# Virtual Seminar on Climate Economics

**Organizing Committee:**

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# THE FOREST AWAKENS

## AMAZON REGENERATION AND POLICY SPILLOVER

Juliano Assunção | *Climate Policy Initiative / PUC-Rio*
Clarissa Gandour | *Climate Policy Initiative / PUC-Rio*
Eduardo Souza-Rodrigues | *University of Toronto*

FED Virtual Seminar on Climate Economics

March 9th, 2022

# WHY RESTORATION MATTERS

- climate change mitigation

  Stern, 2006 | Greenstone & Jack, 2015 | IPCC, 2018 | Nordhaus, 2019

  - carbon capture & storage: protection & restoration of natural – particularly tropical – ecosystems
  - economic impact: watershed protection, improved agricultural yields, forest products, livelihoods, etc

- restoration of 350 million hectares worldwide by 2030

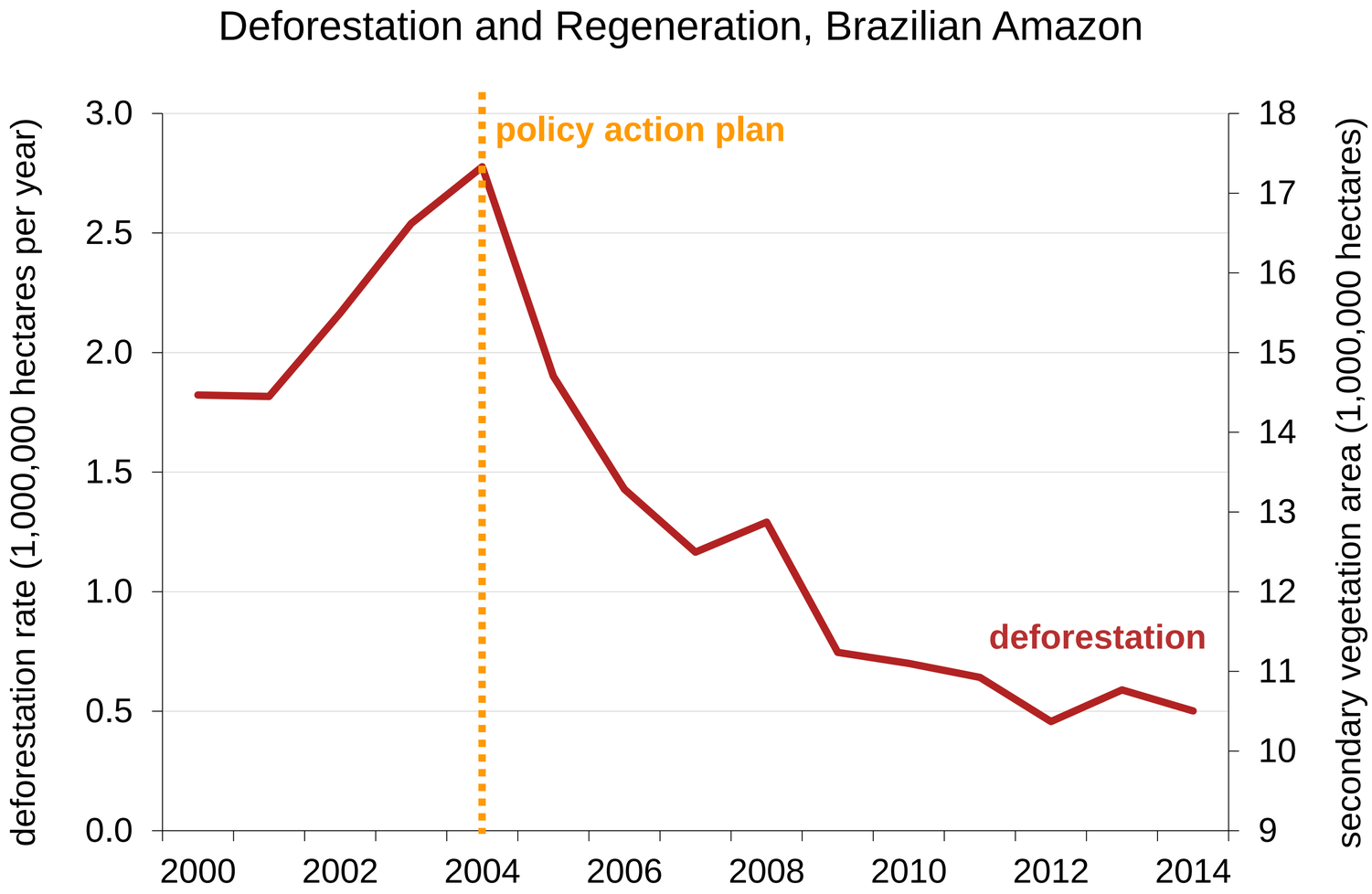
  IUCN and Winrock, 2017

  - absorb 1.7 $GtCO_2$ per year
  - yield USD 170 billion in net annual benefits

- Brazil: unique position
  - potential for restoration-based carbon sequestration: degraded / deforested lands in tropical ecosystems

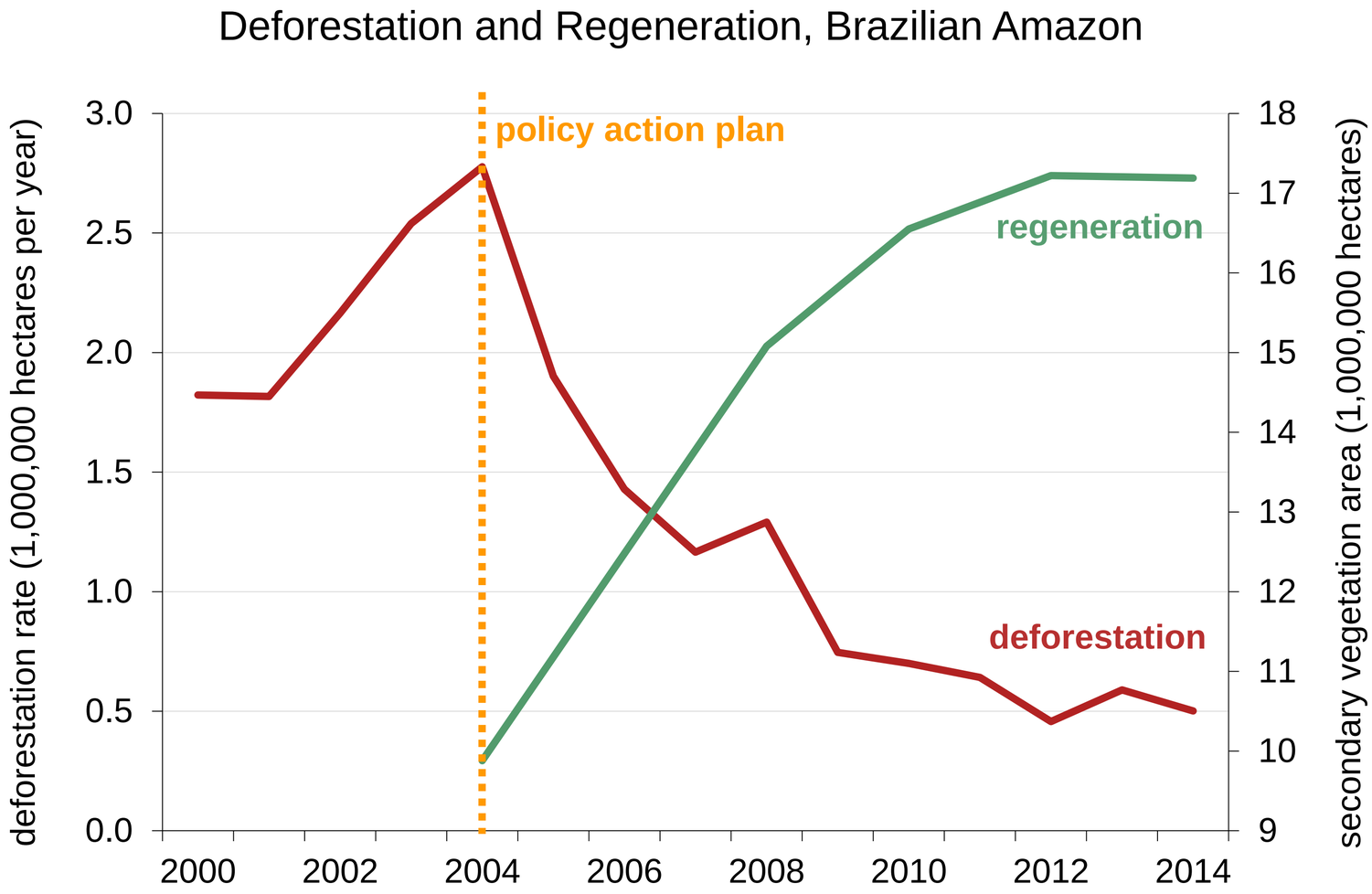
… **not** amongst Brazil's conservation priority over the past two decades

