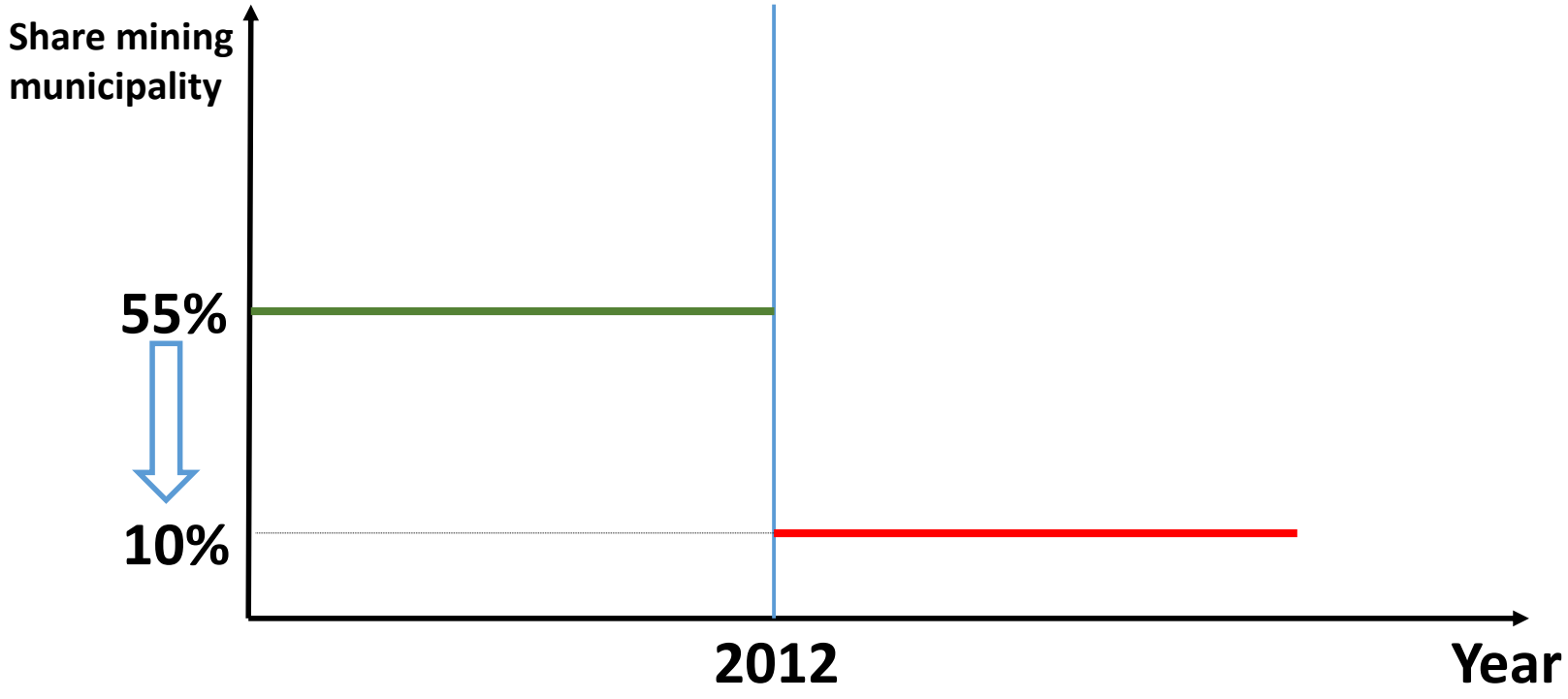

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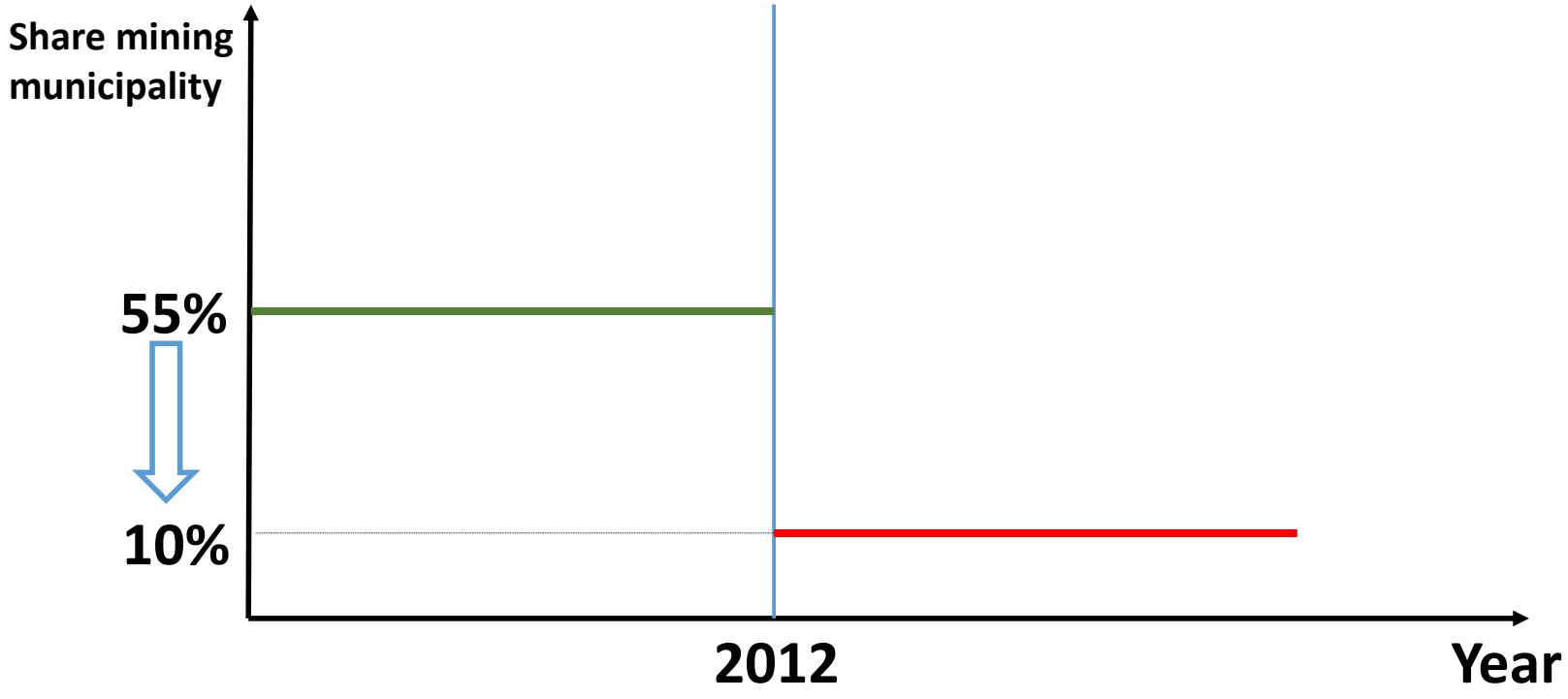

Standard bargaining model between bureaucrat and miner predicts increase in illegal mining.

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- Estimate the effect of the reform on illegal mining:
  - Difference in differences strategy
- Estimate effect of illegal mining on newborn's health:
  - IV strategy with the reform and river flow.

We find large unintended effects of the reform

- Illegally mined area increased after the reform:
  - Illegal mining area increased by 1.63 -4.47 percentage points as share of mined area.
- Reported quantity produced does not change.
- Higher environmental impacts from illegal mines.
  - Larger negative health effects of illegal gold mines on newborns' health.

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  $\Rightarrow$ **Dual use of machine learning: predicting dep. variable and estimating causal effects.**

Outline

1. **Institutional context**
2. Theoretical framework
3. Constructing the illegal mining panel
4. Main results
5. Differential health effects of illegal mining
6. Discussion and conclusions

Mining is an important sector of the Colombian economy

- Mining and hydrocarbons importance for the economy:
  - Around 10% of GDP.
  - Royalties represented 10% of mining municipalities' budget.
- Titles granted for 30 years.
- Illegal mining is a widespread phenomena:
  - 63% of mines are illegal (Mining Census, 2010).
  - 78% of gold mined area illegal (UNODC, 2016).
- Unsuccessful legalization efforts (less than 1% success).

Details of the royalties reform

- Approved in July 2011, implemented on January 2012.
- Objective was to reduce regional inequality. ▸ *
- Reduced direct royalties transfers to mining municipalities from 55% to around 10% .
- Distributes revenue nationally according to poverty, population and unemployment indicators. ▸ *
- Some municipalities won and others lost with the reform. ▸ Example
- Notes:
  - Did not change title fees or taxes paid by mining firms.
  - Illegal mining was not mentioned in the reform documents.

Other events happening at the same time of the reform

- Titling request system closed: November 2011 to July 2013
  - Restrict analysis to illegal mining outside 2014 titles.
- Allow destruction in-situ of illegal mines machinery:
  - Underestimate the effect of the reform.
  - Also approved in Peru.

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Overview of the model and predictions

- Miner and bureaucrat assess the cost-benefit of illegality
- Miner:
  - If legal: pay title registration fees and royalties taxes
  - If illegal: pay bribe and face probability of detection (increasing in size)

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- Bureaucrat:
  - If mine is legal: municipality receives a share of the taxes paid
  - If mine is illegal: receive bribe and face probability of detection
- Two predictions:
  1. Illegal mining increases after the reform.
  2. Larger increase in municipalities with low probability of detection.

The surplus depends on the payoffs when legal and illegal

The "surplus" of illegal mining (S), is the difference between the payoffs for miner and local authority when legal/illegal

$$S(K) = \underbrace{f(B) - f(B + R\beta)}_{Foregone\ \ royalties} + \underbrace{R + Fees}_{Legality\ \ costs} - \underbrace{Pr(K)Kp_K}_{Illegality\ \ costs}$$

- K: capital of the firm
- p_K: price of capital
- R: royalties paid by the firm
- B: other government revenue
- β: share of royalties for the mining municipality
- $f()$: valuation of the local municipality's budget by the local authority

Two main predictions

$$S(K) = \underbrace{f(B) - f(B + R\beta)}_{\textit{Foregone royalties}} + \underbrace{R + Fees}_{\textit{Legality costs}} - \underbrace{Pr(K)Kp_K}_{\textit{Illegality costs}}$$

1. Illegal mining increases after the reform:
   $\downarrow \beta \Rightarrow S \uparrow$ ▸*
2. Larger effect if smaller probability of detection:
   small $Pr(), \downarrow \beta \Rightarrow S \uparrow\uparrow$ ▸*

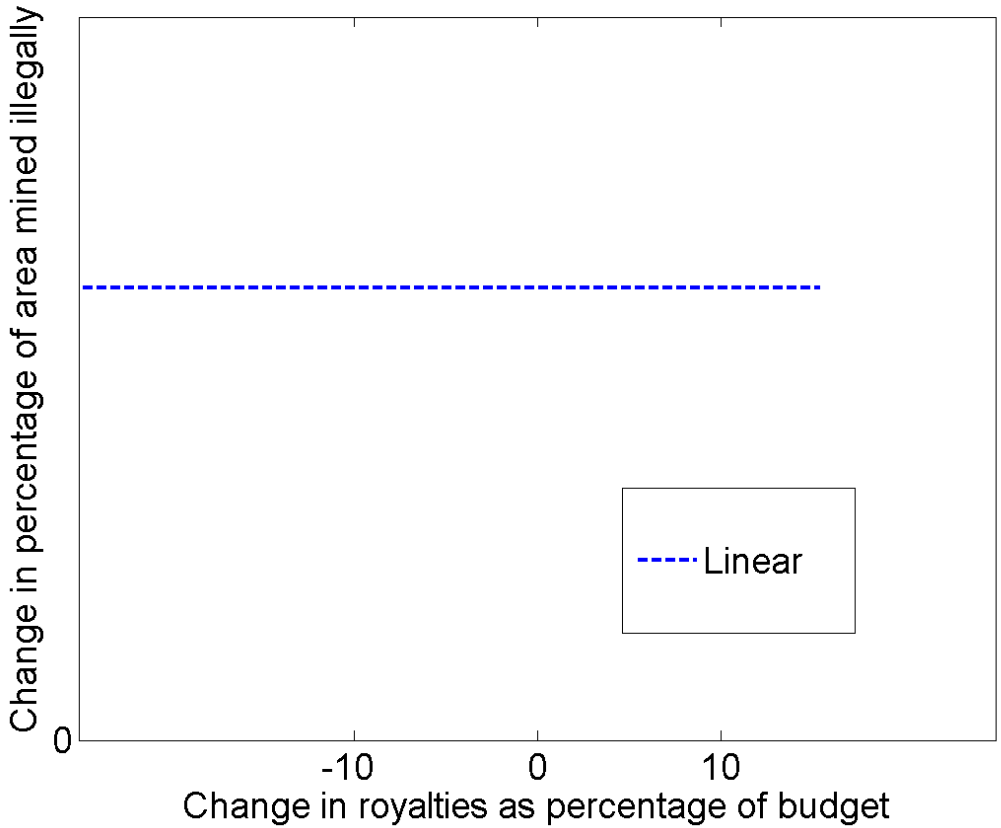
If f is linear, no differential income effect of the reform

The change in illegal mining "surplus" with the reform is

$$\Delta S = \cancel{\left(f(B+B_1) - f(B+B_1+R\beta_1)\right)} - \left(\cancel{f(B)} - \cancel{f(B+R\beta_0)}\right)$$

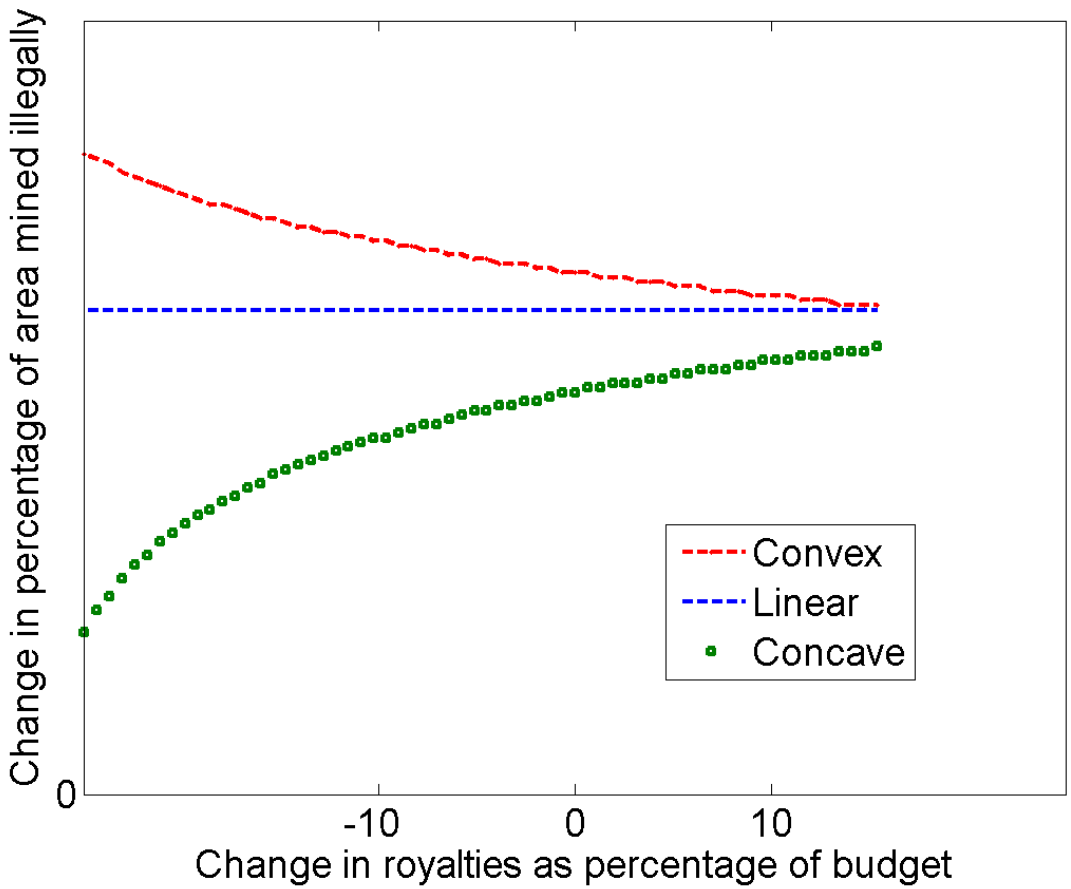
$$= R(\beta_0 - \beta_1)$$

B_1: post-reform transfer based on socioeconomic indicators



Income effect of the reform depends on the concavity of f

$$\Delta S = (f(B + B_1) - f(B + B_1 + R\beta_1)) - (f(B) - f(B + R\beta_0))$$



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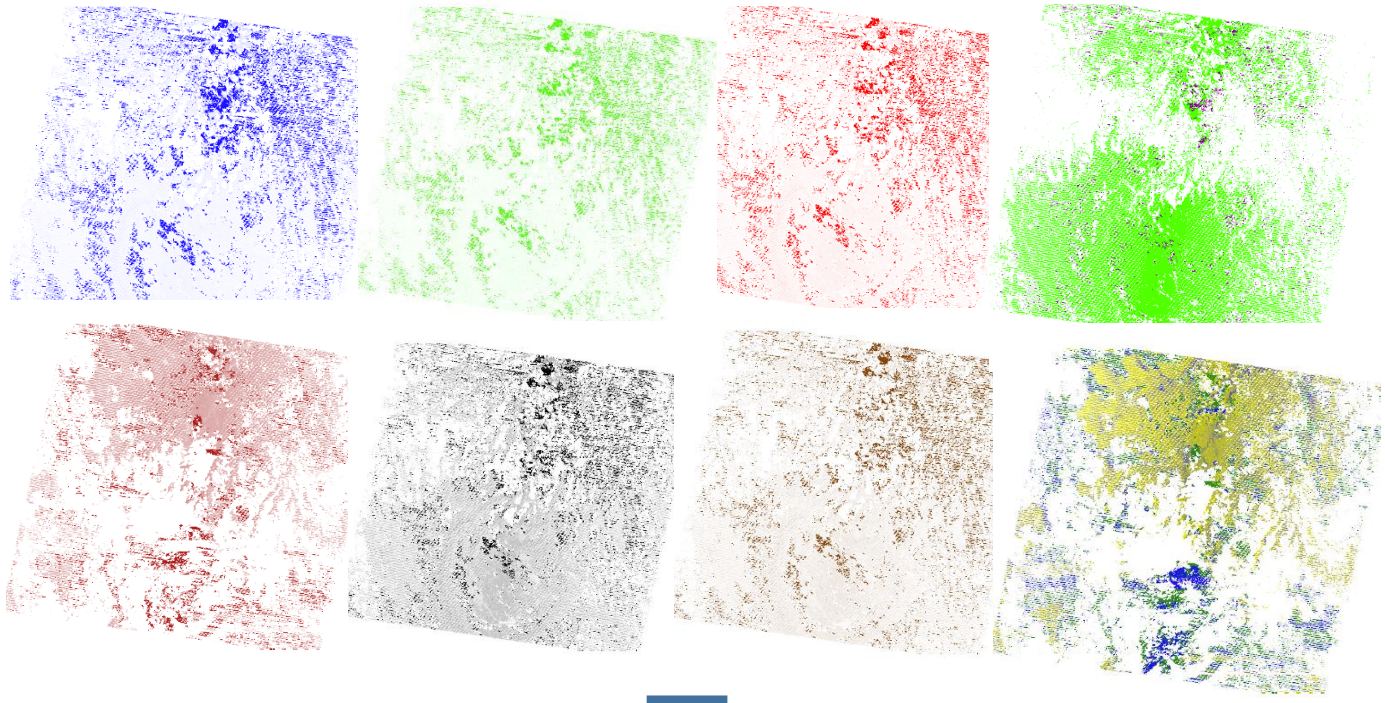
Use random forest model to predict mine location

- Goal: Guess where illegal mines are.
- Solution:
  1. Train a model to predict mining activity.
  2. Assess legality based on National Government registries.
- Training data:
  - Mining Census 2010 point coordinates (MinMinas) ▸ Balance
  - Draw exact shape (Digital Globe)
  - Location of some mines (Open Street Map)
- Information
  - Six color bands (Landsat 7 Satellite, NASA)
  - Deforestation year (Hansen et al,2013)
  - Ecosystem type (Etter, 2006)

Consolidate the information in a single dataset

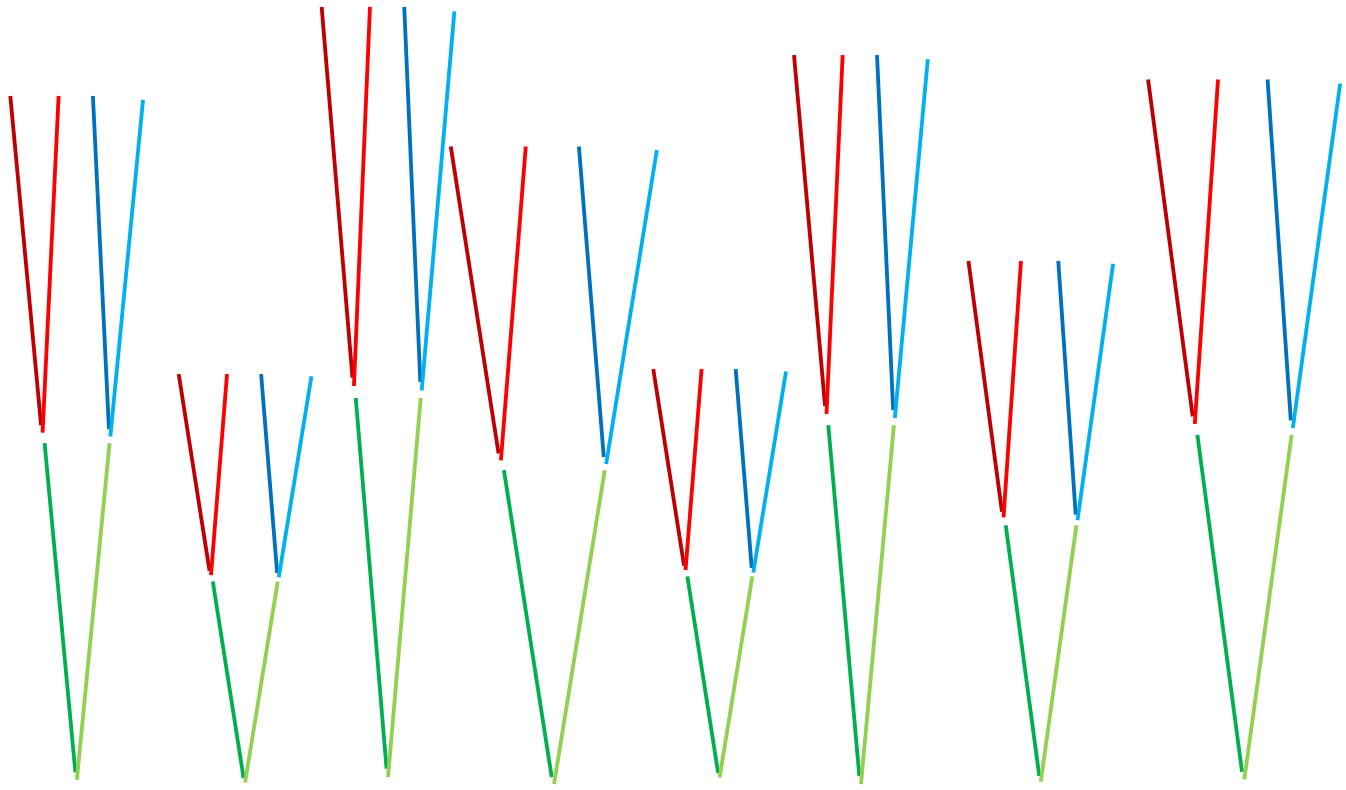


Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Loss year	Ecosystem
207	246	211.5	0	0	364	10	25
204	247	209	0	0	362.5	10	25
205.5	248.5	210.5	0	0	362	10	25
99	147	77.5	1227	495	197.5	0	25

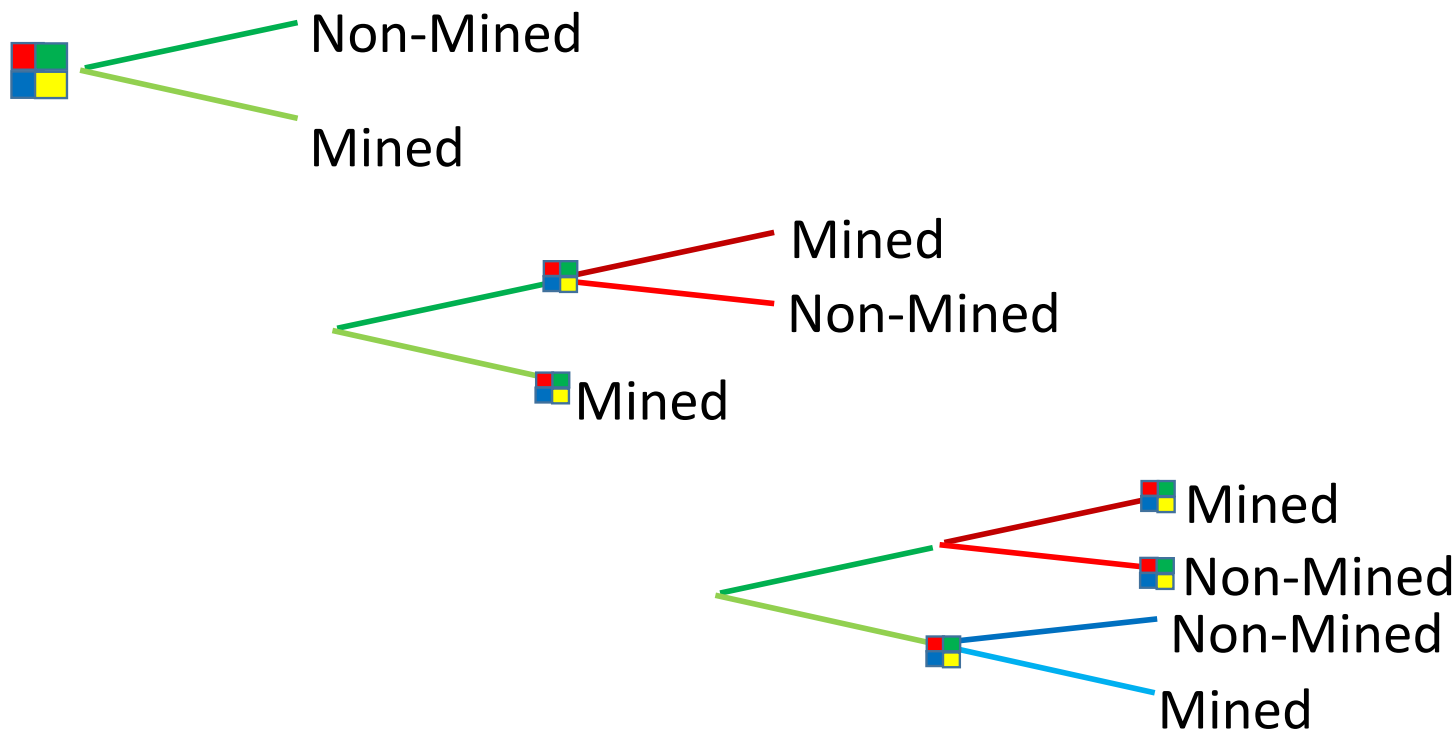
Challenges

- 1 billion pixels (30mx30m) every 2 weeks
  - $\Rightarrow$ Cannot classify by hand
- Cloud presence
  - $\Rightarrow$ Yearly cloudless composite (Zvolev, 2014) ▸ *
- Non-linear relationship between colors and mine presence
  - $\Rightarrow$ Train random forest model (Paleologo et. al. 2010) ▸ Why trees?
    - Performs better than other models

A random forest is a collection of many decision trees

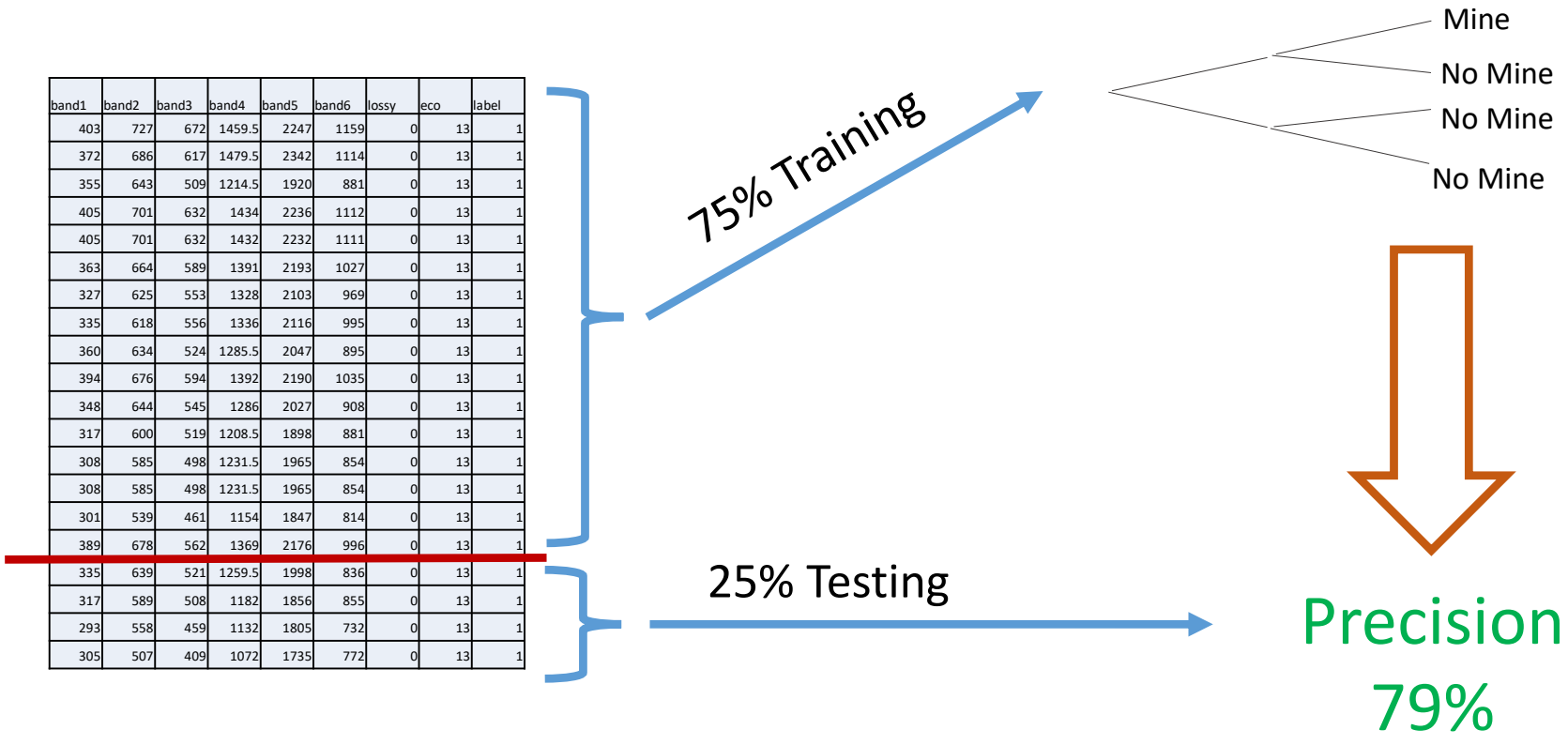


- A decision tree separates the data at each node with the best binary decision separating mined pixels.



- The random part comes from having only a random subset of variables at each decision node.

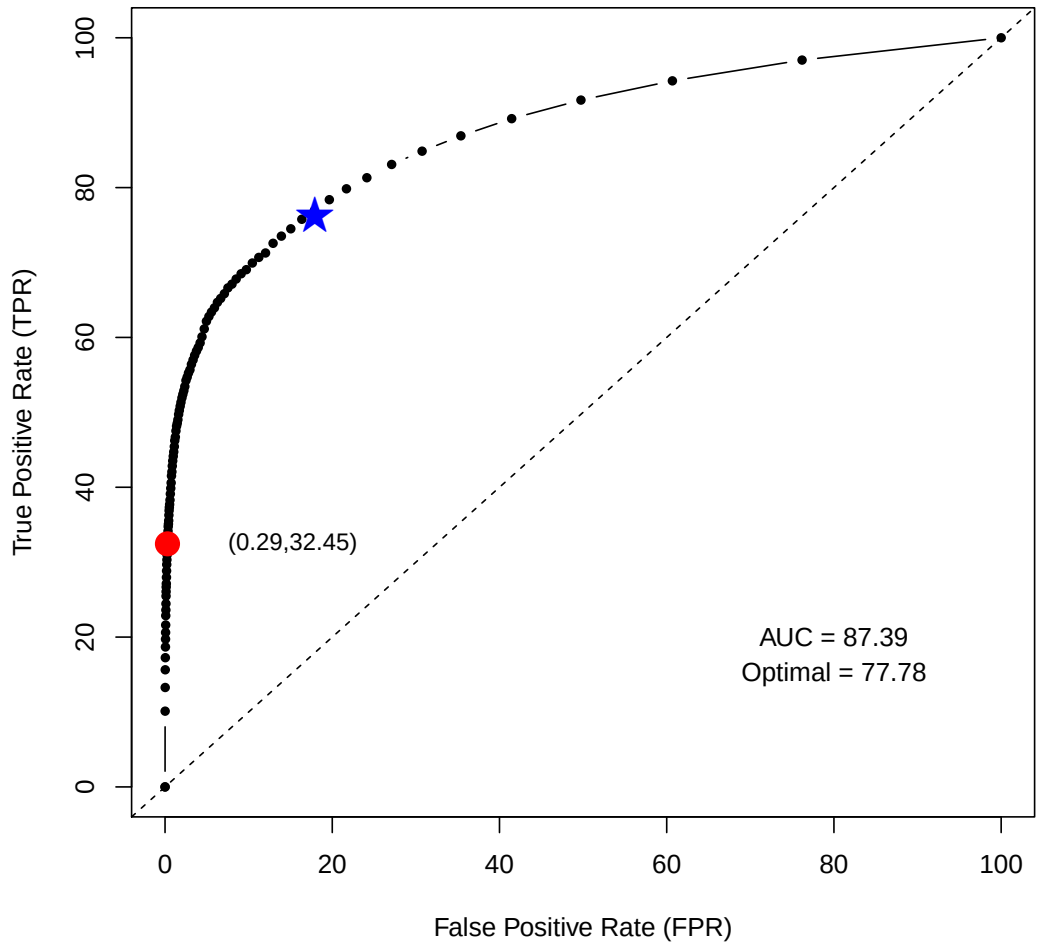
The precision of the mining prediction model is high



Out of 100 pixels the model predict as mined, 79 are truly mined according to the testing data.