# BRAZIL'S TROPICAL CONSERVATION EFFORTS




Data sources: PRODES/Inpe (deforestation rate)

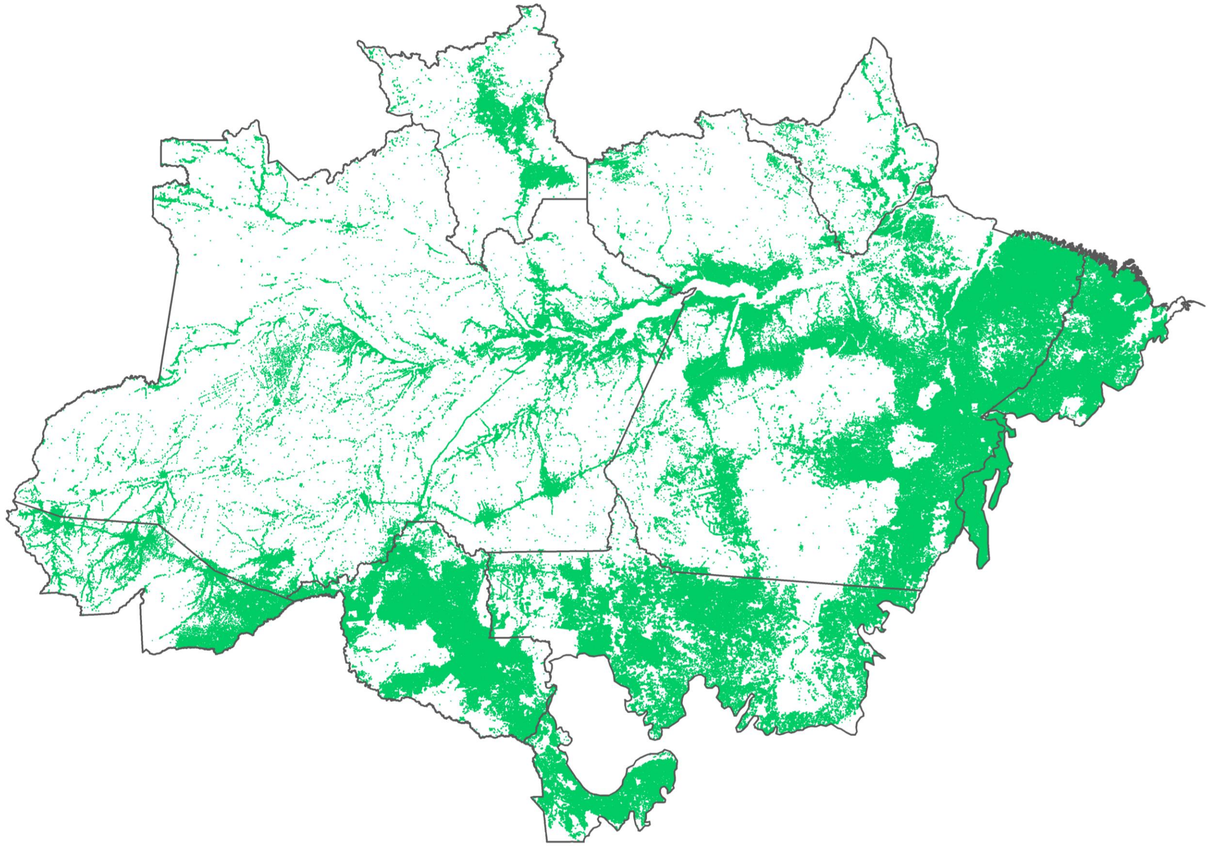
# BRAZIL'S TROPICAL CONSERVATION EFFORTS




Data sources: PRODES/Inpe (deforestation rate); TerraClass/Inpe and Embrapa (secondary vegetation)

# BRAZIL'S TROPICAL CONSERVATION EFFORTS

Amazon Regeneration, 2014



Data sources: PRODES/Inpe (deforestation rate); TerraClass/Inpe and Embrapa (secondary vegetation)

# REGENERATION: UNINTENDED POLICY OUTCOME?

- regeneration was **invisible**
  - to policy: no targeted efforts in action plan
  - to satellite-based monitoring systems

- monitoring and law enforcement strategy was **key driver** of deforestation slowdown
  Assunção, Gandour & Rocha, 2019 | Assunção, McMillan, Murphy & Souza-Rodrigues, 2021
  - increased cost of engaging in illegal deforestation

… did monitoring and law enforcement strategy (**unintentionally**) affect regeneration?

# MONITORING, LAW ENFORCEMENT & REGENERATION

stricter monitoring and law enforcement

↓

increased perceived risk of illegal primary deforestation

# MONITORING, LAW ENFORCEMENT & REGENERATION

stricter monitoring and law enforcement

↓

increased perceived risk of illegal primary deforestation

↙

**greater** demand for previously deforested areas
[to evade monitoring that detects new clearings]

↓

**conversion to** non-forest uses in previously deforested areas

↓

**reduction** in extent of regeneration

---

**displacement**

# MONITORING, LAW ENFORCEMENT & REGENERATION

stricter monitoring and law enforcement

↓

increased perceived risk of illegal primary deforestation

**greater** demand for previously deforested areas
[to evade monitoring that detects new clearings]

↓

**conversion to** non-forest uses in previously deforested areas

↓

**reduction** in extent of regeneration

**displacement**

**lower** demand for previously deforested areas
[use of illegally deforested land is itself illegal]

↓

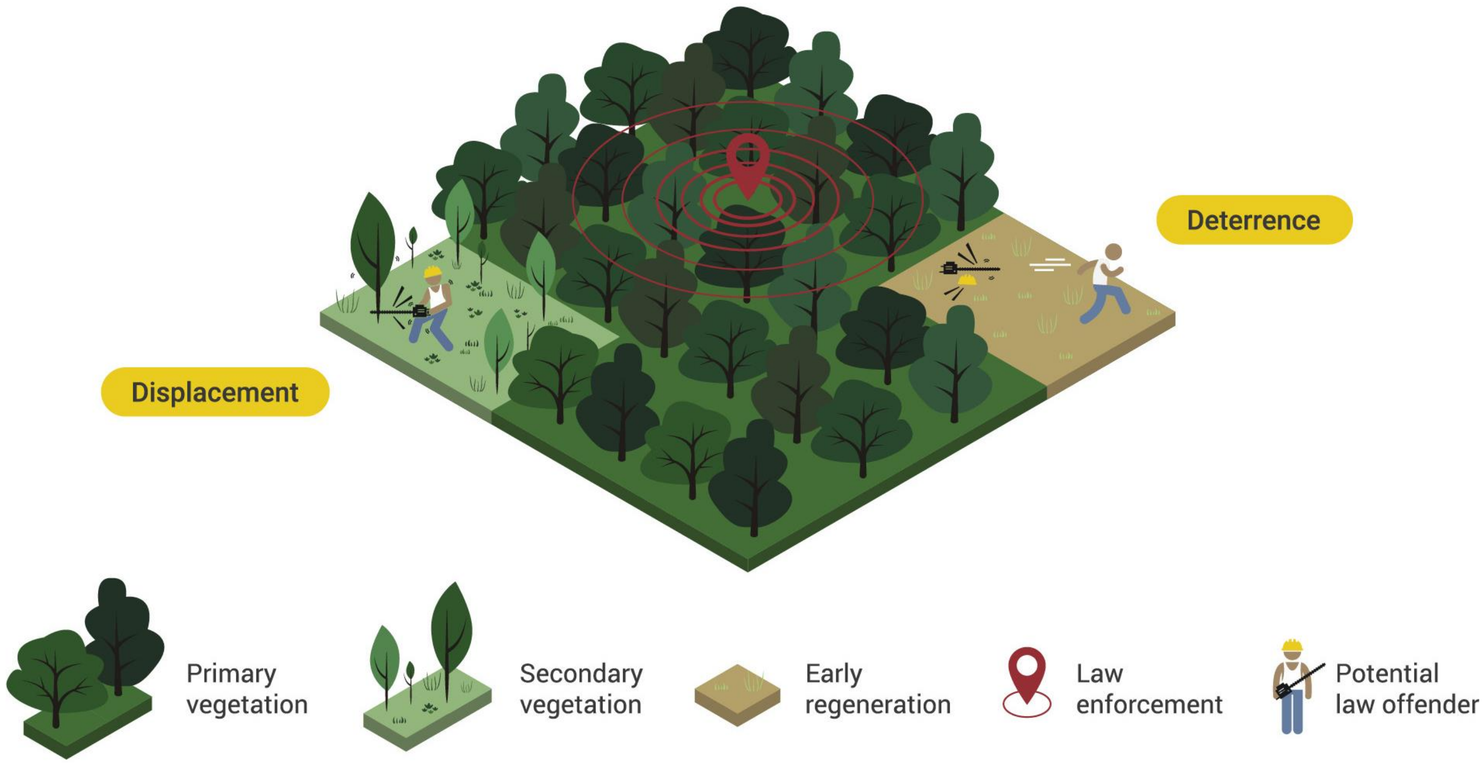
**abandonment of** non-forest uses in previously deforested areas