Prioritize having small false positive rate

Receiver Operating Characteristic (ROC) curve



▸ Importance ▸ Why cutoff? ▸ By Municipality ▸ Conf Mat

Area Under the Curve (AUC) is high compared to the standard of 0.7

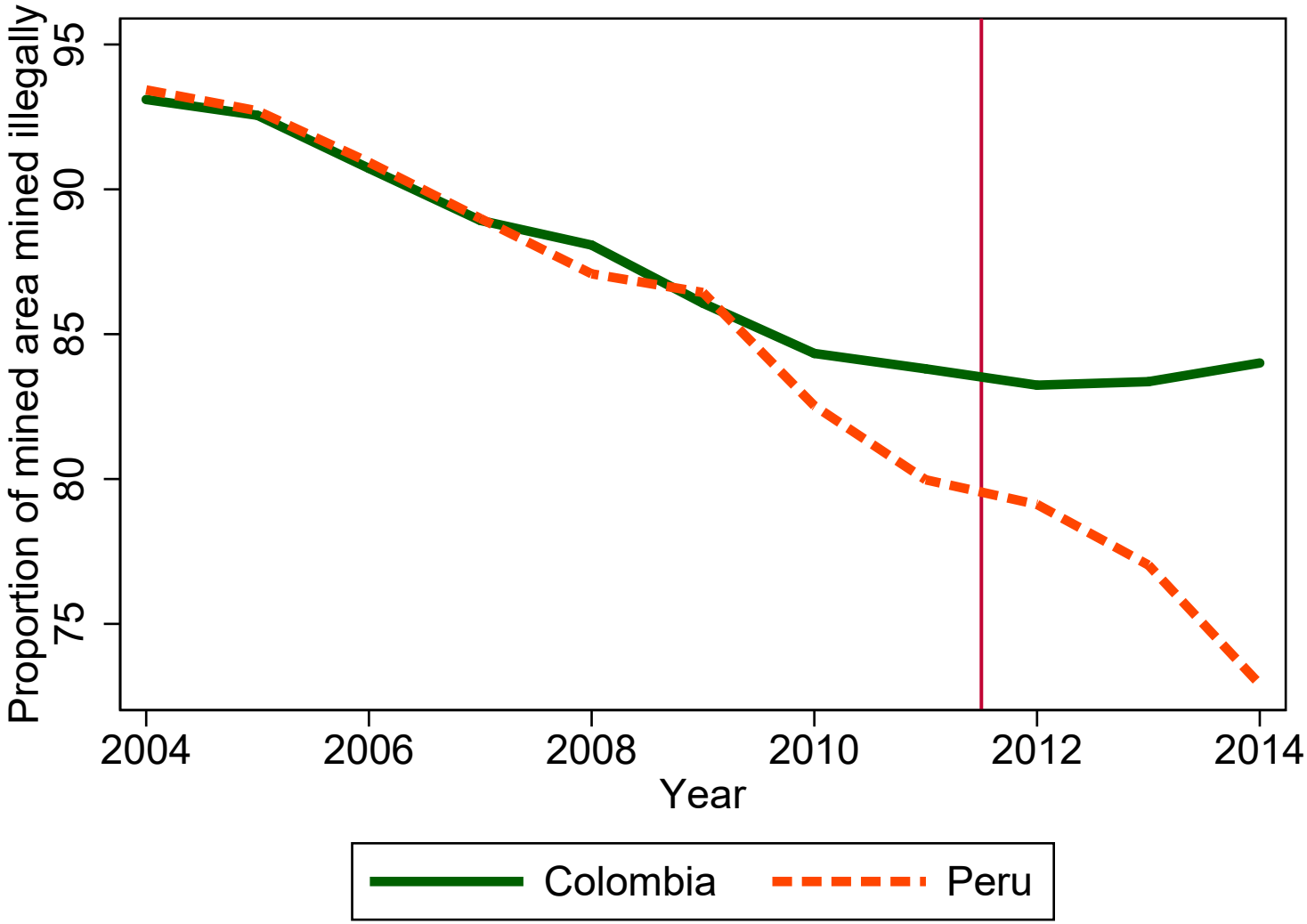
Logit: 19% True Positive Rate - 15% False Positive Rate

Use the prediction model in other years

1. Prepare the satellite data
2. Train the model
3. Prediction for all years
   - Apply the model to each pixel each year
   - Geographic correction
   - Time series correction
   - "Subtract" legal mines (National Mining Registry)
   - Collapse by municipality ("distrito" in Peru)

After predicting mining, we assess legality

Fraction mined area mined illegally by year



▸ Gold Price ▸ Unbalanced panel ▸ Share ▸ Total ▸ WL Balance ▸ Parallel Trends

We use a difference in differences framework

Estimating equations

$$\widehat{y_{mt}} = \beta_C After_t + \gamma_P Price_{mt} + \gamma_m + \delta * t + \varepsilon_{mt}, \quad (1)$$

$$\widehat{y_{mt}} = \beta_C Aft_t Col_m + \beta_P Aft_t Per_m + \gamma_m + \delta_C t + \delta_P t + \varepsilon_{mt}, \quad (2)$$

$$\widehat{y_{mt}} = \beta_C After_t \times Col_m + \gamma_m + \gamma_t + \varepsilon_{mt}, \quad (3)$$

- y_{mt} is a measure of illegal mining on municipality m at time t
- $After_t$ indicates after the reform
- Col_m, Per_m indicate Colombian or Peruvian municipality
- $Price_{mt}$ is an index of the minerals of the municipality

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Illegal mining increased more in Colombia

Dependent variable:	% mined area mined illegally		
	Only Colombia	With Peru	
	(1)	(2)	(3)
After x Colombia	1.63***	1.84***	4.47***
	(0.45)	(0.49)	(0.62)
After x Peru		-2.36***	
		(0.38)	
Time FE-Trend	Trend	Trend	TimeFE
N. of obs.	8796	26355	26355
Municipalities	927	2733	2733
Mean of Dep. Var.	93.7	92.7	85.1
R^2	0.78	0.72	0.73

All regressions include municipality fixed effects. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Results are robust when using only newly mined area

Dependent variable:	% of new mined area mined illegally		
	Only Colombia	With Peru	
	(1)	(2)	(3)
After x Colombia	2.29***	2.00***	5.35***
	(0.61)	(0.59)	(0.75)
After x Peru		-0.86	
		(0.64)	
Time FE-Trend	Trend	Trend	TimeFE
N. of obs.	5156	11568	11608
Municipalities	816	1549	1552
Mean of Dep. Var.	92.2	88.6	88.6
R^2	0.67	0.72	0.72

All regressions include municipality fixed effects and linear trend. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Robustness checks

- Mining prediction cutoff
- Pixels mined probabilities
- Border municipalities
- Unobservables
- Optimal controls
- Weights
- Adjusted predictions
- State trends
- Other measures

Heterogeneous effects municipalities with low enforcement

- Prediction 2 from the model: Larger effect of the reform in municipalities with low probability of detecting illegal mines.
- Municipalities where detection probability could be lower:
  - Municipalities with armed groups present (CEDE,2016).
  - Municipalities where national government's presence is weak (CEDE,2016).
    - Measured with number of national government's institutions (e.g. tax collection or notary's office) per capita.

Larger increase in municipalities with weak presence of the government

Dependent variable:	% mined area mined illegally		
	(1)	(2)	(3)
After x Colombia	1.63***	0.87	1.94***
	(0.45)	(0.56)	(0.60)
After X Weak Institutions		2.83***	
		(1.00)	
After x Armed Groups			-0.76
			(1.00)
N. of obs.	8796	8455	8796
Municipalities	927	890	927
Mean of Dep. Var.	93.7	93.6	93.7
R^2	0.78	0.79	0.78

All regressions include municipality fixed effects. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

▸ Other measures

Illegal mining increased more in loser municipalities

Dependent variable:	% mined area mined illegally		% total area illegally mined	
	All	Poverty 25-35%	All	Poverty 25-35%
After	1.88***	1.11	0.20***	0.16***
	(0.43)	(1.09)	(0.032)	(0.036)
After x % Budget Loss	0.066***	0.043	0.0068*	0.014**
	(0.024)	(0.052)	(0.0040)	(0.0062)
N. of obs.	8796	1753	10204	2049
Municipalities	927	187	940	188
Mean of Dep. Var.	93.7	91.6	0.49	0.27
R^2	0.78	0.75	0.74	0.81

All regressions include municipality fixed effects. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Consistent with convex function of budget valuation.

▸ Non-parametric ▸ Parallel Trends

No effect of the reform on declared production

Dependent variable: Declared production						
	Coal	Gas	Oil	Gold	Silver	Platinum
	(1)	(2)	(3)	(4)	(5)	(6)
After	0.64	-0.44	-0.036	4.52	-1.71	-1.08
	(1.92)	(0.37)	(0.16)	(10.4)	(5.15)	(1.33)
N. of obs.	733	714	772	1401	1191	401
Municipalities	105	80	84	228	196	63
Mean of Dep. Var.	4.26	2.22	1.88	15.4	6.12	1.34
R^2	0.33	0.34	0.59	0.33	0.27	0.77

Production by area for the minerals, normalized production for oil and gas. Normalized to the first year with non zero production of the municipality. All regressions include municipality fixed effects, linear time trend and control for the price of the raw material. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

▸ Raw Product

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Health effects

Mercury is used in gold mining extraction.

- Mercury is used in gold mining for amalgamation (binding gold particles together apart from silt).
- Besides drinking water, mercury is ingested by humans through fish consumption.
- Fetal brain is especially susceptible to damage from exposure to mercury (Davidson, 2004).

Estimate the effect of gold mining on newborns' health.

- Select predicted mining areas with gold potential.
- Income effect: size of mines near to the average inhabitant.
- Pollution effect: size of mines upstream for the average inhabitant ▸ Formulas

Use variation in the timing of mine opening to estimate health impacts

$$HighAPGAR_{imt} = \beta_N NearMine_{mt} + \beta_D DownstreamFromMine_{mt} + X_{imt}\alpha + \gamma_m + \gamma_t + \lambda_{r(m)} \times t + \varepsilon_{imt} \quad (4)$$

- $HighAPGAR_{imt}$ for birth i, municipality m, time t (good health)
- γ_m municipality fixed effects
- γ_t year and week of birth fixed effects
- $\lambda_m \times t$ regional trends
- X_i individual controls (mother's age, education, and marital status).
- ε_{imt} error term

β reduced form estimates of the effect of gold mining on health

Illegal gold mines have larger negative health effects

	Dependent variable: High APGAR				
	(1)	(2)	(3)	(4)	(5)
Near Mine	0.49	0.63*	0.72	0.63	
	(0.36)	(0.34)	(0.48)	(0.50)	
Downstream from mine	-0.30*	-0.71*	-0.56		
	(0.16)	(0.38)	(0.49)		
Downstream from legal mine only				0.17	-0.17
				(0.50)	(0.60)
Downstream from illegal mine only				-0.68	-0.64
				(0.52)	(0.48)
Downstream from both types of mines				-0.71	-0.58
				(0.55)	(0.53)
Near legal mine only					1.30
					(0.84)
Near illegal mine only					0.17
					(0.46)
Near both types of mines					-0.012
					(0.51)
Mines	Titles	All	Open pit	Open pit	Open pit
N. of observations (babies)	3632569	3632569	3129368	3129368	3129368
Mean of Dep. Var.	95.2	95.2	95.2	95.2	95.2
p-value (H_0:Legal=Illegal)				0.028	0.17

▸ Intensity ▸ Near ▸ Downstream

First stage: Instrument with the reform

Dependent variable: Downstream from illegal mining	(1)	(2)
After X Weak Institutions Municipality Upstream	0.14***	
	(0.051)	
After X Weak Institutions Municipality Downstream		-0.033
		(0.030)
N. of observations	2861263	593096
Municipalities	572	121
Mean of Dep. Var.	0.79	0.92
R^2	0.75	0.73
F-stat	7.57	1.21

All regressions include mother characteristics, municipality FE, week FE, year FE, and state trends. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

IV: downstream from illegal mining with the reform

Dependent variable: High APGAR		
	(1)	(2)
Downstream from illegal mine	-0.73*	-2.46*
	(0.39)	(1.44)
Method	OLS	IV Inst
N. of observations	2861263	2861263
Municipalities	572	572
Mean of Dep. Var.	95.2	95.2
R^2	0.012	0.012

All regressions include mother characteristics, municipality FE, week FE, year FE, and state trends. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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Discussion

- The mechanism in the model is a reduction in the bribe
  - Understandably, no data to test this.
- Alternative explanations
- Miners know that their taxes will be misused in other municipalities (Gadenne, 2016)
  - Only 25% of the mines have an owner from the same municipality.

For every dollar redistributed 7 cents lost to evasion

1. Estimate increase in area illegally mined
   - Coefficient of After as percentage of municipality area 0.13. Analyzed area $457,840 km^2 \rightarrow 595 km^2$
   - Coefficient of After X Loser 0.29. Analyzed area losers $136,170 km^2 \rightarrow 395 km^2$ in the losers.
   - This is a total of $990 km^2 = 99,000 ha$. (310,000 adjusted)
2. Estimate the lost title fees
   - Daily legal minimum wage ($10.5) per ha $\rightarrow 1M$
3. Estimate the lost royalties taxes
   - Half a kilo of gold per ha. (NatGeo)
   - Price of gold per kg $ 44,000 $\times$ royalties rate of gold $\rightarrow 111M$
   - % of illegally mined area that extracts gold: 40% $\rightarrow 44M$
4. Mining royalties: $660M$
5. Revenue lost: $0.07 = 45M/660M$

For every dollar redistributed, health costs of 4 cents

1. Estimate cost per affected baby: $1,590
   - Effect of low APGAR on IQ: -2.6 (Ehrenstein et al, 2009)
   - Effect of IQ point on wages: 0.53% (Psacharopoulos-Velez, 1992)
   - Minimum monthly wage in Colombia 2011: $ 240
   - Working years: 40
2. Estimate affected babies: 1,886
   - Differential APGAR effect: 0.7 percentage points.
   - 626,507 births in 2011.
   - 43% downstream from a mine
3. Gold royalties: 66M
4. Lower bound health cost: $0.04 = 3M/66M$

Conclusions

- Evasion responds to the tax revenue allocation in the case of illegal mining in Colombia.
  - For every dollar redistributed 7 cents are lost through evasion.
- No evidence of evasion through reported quantity of legal mines.
- Another unintended consequence of the reform is higher environmental and health impacts.

Thank you

- Gracias
- Asante Sana
- Merci
- Obrigado
- Grazie

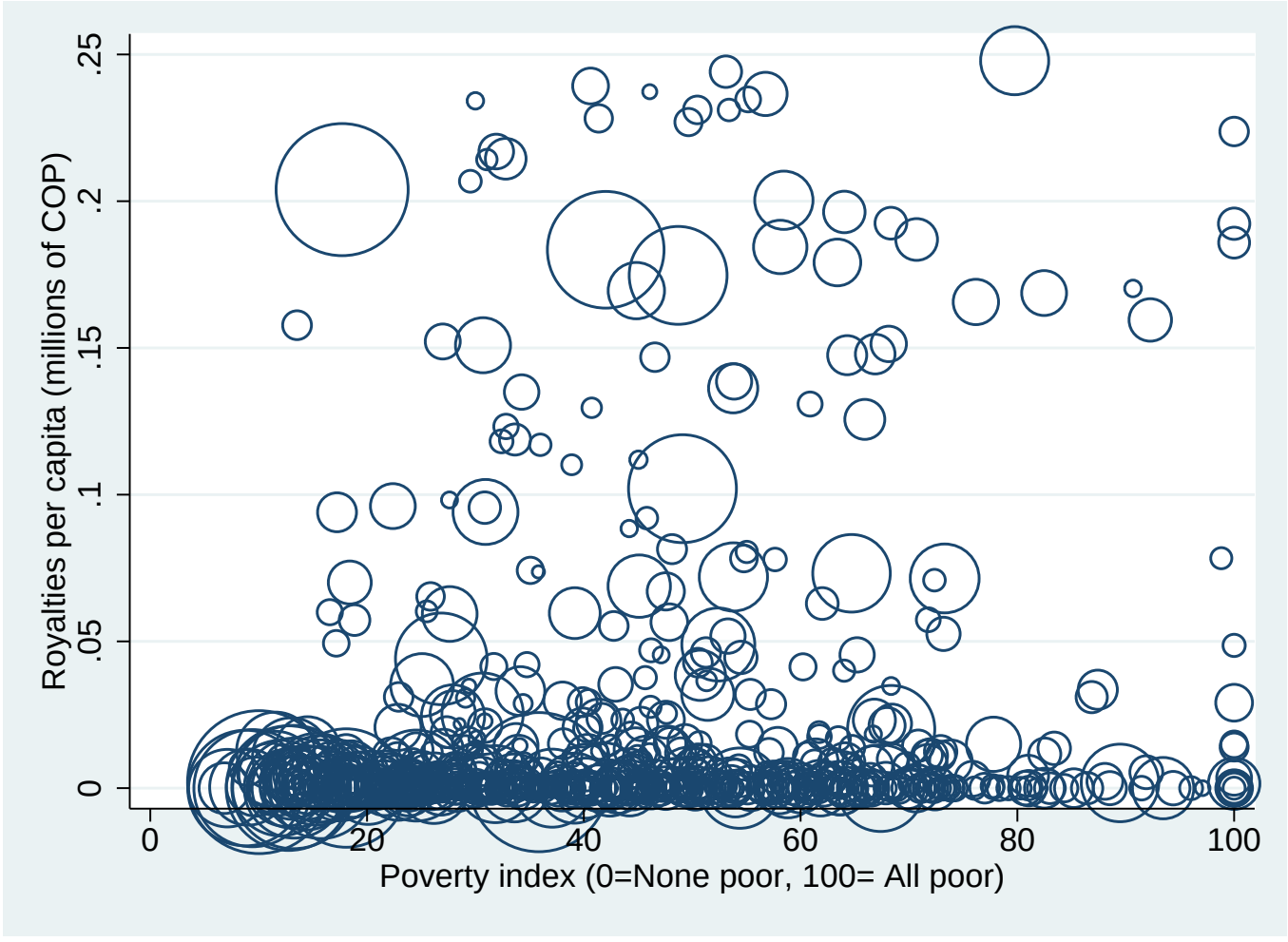
Legal titling slows down in Colombia after reform

Dependent variable:	Area mining titles (ha)		
	Only Colombia	With Peru	
	(1)	(2)	(3)
After x Colombia	-6.02***	-8.88***	-1.22***
	(0.46)	(0.48)	(0.31)
After x Peru		-13.8***	
		(0.38)	
Time FE-Trend	Trend	Trend	TimeFE
N. of obs.	8796	26355	30021
Municipalities	927	2733	2748
Mean of Dep. Var.	82.9	82.0	4.70
R^2	0.78	0.71	0.86

All regressions include municipality fixed effects. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

▸ Plot

Inequality in royalties distribution



Back

Further details of the reform

- Transition period of decreasing direct royalties share
- Guarantee to mining municipalities that royalties won't fall below 50% of 2007-2010 average
- The regional **development** fund resources are distributed among states according to:

$$w_i = \left(\frac{Population_i}{Population_{COL}}\right)^{0.6} \left(\frac{NBI_i}{NBI_{COL}}\right)^{0.4}$$

- The regional **compensation** fund resources are distributed among poor states ($NBI > 30$) according to:

$$w_i = \left(\frac{Population_i}{Population_{COL}}\right)^{0.4} \left(\frac{NBI_i}{NBI_{COL}}\right)^{0.5} \left(\frac{Unemployment_i}{Unemployment_{COL}}\right)^{0.1}$$

▸ Back

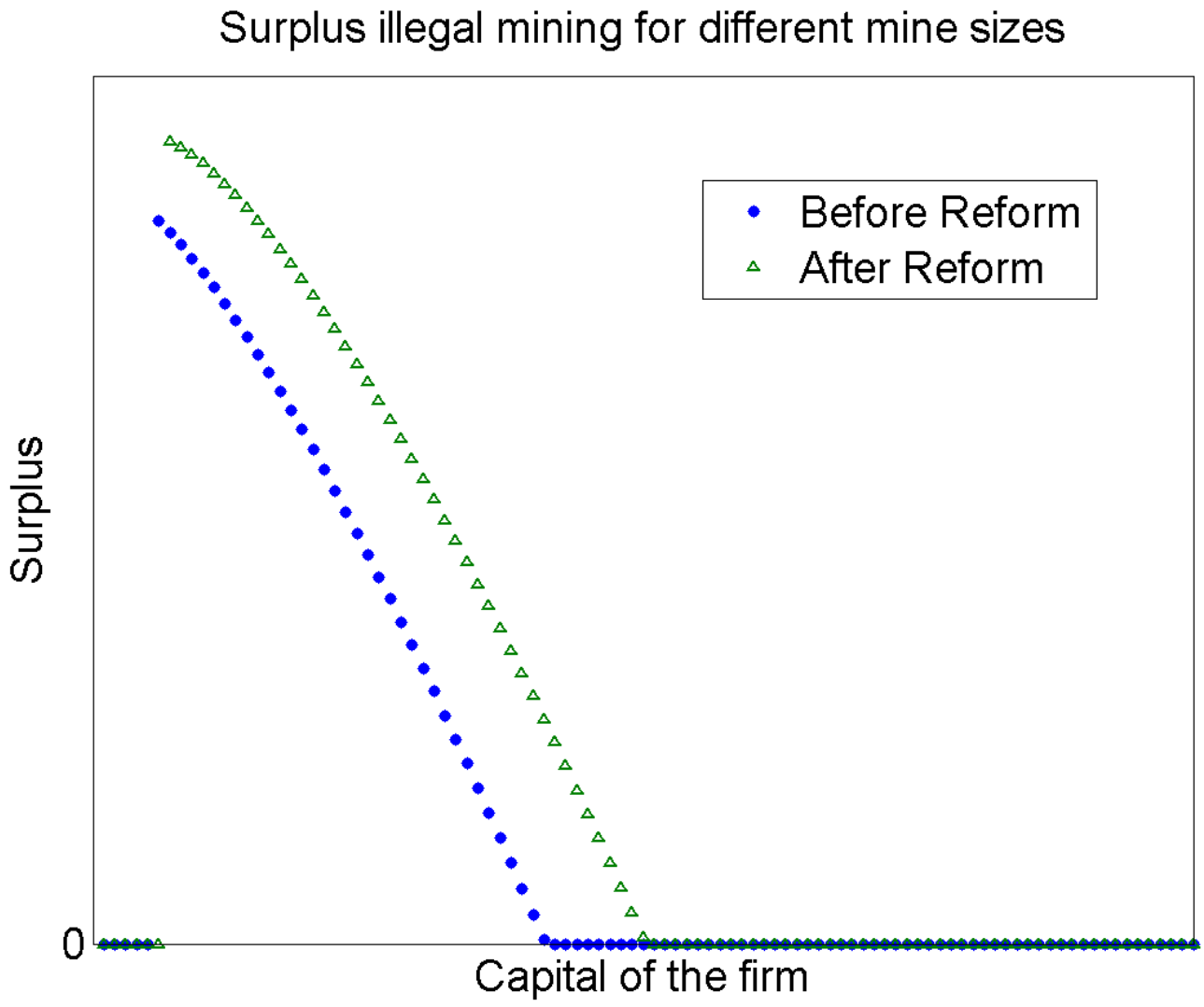
Example of a winner and a loser with the reform

- El Carmen de Atrato, Choco won with the reform
  - Royalties as % of budget before the reform: 10%
  - Poverty: 32%
  - Net budget change with the reform: 1.3 %

- Titiribí, Antioquia lost with the reform
  - Royalties as % of budget before the reform: 12%
  - Poverty: 28%
  - Net budget change with the reform: -4.7 %

Return

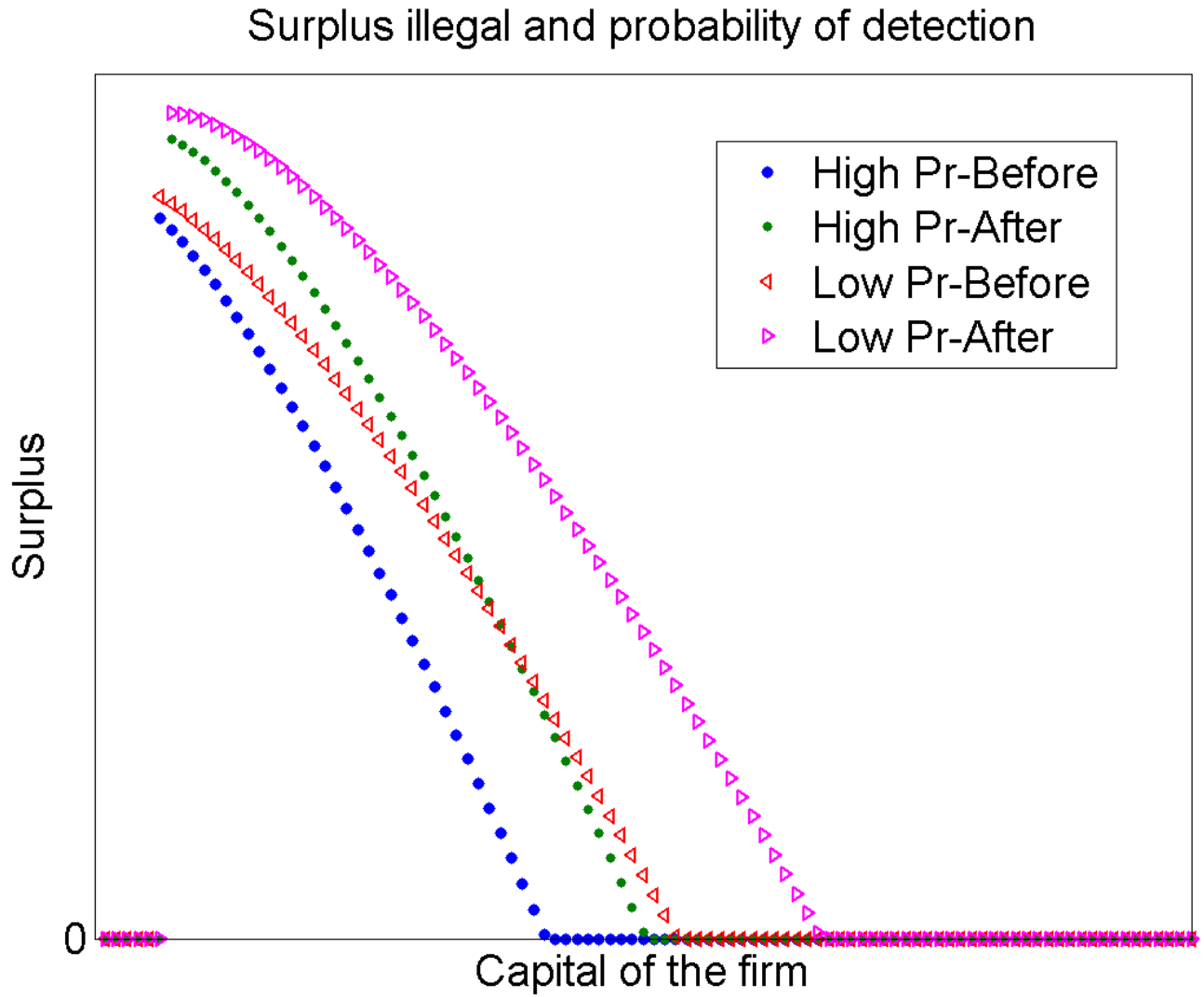
Prediction 1: Illegal mining increases after the reform



Param

Back

Prediction 2: Larger effect if smaller probability of detection



Back

The bribe is determined by bargaining

Consider the profits if the firm is legal/illegal

$$\Pi_L = pq(K)(1-\alpha) - C(q(K)) - T$$

$$\Pi_I = pq(K) - C(q(K)) - Pr(K)p_K K - b$$

Consider also the local government payouts in each case:

$$G_L = f(pq\alpha\beta + R) - \gamma q$$

$$G_I = f(R) - \gamma q - Pr(K)V + b$$

- p: international price of the mineral
- q: quantity extracted
- K is the capital (machinery) that is destroyed if caught
- p_K is the price of capital
- α: royalties rate of the mineral
- $C(q)$: cost function
- T the annualized cost of the mining title
- α_m: share of royalties for the mining municipality
- $Pr(\beta, K)$: probability of illegal mining being detected
- b: the bribe
- R: other government revenue
- γ: local (pollution) costs of mining
- V is the penalty associated with illegal mining

Return

Parameters used in the simulation

- $p = 0.75$
- $p_K = 1$
- $q(K) = 200 * (K/2)^{0.5}$
- $K \sim U(1, 100)$
- $\alpha = 5\%$
- $C(q) = 0.6q$
- $T = 10$
- $\beta = 0.55, 0.1$
- $Pr(K) = K/600, K/300$
- $B = 140$
- $V = 0$

Return

Differential effect of the reform depends on the shape of the shadow value of public funds

$$\Delta S = [f(B + B_1) - f(B + B_1 + R\beta_1)) - (f(B) - f(B + R\beta_0)]$$

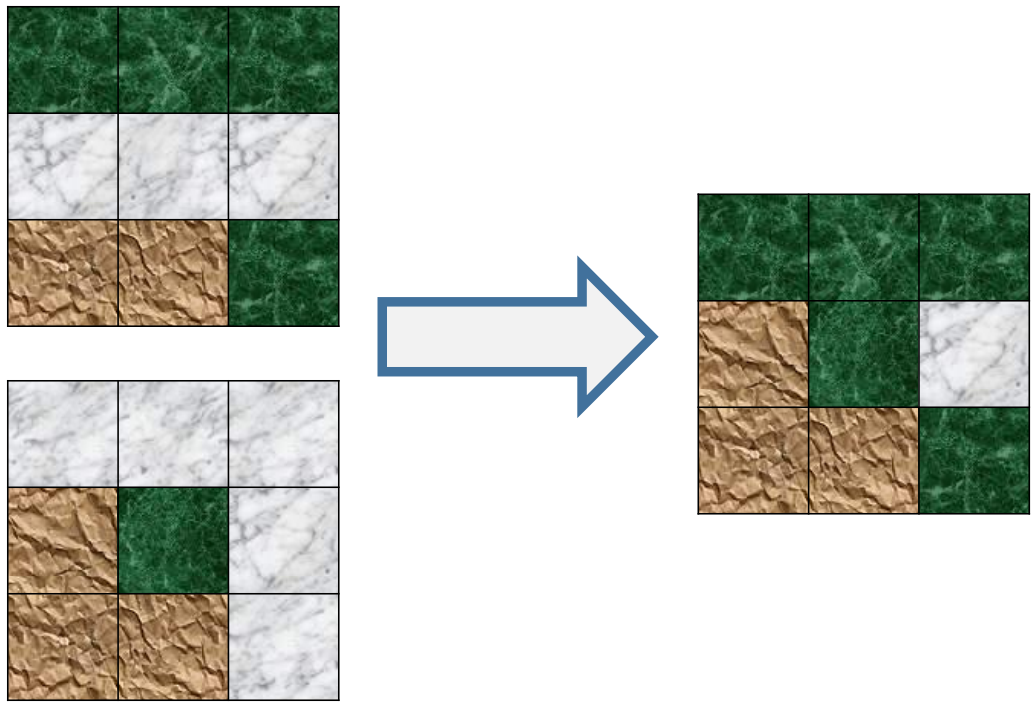
$$f(B) = \delta(B)B + g((1 - \delta(B))B)$$

f is convex if

- Capture increasing share of budget $\delta(B)$ (Brollo et al, 2013)
- g is convex (e.g. lumpy investments)
  - The median municipality spent 86 % of the royalties in lumpy investments like construction of a hospital or a bridge.

Return

We remove clouds



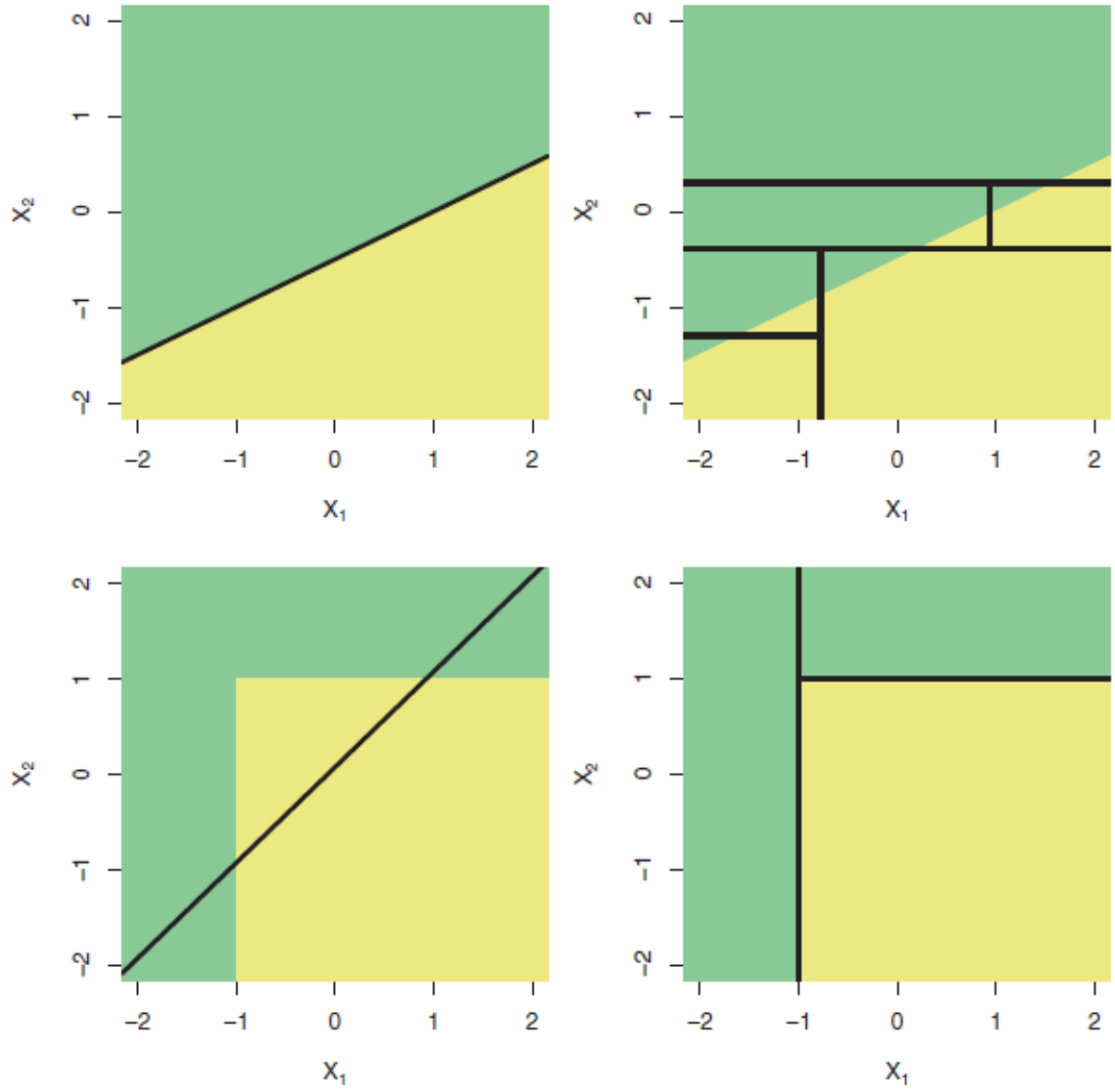
Balance between census and not censused municipalities

	All	Censused	Not Censused	Difference
% Loss	-4.03	-5.14	-3.10	2.04***
	(11.6)	(10.3)	(12.5)	(0.76)
Royalties from precious metals	0.32	0.34	0.31	-0.032
	(0.47)	(0.47)	(0.46)	(0.031)
Royalties from oil-gas	0.14	0.11	0.16	0.051**
	(0.35)	(0.31)	(0.37)	(0.023)
Armed group presence before reform	0.40	0.39	0.40	0.0074
	(0.49)	(0.49)	(0.49)	(0.032)
Population	25280.0	23160.5	27072.4	3911.9
	(40628.4)	(41049.0)	(40223.3)	(2685.3)
Area (km2) of municipality in raster	638.1	633.1	642.4	9.30
	(1330.7)	(1348.7)	(1316.7)	(88.1)

An observation is a municipality. There are 927 , of which 475 were censused.