↓

**expansion** in extent of regeneration

**deterrence**

# MONITORING, LAW ENFORCEMENT & REGENERATION

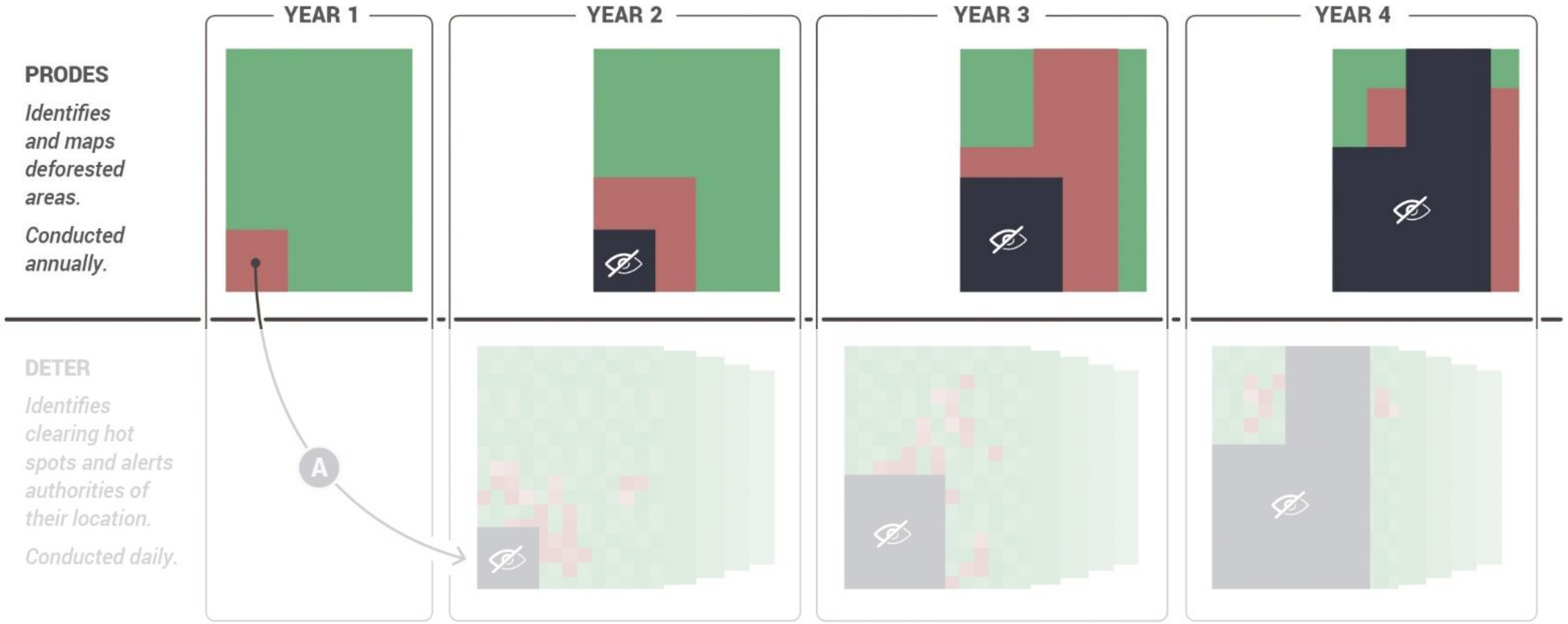



***Source:*** *Climate Policy Initiative/ PUC-Rio (2020).*

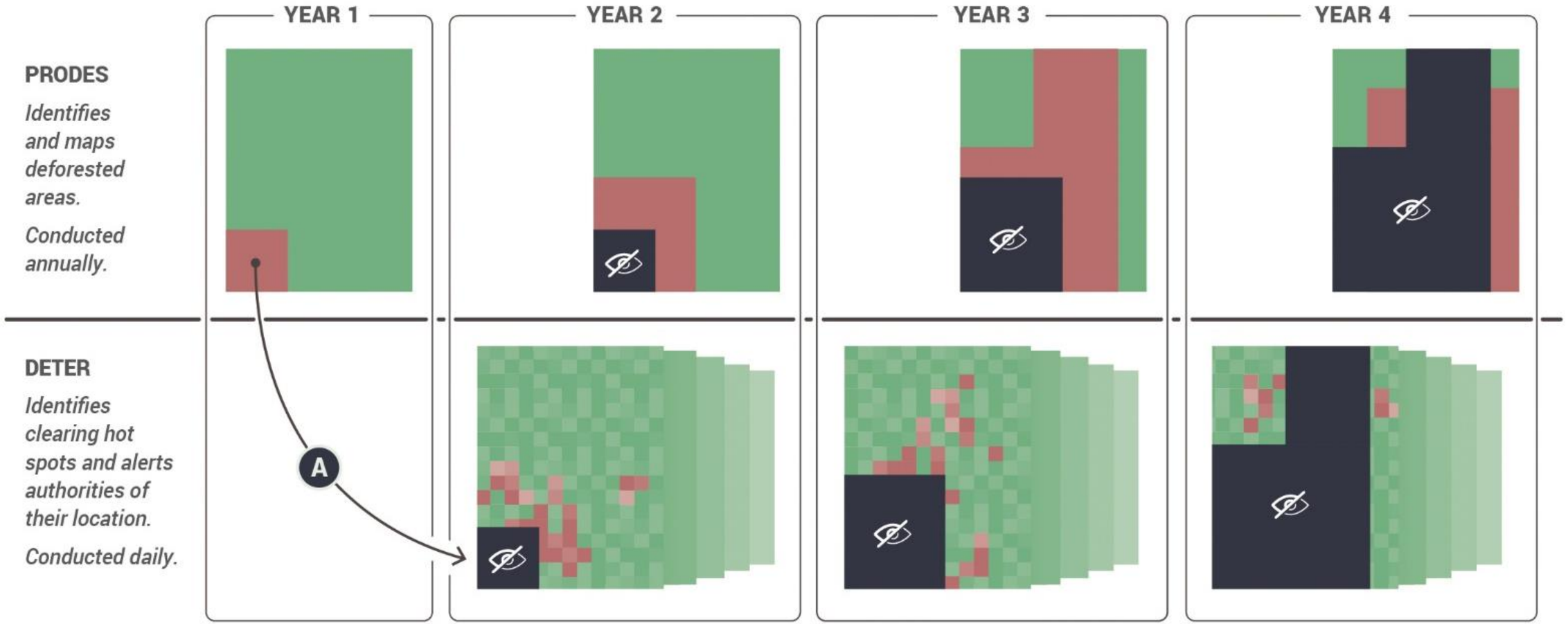
… both constitute **spillover**

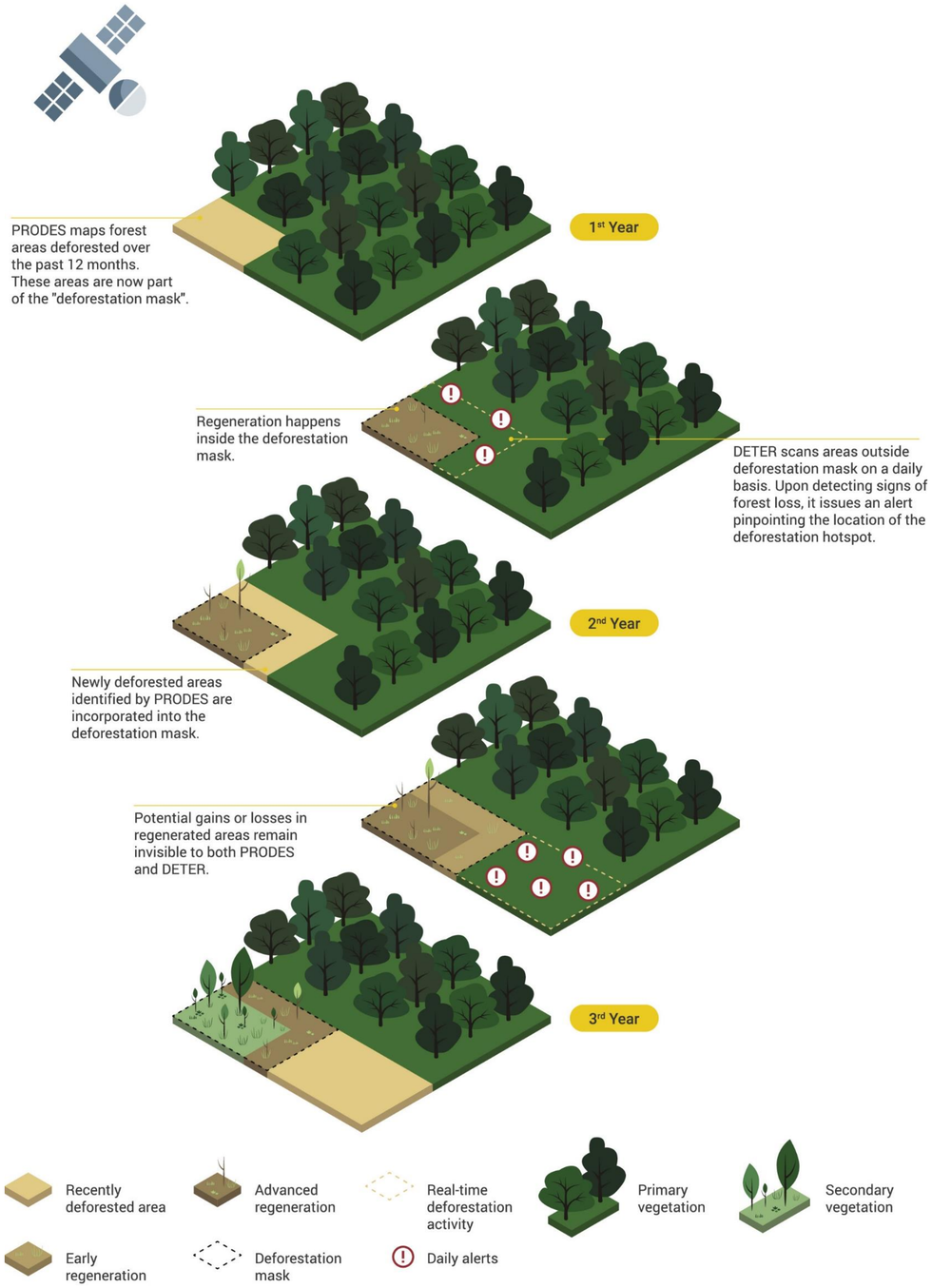