▸ Return

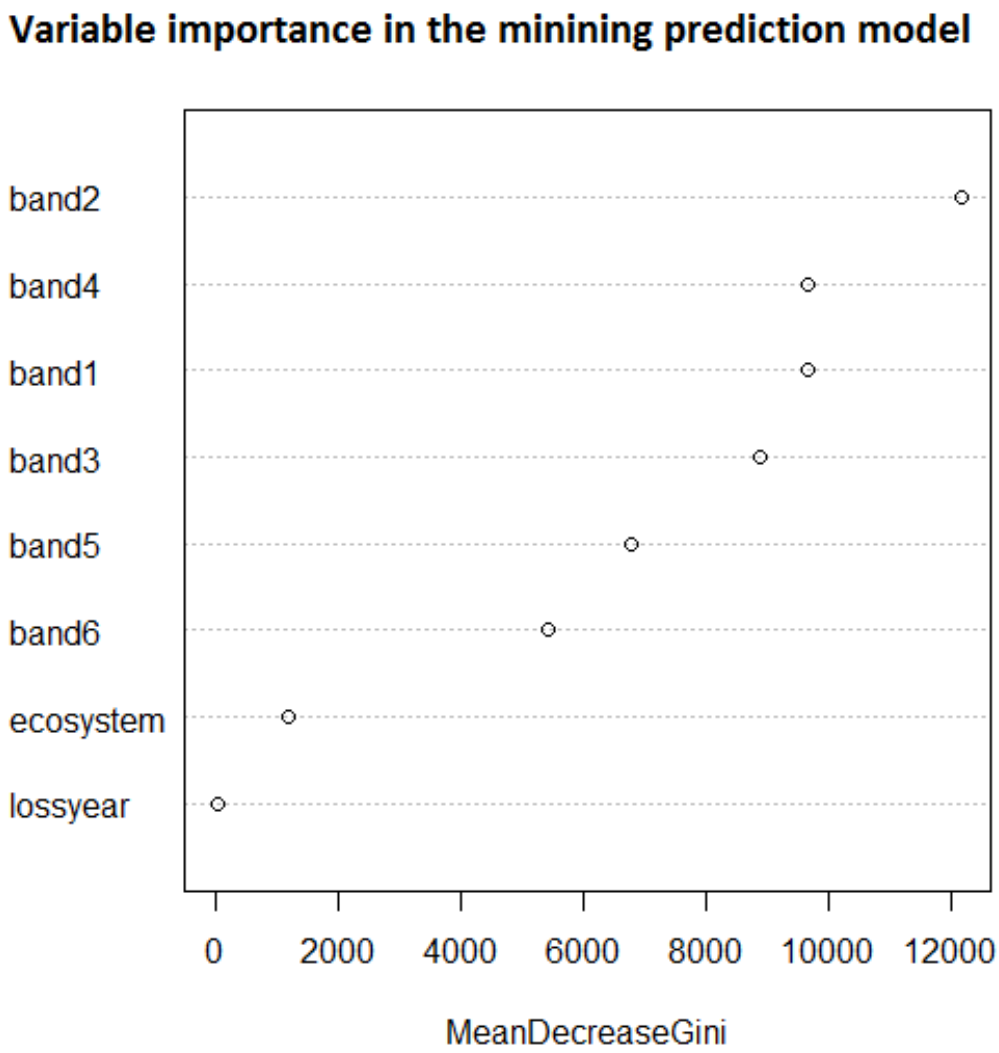
Regression trees capture better non-linear relations



Source: James et al(2014)

▸ Return

The most important variable is the green band



Back

The error of the predictions

$$\widehat{y_{mt}} = \sum_{i \in Mines} (Pred(pix_i) = 1) + \sum_{i \notin Mines} (Pred(pix_i) = 1)$$

- In each mine pixel the probability of predicting a mine is TPR and in a NO mine FPR.
- Each pixel is a Bernoulli, the sum is binomial and we can approximate with a normal.

$\widehat{y_{mt}} = y_{mt} TPR + y_{Nmt} FPR + \epsilon_{mt}$, where

$$\epsilon_{mt} \sim N(0, y_{mt} TPR(1 - TPR) + y_{Nmt} FPR(1 - FPR))$$

$y_{Nmt} = Y_m - y_{mt}$

The error of the predictions

Thus,

$$\widehat{y_{mt}} = (TPR - FPR)\, y_{mt} + FPR * Y_m + \epsilon_{mt}$$

Or equivalently:

$$\frac{\widehat{y_{mt}}}{Y_m} = \frac{y_{mt}}{Y_m}(TPR - FPR) + FPR + \upsilon_{mt}$$

Where $\upsilon_{mt} \sim N\left(0, \frac{y_{mt} TPR(1-TPR) + y_{Nmt} FPR(1-FPR)}{Y_m^2}\right)$ Therefore we choose a threshold such that:

$$\rho^* = \arg\min_{\rho} \left(TPR(\rho)\frac{y_{2010}}{Y_{2010}} + FPR(\rho)\left(1 - \frac{y_{2010}}{Y_{2010}}\right) - \frac{y_{2010}}{Y_{2010}} \right)^2$$

Back

TPR and FPR balanced between legal and illegal

	All	Illegal	Legal	Difference
TPR Winner	46.9	54.8	40	-14.8
	(25.4)	(24.5)	(25.5)	(11.8)
TPR Loser	43.2	61.4	30.8	-30.6
	(36.5)	(30.3)	(37.8)	(23.8)
FPR Winner	0.66	0.83	0.060	-0.76
	(1.36)	(1.49)	(0.58)	(0.61)
FPR Loser	3.33	3.22	3.90	0.69
	(4.16)	(1.24)	(10.7)	(4.27)

Back

The precision of the model is 79%

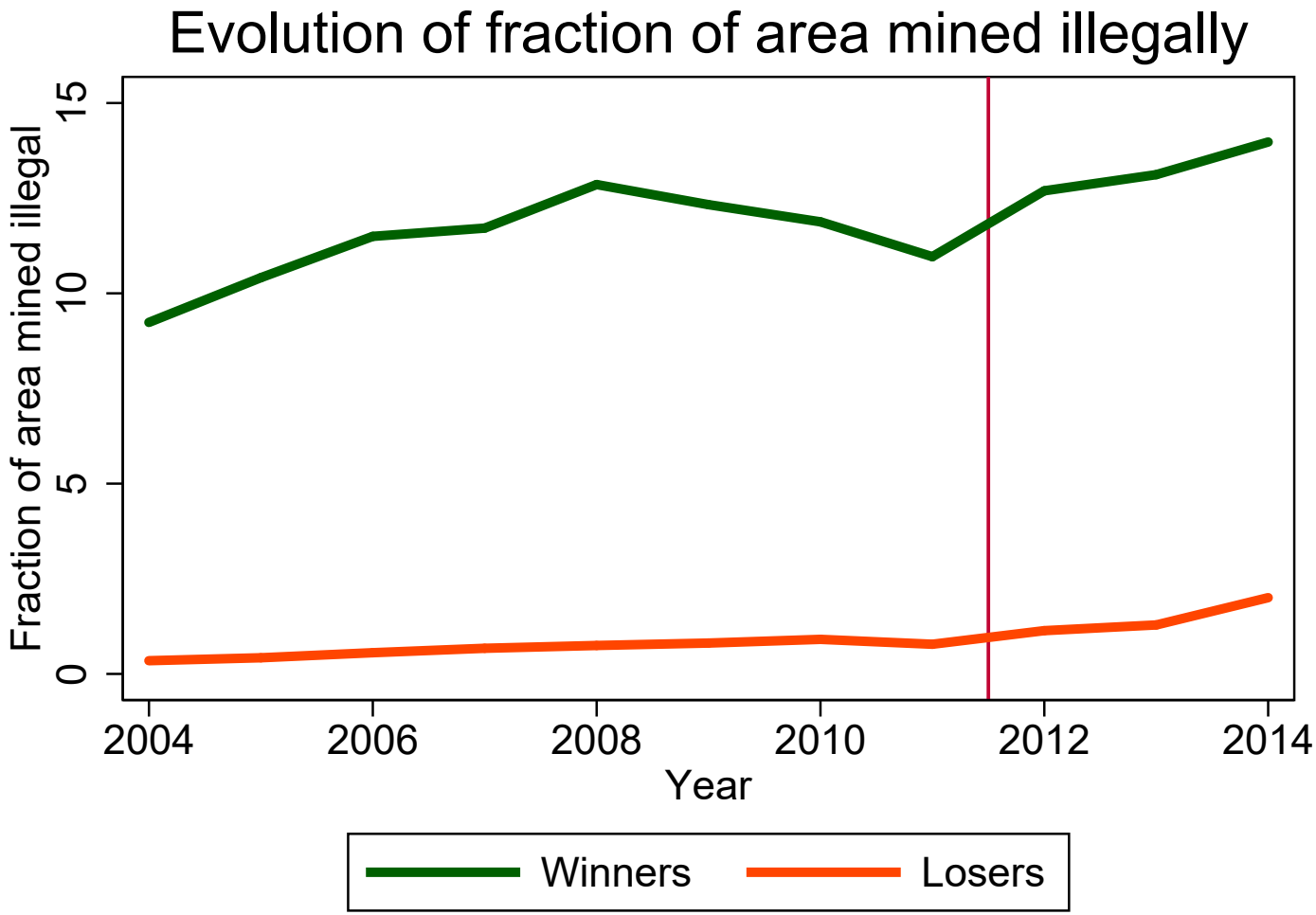
Confusion Matrix

	True NO Mine	True Mine
Predicted NO Mine	131747	2972
Predicted Mine	382	1428

- Of the pixels we predict as mines 78.89 % are truly mines.
- We detect 32.46 % of the true mine pixels.
- We wrongly classify 0.29 % of the true NO mine pixels.
- We are working on improving these measures.

Back

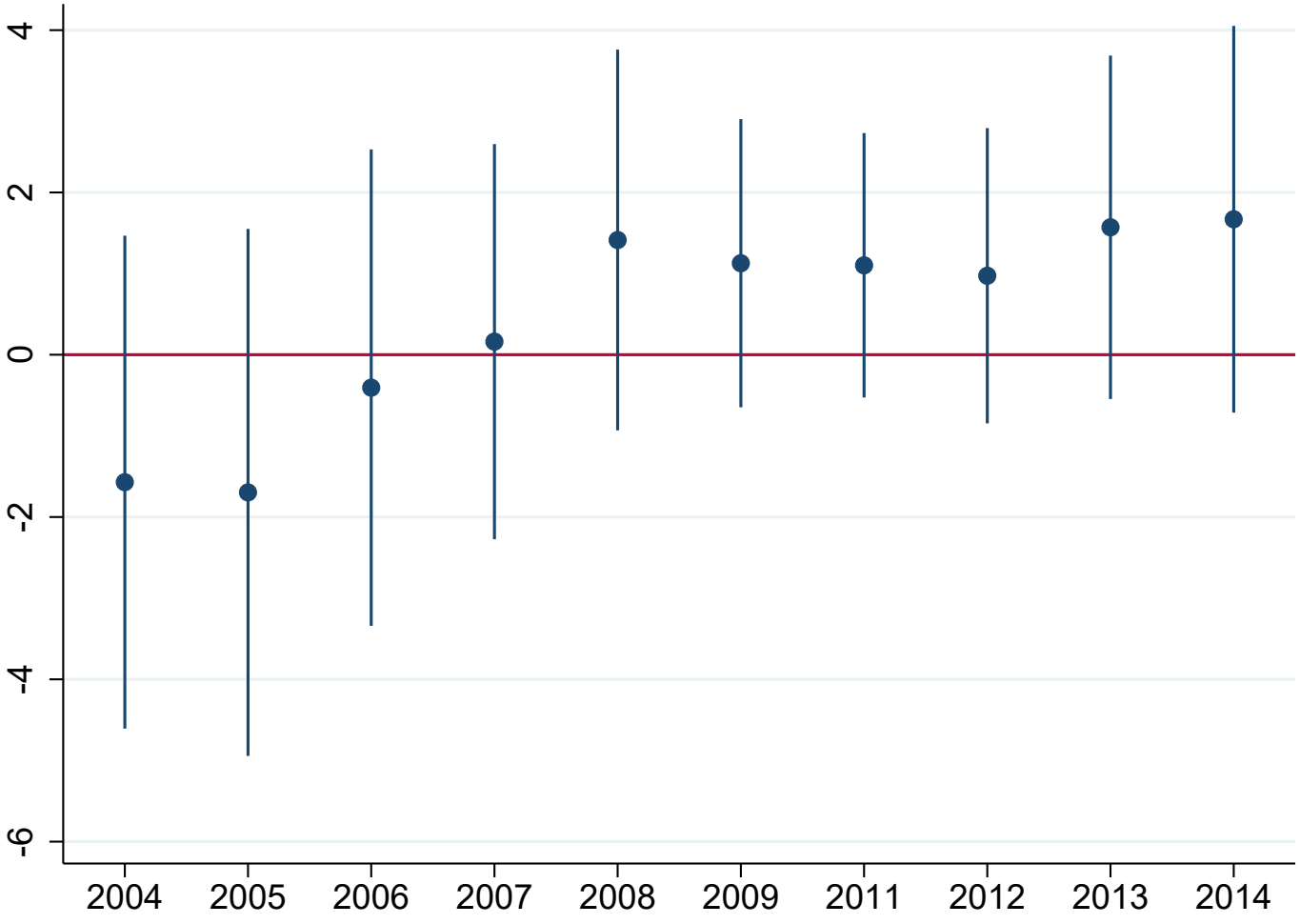
Illegal mining increased more in municipalities that lost with the reform



▸ Back

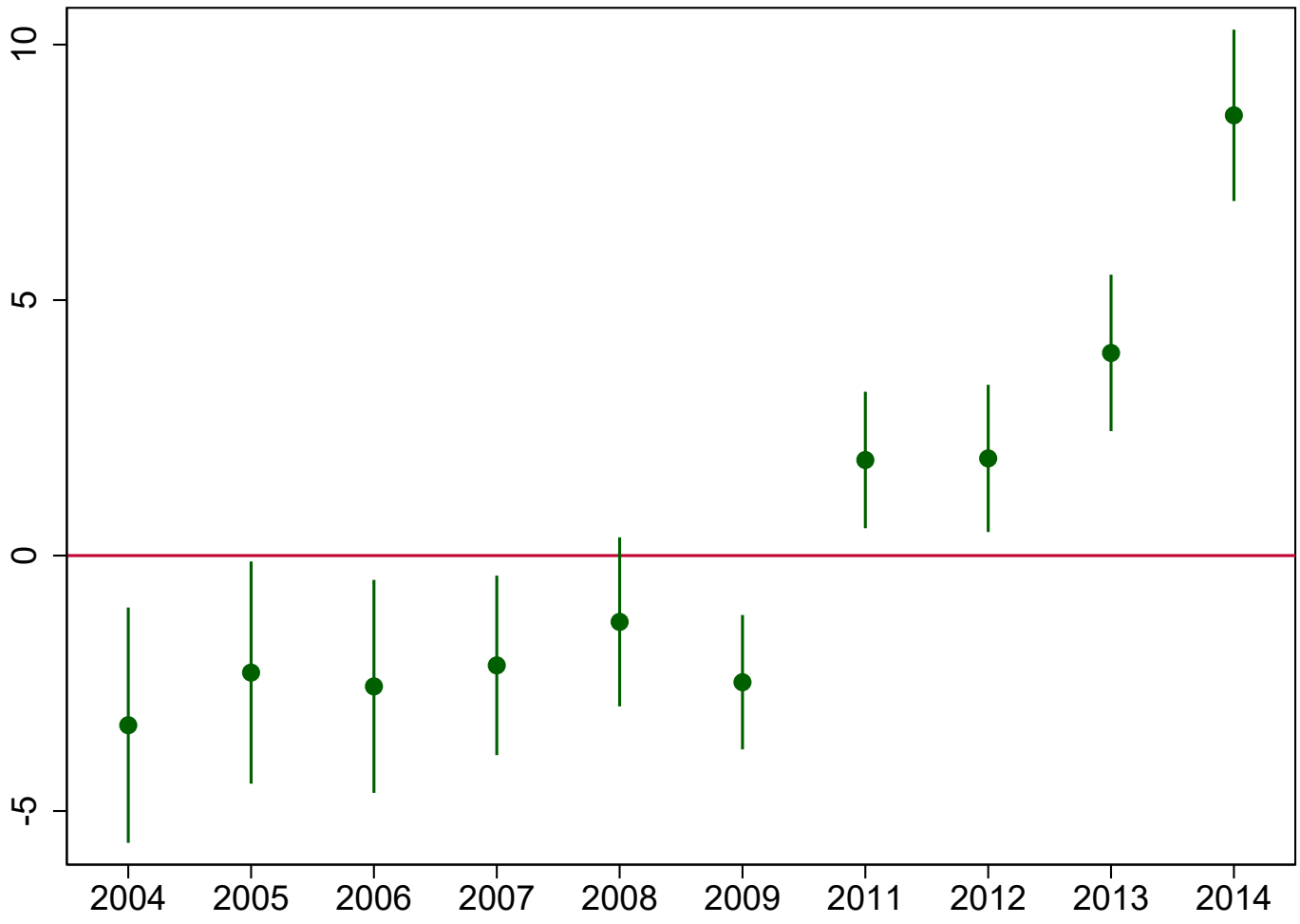
▸ Constant sample

Parallel trends winner-losers



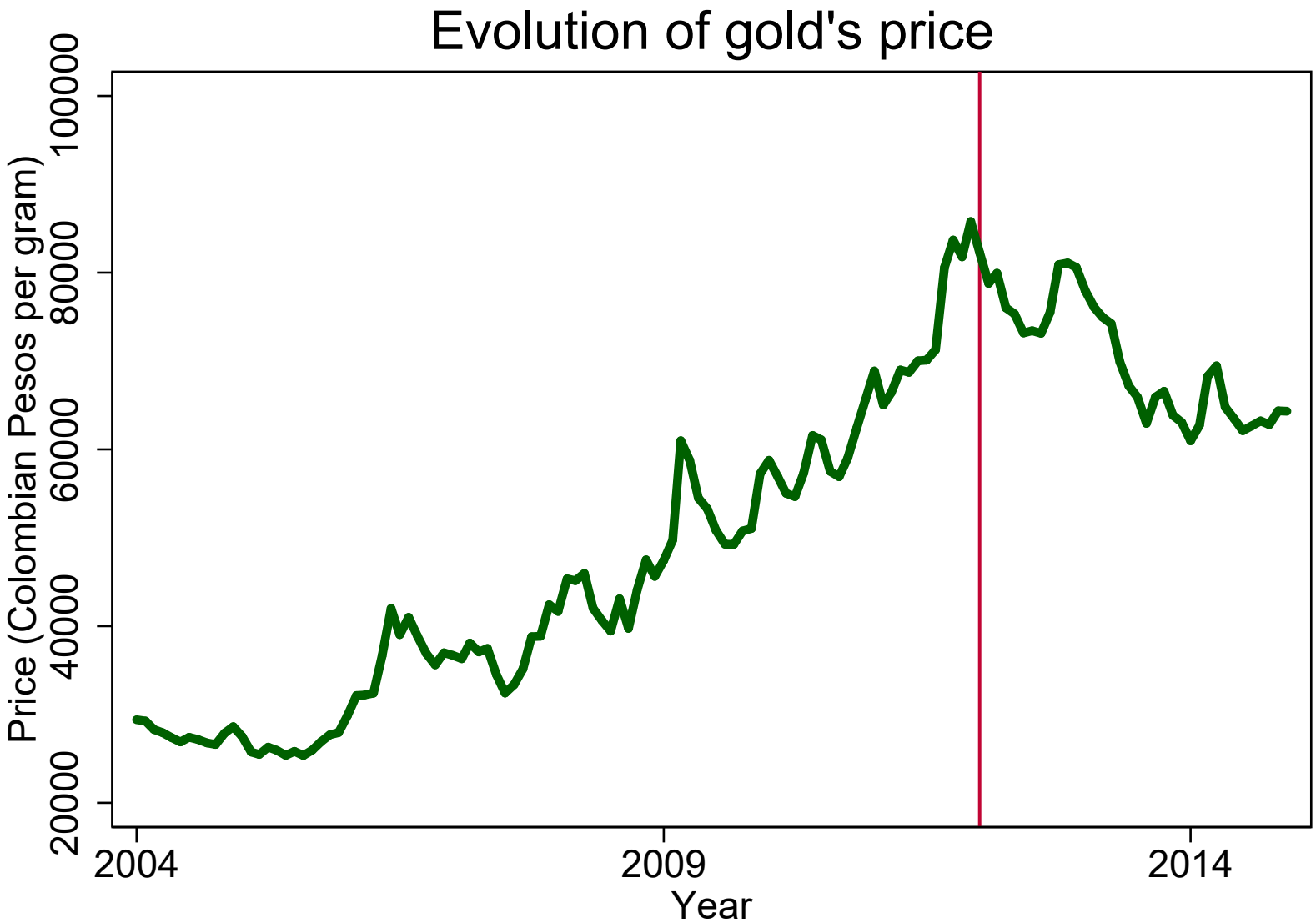
Back

Parallel trends Colombia-Peru



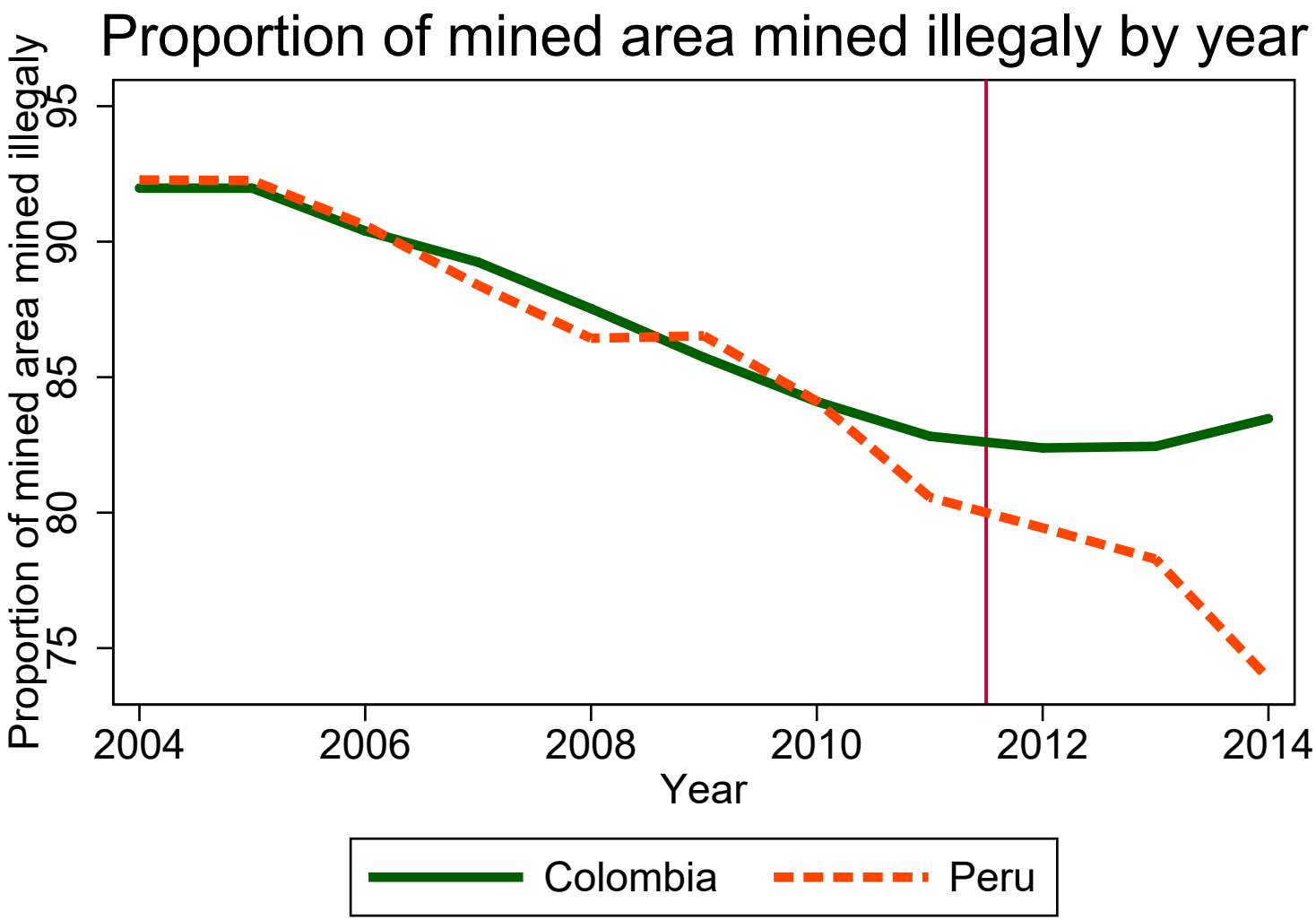
Back

The price of gold was increasing before the reform



Back

Fraction mined area mined illegally by year



Back

Summary statistics

	Mean	Median	Std. Dev.	Min	
Population	25280.0	13226	40628.4	984	39
Area (km2) of municipality in raster	638.1	264.5	1330.7	15.4	17
Mining municipality	0.43	0	0.50	0	
Royalties from precious metals	0.32	0	0.47	0	
Royalties from oil-gas	0.14	0	0.35	0	
Change in royalties as percentage of budget	4.03	7.51	11.6	-62.5	4
Armed group presence before reform	0.40	0	0.49	0	
% illegal mines Census	0.47	0.50	0.40	0	
% open pit mines (Census)	0.78	1	0.35	0	

An observation is a municipality. There are 927 in Colombia, of which 148 are negatively affected.

▸ Return

Summary statistics

	All	Winners	Losers	Difference
% of mined area illegal before	87.7	87.7	87.4	-0.26
	(22.3)	(22.2)	(24.5)	(0.70)
% of mined area illegal after	79.2	78.9	83.2	4.32***
	(26.5)	(26.6)	(24.5)	(1.30)
Change in royalties as percentage of budget	4.10	8.17	-16.8	-25.0***
	(11.6)	(4.07)	(15.0)	(0.19)
Armed group presence before reform	0.40	0.39	0.44	0.047
	(0.49)	(0.49)	(0.50)	(0.044)
% of mined area illegal before AG	89.1	88.8	90.2	1.40
	(22.8)	(23.1)	(21.4)	(1.15)
% of mined area illegal after AG	83.3	82.9	85.2	2.23
	(24.3)	(24.6)	(23.0)	(1.92)

.

An observation is a municipality. There are 927 , of which 148 are negatively affected.

. Return

The winners and losers are balanced on illegal mining measures

	All	Winners	Losers	Difference
Change in royalties as percentage of budget	4.03	8.11	-16.8	-24.9***
	(11.6)	(3.80)	(15.1)	(0.62)
Royalties from precious metals	0.32	0.31	0.37	0.059
	(0.47)	(0.46)	(0.48)	(0.042)
Royalties from oil-gas	0.14	0.060	0.56	0.50***
	(0.35)	(0.23)	(0.50)	(0.026)
% open pit mines (Census)	0.78	0.77	0.80	0.021
	(0.35)	(0.35)	(0.35)	(0.040)
Armed group presence before reform	0.40	0.39	0.44	0.047
	(0.49)	(0.49)	(0.50)	(0.044)
Population	25280.0	22539.8	39252.9	16713.1***
	(40628.4)	(35257.3)	(59297.3)	(3575.7)
Area (km2) of municipality in raster	631.7	597.5	1198.2	600.7***
	(1535.4)	(1495.9)	(2007.6)	(128.2)

An observation is a municipality. There are 927 , of which 148 are negatively affected.

▸ Return

Summary statistics

	Peru	Colombia	Difference
Pctg of mined area illegal before	87.7	90.0	2.32***
	(21.5)	(22.1)	(0.34)
Pctg of mined area illegal after	77.2	85.5	8.25***
	(27.1)	(23.3)	(0.62)
Difference	-10.43***	- 4.49***	5.93***
	(0.39)	(0.52)	(0.58)

An observation is a municipality. There are 2738 municipalities, 932 in Colombia. There are 1,123 total municipalities in Colombia but we exclude those without minerals in the subsoil.

Back

Summary statistics

	All	Winners	Losers	Difference
Pct. of area illegal Colombia before	0.35	0.29	0.66	0.37***
	(1.24)	(0.95)	(2.15)	(0.039)
Pct. of area illegal Colombia after	0.88	0.77	1.47	0.71***
	(2.47)	(2.24)	(3.37)	(0.13)
Pct. of area illegal Peru before	16.4	16.4	.	-16.4***
	(23.8)	(23.8)	(.)	(0.20)
Pct. of area illegal Peru after	18.9	18.9	.	-18.9***
	(24.4)	(24.4)	(.)	(0.34)

An observation is a municipality.

Back

Reform effects present in non-parametric estimation

Dependent variable:	% of area illegal		% mined illegal	
	(1)	(2)	(3)	(4)
After	1.88***	1.62**	0.20***	0.19**
	(0.43)	(0.71)	(0.032)	(0.074)
After x % Budget Loss	0.066***		0.0068*	
	(0.024)		(0.0040)	
After X Bottom half winner		-0.41		-0.14
		(1.11)		(0.11)
After X Bottom half loser		-0.98		0.12
		(1.71)		(0.18)
After X Top half loser		3.04***		0.36*
		(0.96)		(0.20)
N. of obs.	8796	8796	10204	10204
Municipalities	927	927	940	940
Mean of Dep. Var.	93.7	93.7	0.49	0.49
R^2	0.78	0.78	0.74	0.74

All regressions include municipality fixed effects and control for the price index. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Results are robust to alternative mining prediction cutoff

Dependent variable:	% of mined area mined illegally		
	Only Colombia	With Peru	
	(1)	(2)	(3)
After x Colombia	3.02***	2.76***	7.54***
	(0.31)	(0.29)	(0.44)
After x Peru		-0.95***	
		(0.29)	
Time FE-Trend	Trend	Trend	TimeFE
N. of obs.	10188	28885	28952
Municipalities	940	2748	2748
Mean of Dep. Var.	75.9	82.4	82.4
R^2	0.79	0.77	0.77

This alternative optimal cutoff is the closest point to 100% TPR and 0% FPR. In this case, 80% TPR and 20% FPR. All regressions include municipality fixed effects. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Results are robust to using pixels mined probabilities

Dependent variable:	% of mined area mined illegally	
Mined:	Dummy	Probability
	(1)	(2)
After x Colombia	1.48***	1.18**
	(0.53)	(0.49)
N. of obs.	8796	9952
Municipalities	927	940
Mean of Dep. Var.	86.2	84.1
R^2	0.79	0.76

All regressions include municipality fixed effects and linear trend. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Legalization

Dependent variable:	% of area illegal that legalizes		
	Only Colombia	With Peru	
	(1)	(2)	(3)
After x Colombia	-0.17	0.072	-0.33
	(0.68)	(0.60)	(0.56)
After x Peru		-0.51	
		(0.43)	
Time FE-Trend	Trend	Trend	TimeFE
N. of obs.	4153	9962	9996
Municipalities	767	1485	1488
Mean of Dep. Var.	2.94	2.69	2.69
R^2	0.33	0.28	0.28

All regressions include municipality fixed effects. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

We discard the results are driven by unobservables

- We perform tests a la Altonji et al (2005) using Oster(2013) procedure
- We left the more stringent parameters of $R_{max} = 1$ and $\delta = 1$
- The identified set for the coefficient of After X Colombia is (0.11 ,3.32) percentage points
- The identified set for the coefficient of After X % Budget Loss is (0.05 ,0.07) percentage points

Back

Results are robust to optimally selecting controls Post-Lasso Belloni and Chernozhukov(2013)

Dependent variable:	% of area illegal			% of mined illegal		
	(1)	(2)	(3)	(4)	(5)	(6)
After	0.17***	0.054*	0.16***	1.88***	1.13**	1.74***
	(0.031)	(0.030)	(0.023)	(0.49)	(0.53)	(0.49)
After x Pctg Budget Loss	0.0058	0.0046	0.0051	0.044*	0.033	0.036
	(0.0038)	(0.0037)	(0.0037)	(0.023)	(0.022)	(0.022)
Controls	Main	All	DLasso	Main	All	DLasso
N. of obs.	9342	9225	9225	8211	8103	8103
Municipalities	944	944	944	932	932	932
Mean of Dep. Var.	0.56	0.55	0.55	88.2	88.2	88.2
R^2	0.79	0.78	0.78	0.81	0.81	0.81

All includes the price index, population, armed groups homicides and all these variables squared, lagged, interacted among them, interacted with linear trend, and interacted with quadratic trend. Lasso includes the variables from All selected from a Lasso procedure, in this case the model only selects Lagged price. All regressions include municipality fixed effects. Standard errors, clustered by municipalities, in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Results are robust to optimally selecting controls Post-Lasso Belloni and Chernozhukov(2013)

Dependent variable:	% of area illegal			% of mined illegal		
	(1)	(2)	(3)	(4)	(5)	(6)
After	0.17***	0.054*	0.16***	1.88***	1.13**	1.74***
	(0.031)	(0.030)	(0.023)	(0.49)	(0.53)	(0.49)
After x Pctg Budget Loss	0.0058	0.0046	0.0051	0.044*	0.033	0.036
	(0.0038)	(0.0037)	(0.0037)	(0.023)	(0.022)	(0.022)
Controls	Main	All	DLasso	Main	All	DLasso
N. of obs.	9342	9225	9225	8211	8103	8103
Municipalities	944	944	944	932	932	932
Mean of Dep. Var.	0.56	0.55	0.55	88.2	88.2	88.2
R^2	0.79	0.78	0.78	0.81	0.81	0.81

All includes the price index, population, armed groups homicides and all these variables squared, lagged, interacted among them, interacted with linear trend, and interacted with quadratic trend. Lasso includes the variables from All selected from a Lasso procedure, in this case the model selects population, Lagged price and Lagged population. All regressions include municipality fixed effects. Standard errors, clustered by municipalities, in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

The results are robust when using the adjusted predictions

Dependent variable:	% area illegal adjusted		% mined illegal adjusted	
	(1)	(2)	(3)	(4)
After x Colombia	3.20***	3.31***	6.59***	
	(0.54)	(0.58)	(0.70)	
After x Peru		-2.37***		
		(0.40)		
N. of obs.	2801	17759	17759	
Municipalities	495	2183	2183	
Mean of Dep. Var.	92.2	92.2	83.7	
R^2	0.94	0.77	0.79	

Adjusted refers to using the formula taking into account the FPR and TPR of the prediction model. All regressions include municipality fixed effects and control for the price index. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Results are robust to weights by fraction of analyzed area

Dependent variable:	% mined area mined illegally			
	(1)	(2)	(3)	
After x Colombia	1.48***	1.51***	1.48***	1.52***
	(0.53)	(0.49)	(0.51)	(0.48)
After x Peru			-1.35***	-1.62***
			(0.39)	(0.34)
Weights		Yes	No	Yes
N. of obs.	8796	704106	26355	1673601
Municipalities	927	927	2733	2732
Mean of Dep. Var.	86.2	86.0	85.2	85.1
R^2	0.79	0.80	0.73	0.78

Weights by fraction of municipality area analyzed. All regressions include municipality fixed effects and linear trend. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Robustness of results to state trends

Dependent variable:	% of area illegal		% of mined illegal	
	(1)	(2)	(3)	(4)
After	0.13***	0.090***	1.33**	1.29**
	(0.027)	(0.032)	(0.52)	(0.56)
After x Loser		0.25**		0.27
		(0.12)		(1.08)
State Year FE	No	Yes	No	Yes
State Trend	Yes	No	Yes	No
N. of obs.	10204	10204	8796	8796
Municipalities	940	940	927	927
Mean of Dep. Var.	0.49	0.49	86.2	86.2
R^2	0.78	0.78	0.79	0.79

All regressions include municipality fixed effects and control for the price index. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Robustness of results to other measures

Dependent variable:	% municipality area		Area illegal	Log (Area+1)
	(1)	(2)	(3)	(4)
After x Colombia	0.17***	1.26***	0.068***	
	(0.029)	(0.33)	(0.0099)	
N. of obs.	10204	10204	10204	
Municipalities	940	940	940	
Mean of Dep. Var.	0.49	2.90	0.49	
R^2	0.74	0.56	0.89	

All regressions include municipality fixed effects and linear trend. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Results are robust when using only newly mined area

Dependent variable:	% of new mined area mined illegally		
	(1)	(2)	(3)
After x Colombia	2.29***	2.00***	5.35***
	(0.61)	(0.59)	(0.75)
After x Peru		-0.86	
		(0.64)	
Time FE-Trend	Trend	Trend	TimeFE
N. of obs.	5156	11568	11608
Municipalities	816	1549	1552
Mean of Dep. Var.	92.2	88.6	88.6
R^2	0.67	0.72	0.72

All regressions include municipality fixed effects and linear trend. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

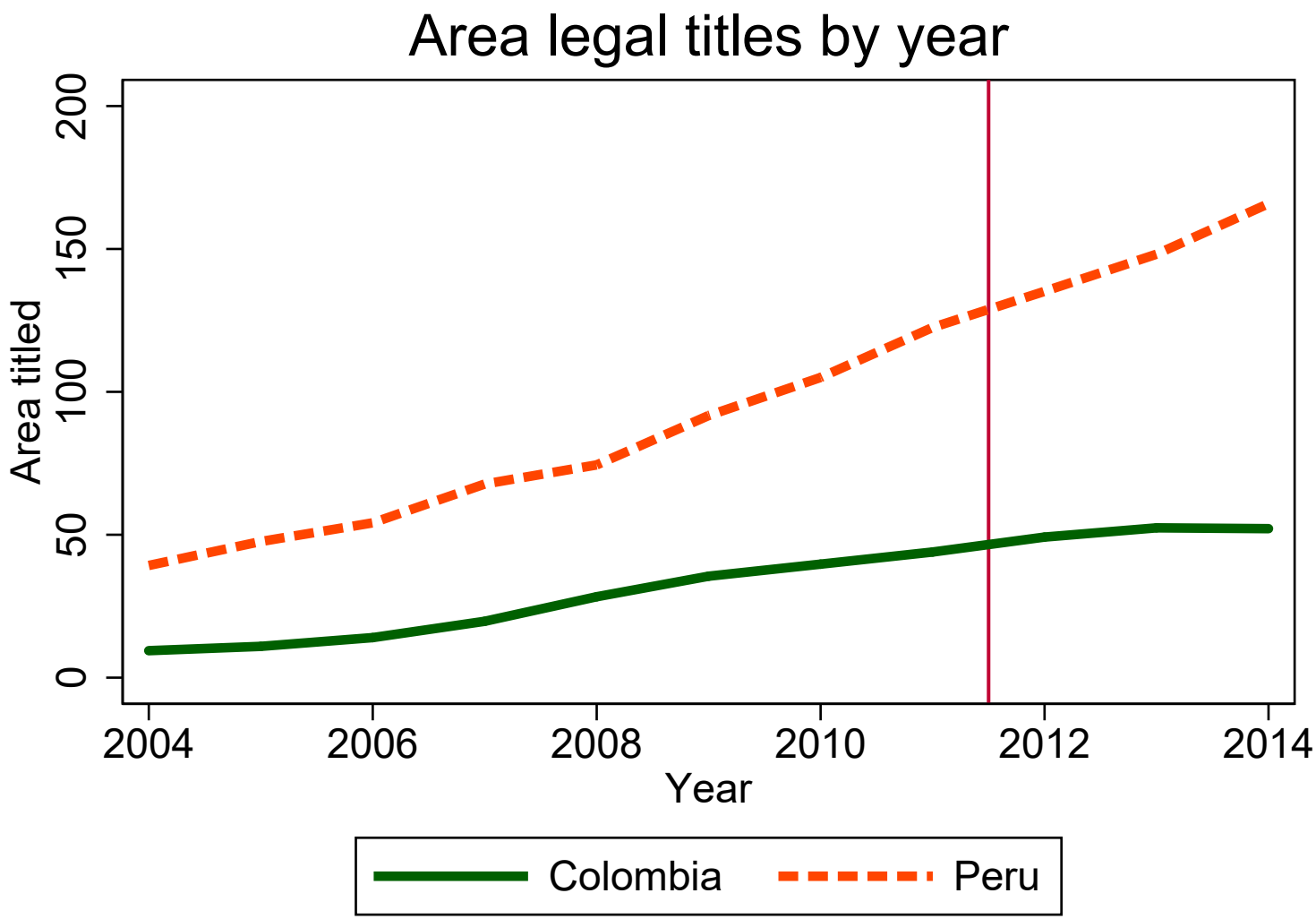
Restricting to municipalities close to the border

Dependent variable:	% of mined area mined illegally		
	All	$< 1,000km$	$< 500km$
	(1)	(2)	(3)
After x Colombia	1.48***	1.29**	0.80
	(0.51)	(0.54)	(0.85)
After x Peru	-1.35***	-1.86***	-1.00
	(0.39)	(0.68)	(1.67)
N. of obs.	26355	15609	2511
Municipalities	2733	1718	279
Mean of Dep. Var.	85.2	86.1	90.0
R^2	0.73	0.73	0.72

All regressions include municipality fixed effects and country linear trends. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Area legal titles by year



Back

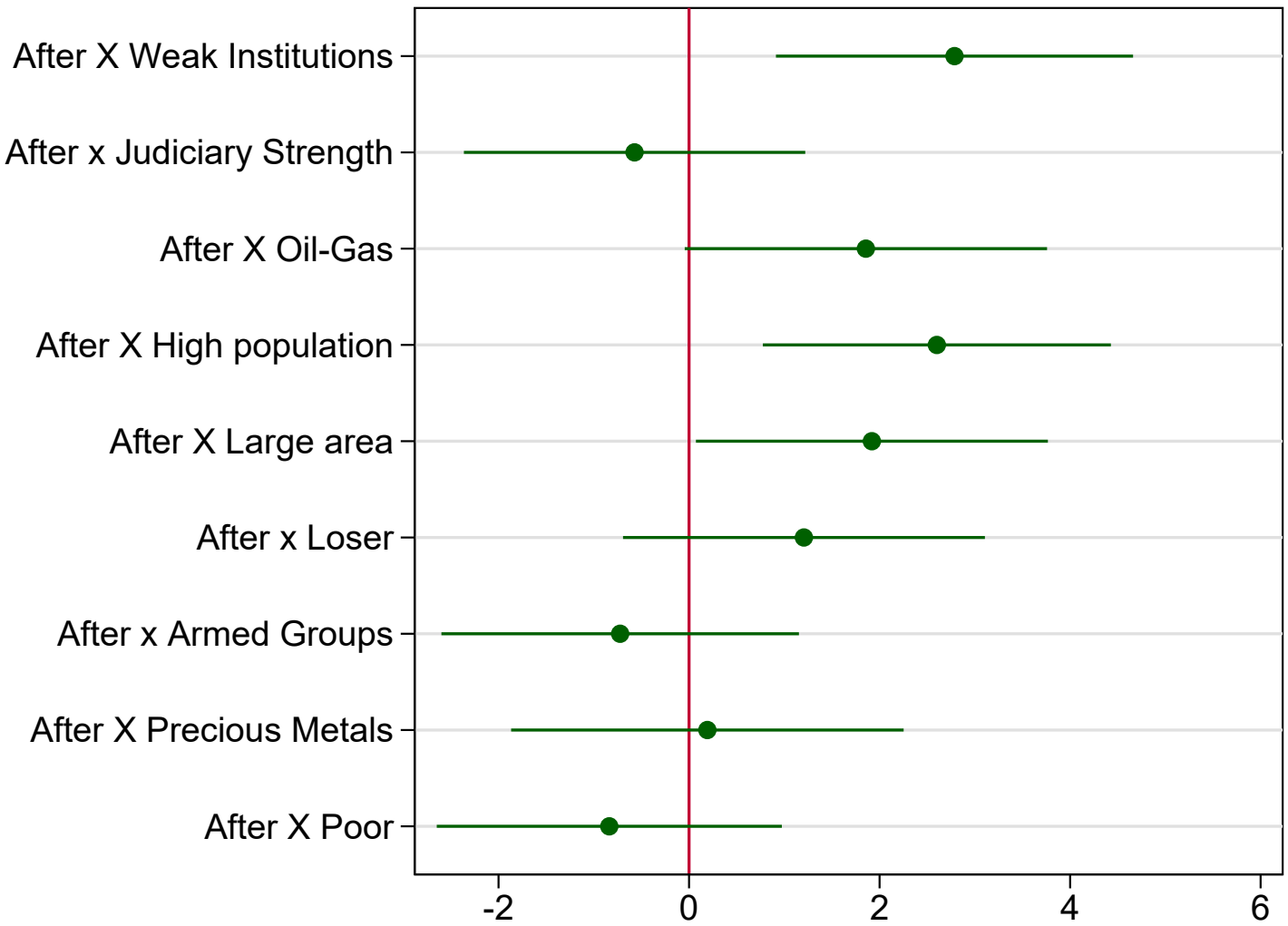
Summary statistics by institutional presence of the national government

	All	Strong	Weak	Difference
% of mined area illegal before	87.6	87.2	89.0	1.81**
	(24.0)	(24.7)	(21.7)	(0.73)
Poverty index 2011 measure	42.3	41.3	45.4	4.16***
	(19.1)	(17.5)	(23.2)	(0.45)
% Loss	-4	-4.13	-3.54	0.59**
	(11.6)	(11.6)	(11.8)	(0.28)
Royalties from precious metals	0.31	0.26	0.47	0.21***
	(0.46)	(0.44)	(0.50)	(0.011)
Royalties from oil-gas	0.14	0.12	0.21	0.089***
	(0.35)	(0.33)	(0.41)	(0.0083)
Armed group presence before reform	0.39	0.34	0.54	0.20***
	(0.49)	(0.47)	(0.50)	(0.011)
Population	24605.5	14831.4	56270.2	41438.7***
	(39124.8)	(19531.8)	(62793.5)	(830.0)
Area (km2) of municipality in raster	645.5	519.1	1055.1	535.9***
	(1348.1)	(1194.9)	(1691.5)	(31.6)

An observation is a municipality. There are 927 , of which 475 were censused.

Back

Heterogeneous effects



▸ Reg1 ▸ Reg2 ▸ Summary Statistics ▸ Back

Larger increase in municipalities with weak presence of the government

Dependent variable:	% mined area mined illegally					
	Only Colombia					
	(1)	(2)	(3)	(4)	(5)	
After x Colombia	1.63***	0.87	1.96***	1.36***	0.23	0.39
	(0.45)	(0.56)	(0.63)	(0.51)	(0.72)	(0.77)
After X Weak Institutions		2.83***				
		(1.00)				
After x Judiciary Strength			-0.62			
			(0.96)			
After X Oil-Gas				1.71*		
				(1.02)		
After X High population					2.75***	
					(0.98)	
After X Large area						2.14**
						(1.00)
N. of obs.	8796	8455	8796	8796	8796	8796
Municipalities	927	890	927	927	927	927
Mean of Dep. Var.	93.7	93.6	93.7	93.7	93.7	93.7
R^2	0.78	0.79	0.78	0.78	0.78	0.78

All regressions include municipality fixed effects. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Larger increase in municipalities with weak presence of the government

Dependent variable:	% mined area mined illegally				
	Only Colombia				
	(1)	(2)	(3)	(4)	(5)
After x Colombia	1.63***	1.40***	1.94***	1.68***	2.16***
	(0.45)	(0.52)	(0.60)	(0.54)	(0.71)
After x Loser		1.32			
		(1.00)			
After x Armed Groups			-0.76		
			(1.00)		
After X Precious Metals				-0.16	
				(1.11)	
After X Poor					-1.06
					(0.97)
N. of obs.	8796	8796	8796	8796	8796
Municipalities	927	927	927	927	927
Mean of Dep. Var.	93.7	93.7	93.7	93.7	93.7
R^2	0.78	0.78	0.78	0.78	0.78

All regressions include municipality fixed effects. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Summary statistics

	Mean	Median	Std. Dev.	Min	Max	
Dummy High APGAR	95.5	96.6	5.06	0	100	67
Near mine measure	0.76	1	0.43	0	1	67
Near illegal mine measure	0.57	1	0.50	0	1	67
Near legal mine measure	0.35	0	0.48	0	1	67
Near mine	6393680.1	944530.8	14382387.3	0	97992872	67
Near illegal mine	196755.2	480.8	980996.8	0	9050777.1	67
Near legal mine	56865.4	0	253084.7	0	2756257.0	67

An observation is a baby.

Return

Summary statistics

	Mean	Median	Std. Dev.	Min	Max	
Dummy High APGAR	95.5	96.6	5.06	0	100	67
Downstream from mine measure	0.87	1	0.33	0	1	67
Downstream from illegal mine measure	0.68	1	0.47	0	1	67
Downstream from legal mine measure	0.46	0	0.50	0	1	67
Downstream from mine	24.9	4.11	55.7	0	307.5	67
Downstream from illegal mine	0.80	0.0063	3.55	0	27.0	67
Downstream from legal mine	0.068	0	0.32	0	3.53	67

An observation is a baby.

Return

Illegal mines cause larger negative health effects

Dependent variable: High APGAR	(1)	(2)
Near open pit mine	0.72	0.77
	(0.60)	(0.58)
Downstream from open pit mine q1	-0.42	
	(0.59)	
Downstream from open pit mine q2	-0.55	
	(0.57)	
Downstream from open pit mine q3	-0.39	
	(0.56)	
Downstream from open pit mine q4	-0.20	
	(0.64)	
Downstream from legal open pit mine q1		-0.10
		(0.14)
Downstream from illegal open pit mine q1		-0.82
		(0.56)
Downstream from legal open pit mine q2		-0.17
		(0.17)
Downstream from illegal open pit mine q2		-0.97*
		(0.53)
Downstream from legal open pit mine q3		-0.065
		(0.26)
Downstream from illegal open pit mine q3		-0.64
		(0.50)
Downstream from legal open pit mine q4		0.12
		(0.41)
Downstream from illegal open pit mine q4		-0.63
		(0.54)
N. of observations (babies)	2585545	2585545
Municipalities	614	614
Mean of Dep. Var.	95.5	95.5
R^2	0.017	0.017

All regressions include mother characteristics, municipality FE, week FE, year FE, and state trends. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

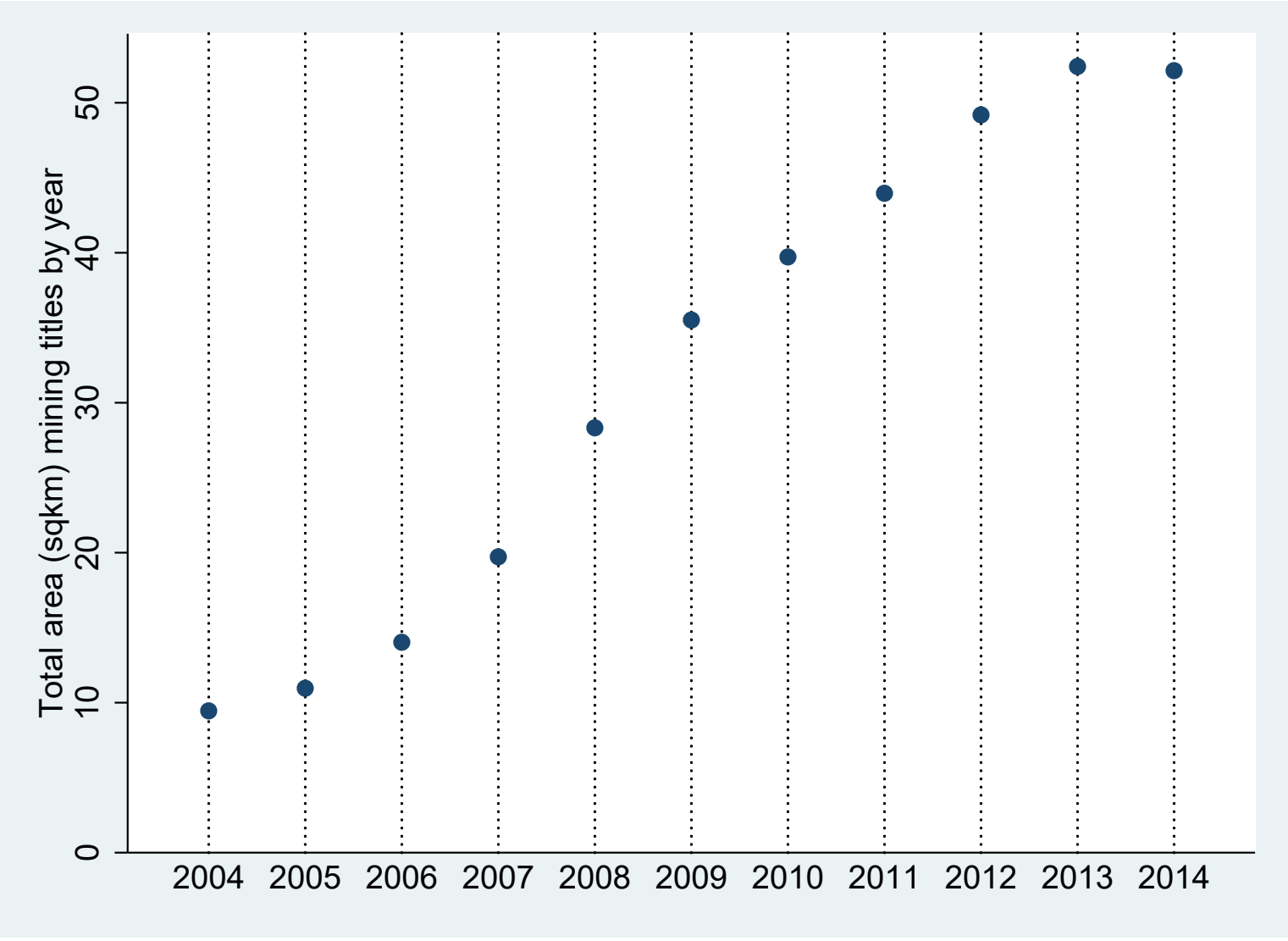
Results robust in sub-sample around poverty cutoff

Dependent variable:	% area illegal		% mined illegal	
	All	Poverty 25-35%	All	Poverty 25-35%
	(1)	(2)	(3)	(4)
After	1.88***	1.11	0.20***	0.16***
	(0.43)	(1.09)	(0.032)	(0.036)
After x % Budget Loss	0.066***	0.043	0.0068*	0.014**
	(0.024)	(0.052)	(0.0040)	(0.0062)
N. of obs.	8796	1753	10204	2049
Municipalities	927	187	940	188
Mean of Dep. Var.	93.7	91.6	0.49	0.27
R^2	0.78	0.75	0.74	0.81

Poverty 25-35%, refers to municipalities with poverty index in this range, centered around the sharp cutoff of 30% for the post reform transfer. All regressions include municipality fixed effects, linear time trend and control for the price index. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Area of mining titles by year



Back

Results are robust to fixing legal titles in 2014

Dependent variable:	% of mined area mined illegally	
Legal titles:	Year	2014
	(1)	(2)
After x Colombia	1.48***	0.57
	(0.53)	(0.56)
N. of obs.	8796	8796
Municipalities	927	927
Mean of Dep. Var.	86.2	86.0
R^2	0.79	0.78

Legal titles Year refers to using the registered titles of the respective year to define illegal mining. 2014 refers to fixing the titles that will be eventually given out. All regressions include municipality fixed effects and country linear trends. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

There is no evidence of an effect of the reform on declared production

Dependent variable: Raw production						
	Coal	Gas	Oil	Gold	Silver	Platinum
	(1)	(2)	(3)	(4)	(5)	(6)
After	-146876.3	4354.0	-1133781.9	42954.8	-12666.4	8640.4
	(159808.5)	(4762.1)	(1086202.1)	(40716.3)	(13571.2)	(5274.6)
After x Loser	1328840.3	-5643.2	2187222.1	-10817.2	36267.4	6259.1
	(883863.6)	(6495.7)	(1841075.9)	(75076.5)	(57592.4)	(9301.2)
N. of obs.	995	714	772	2927	2466	811
Municipalities	114	80	84	268	226	74
Mean of Dep. Var.	270030.2	17174.3	3141213.1	156410.7	54302.5	15053.6
R^2	0.45	0.91	0.64	0.56	0.70	0.78

All regressions include municipality fixed effects, linear time trend and control for the price of the raw material. Standard errors, clustered by municipalities, are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Back

Estimate the exposure to mining in each municipality

- Romero-Saavedra (2016) studies the effect of gold mining on newborns' health.
- Near mine measure:

$$Near\_Exposure_{mti} = \frac{\sum_{p \in m} Pop_p \times Area\_Exposure_{pti}}{\sum_{p \in m} Pop_p}$$

- Identify the closest river to each mine.
- For each river segment r create a "pollution" index equal to the size of the mines type i upstream in time t.

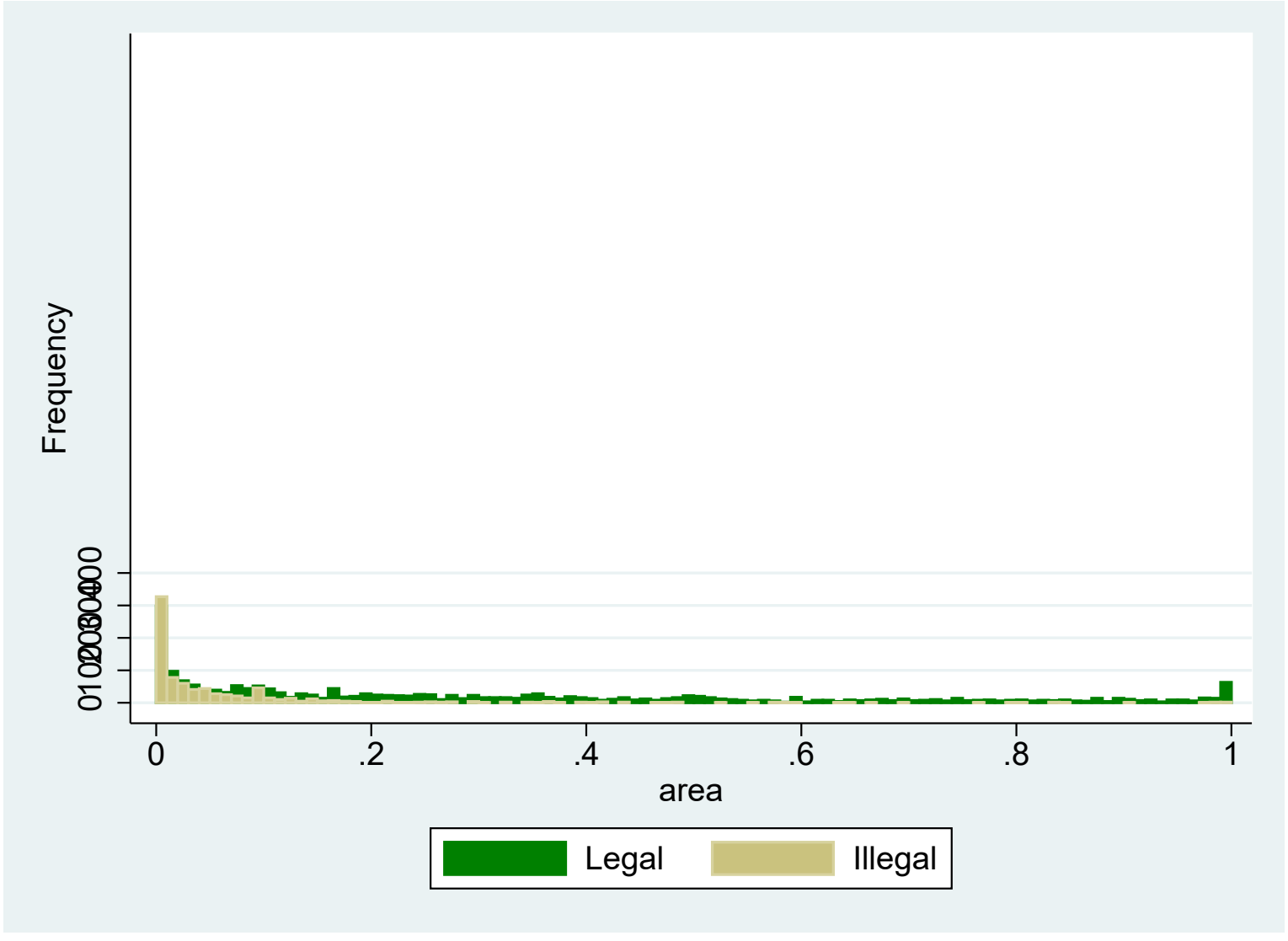
$$River\_Exposure_{rti} = \sum_{j \in U_r} 1_{D(r,j)<25} Area_{tij},$$

- Combine with population density to find an average (weighted) exposure to river pollution.

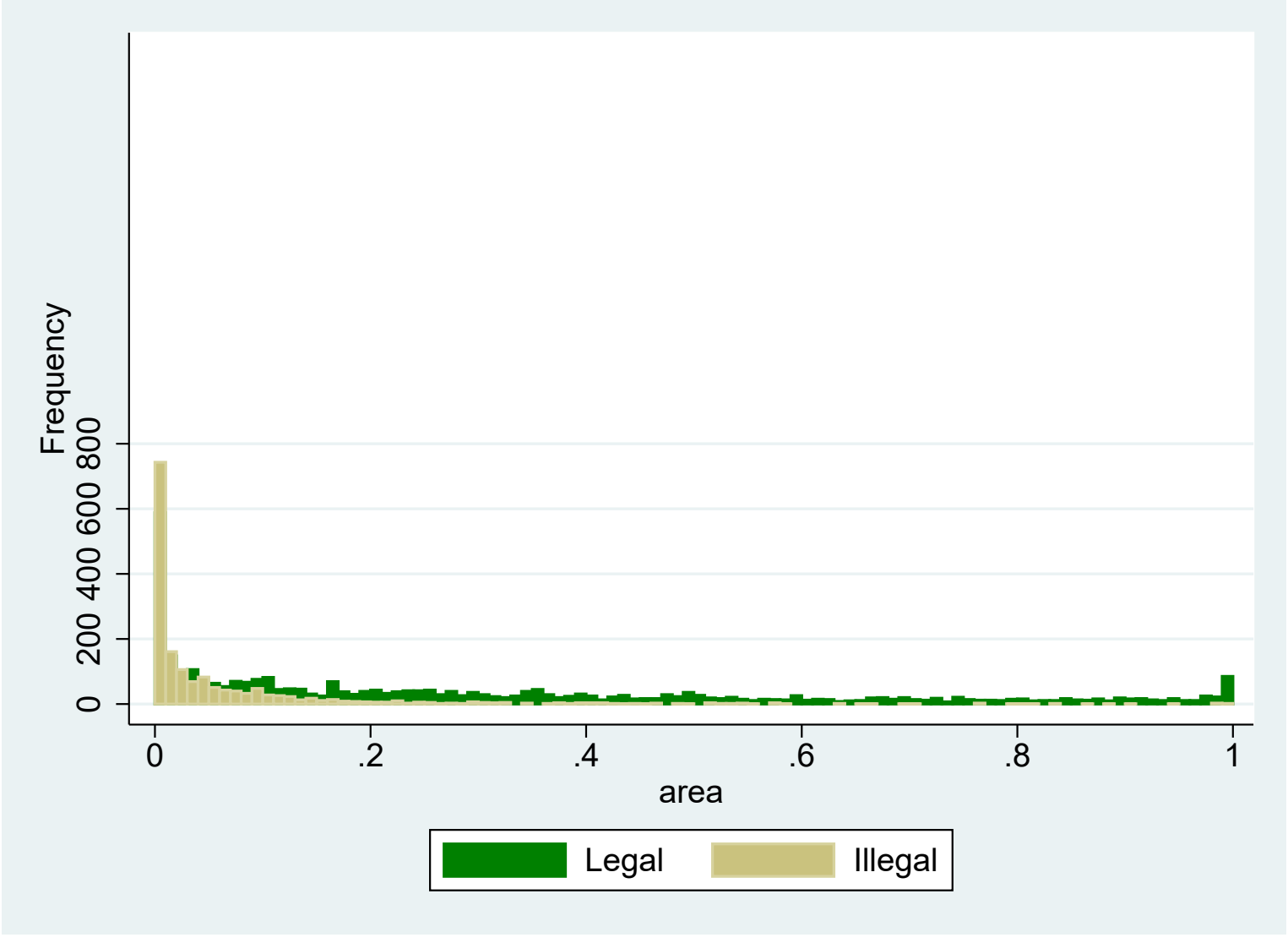
$$Downstream\_from\_Mine_{mti} = \frac{\sum_{p \in m} Pop_p \times River\_Exposure_{pti}}{\sum_{p \in m} Pop_p}$$

Back

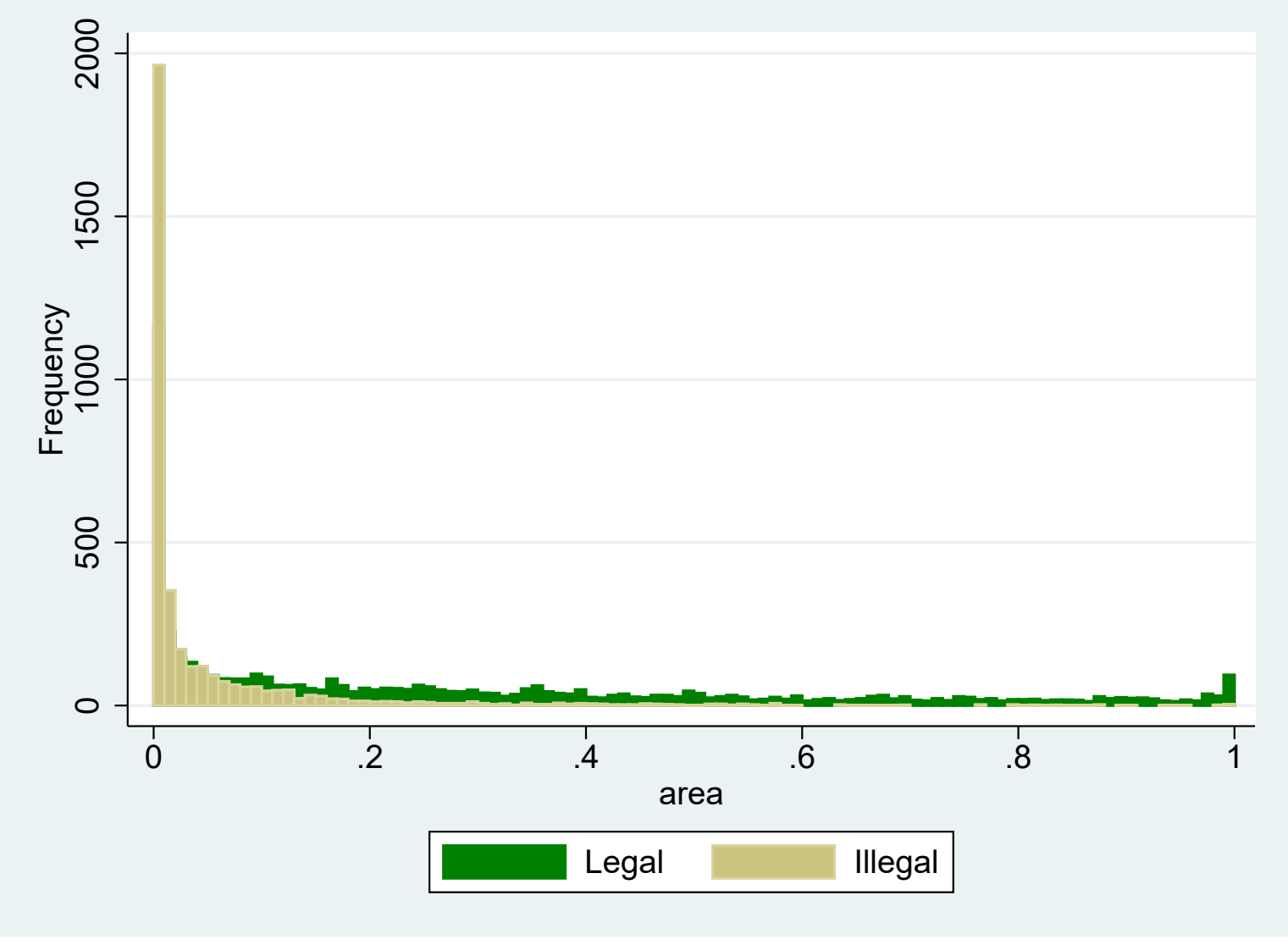
Histogram size of mines 2005



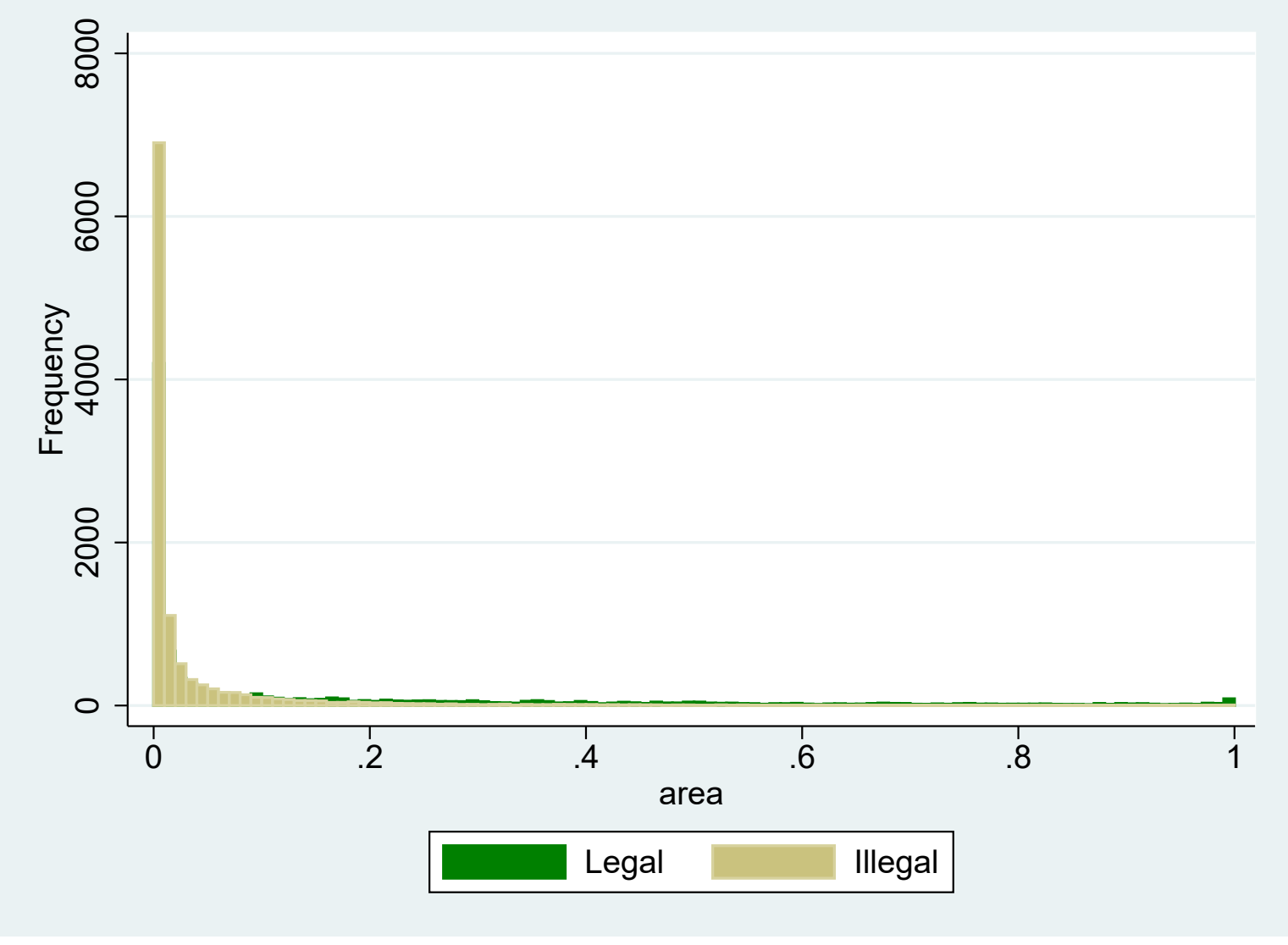
Histogram size of mines 2008



Histogram size of mines 2011



Histogram size of mines 2014



Bibliography I