# CONTEXT

# MONITORING DEFORESTATION



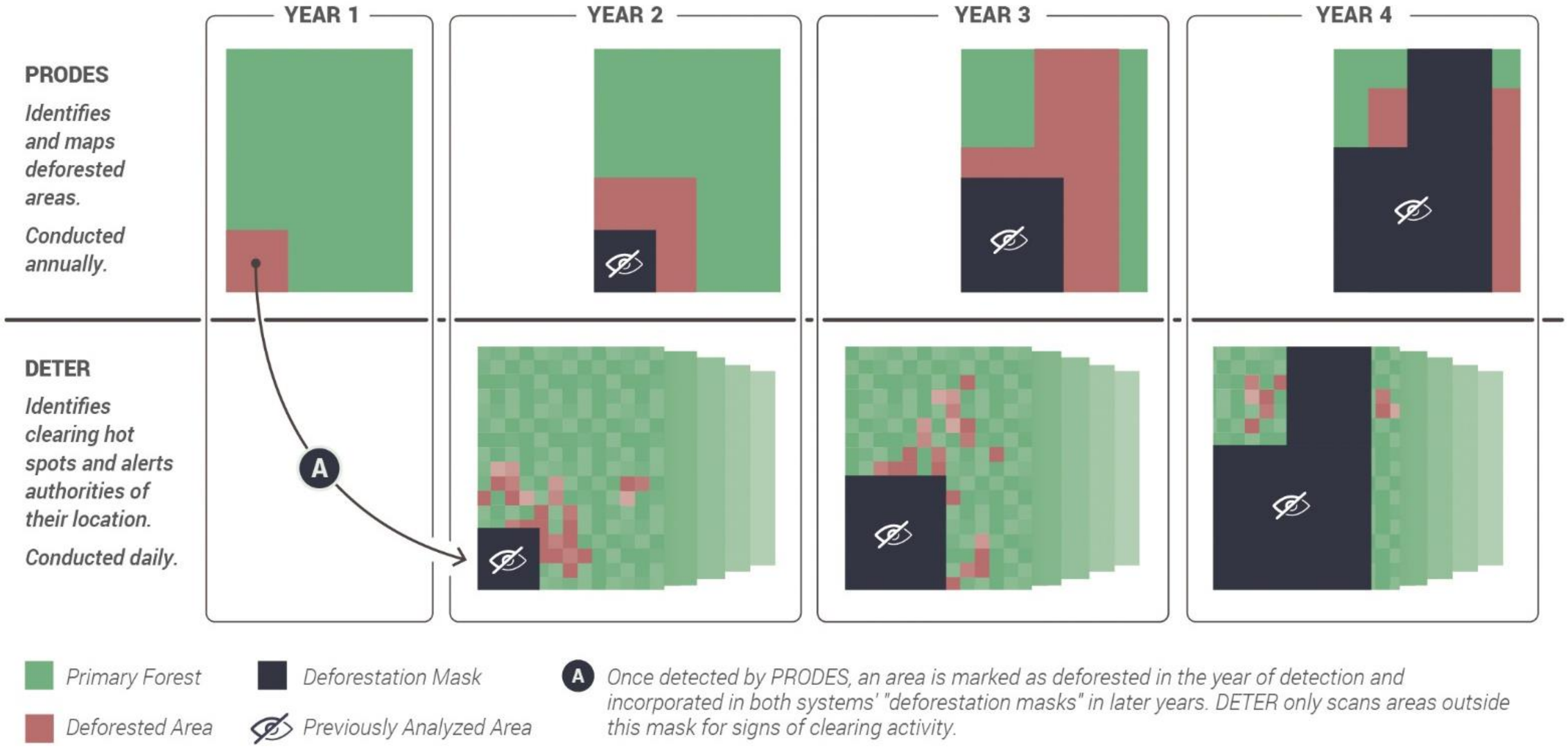
# MONITORING DEFORESTATION



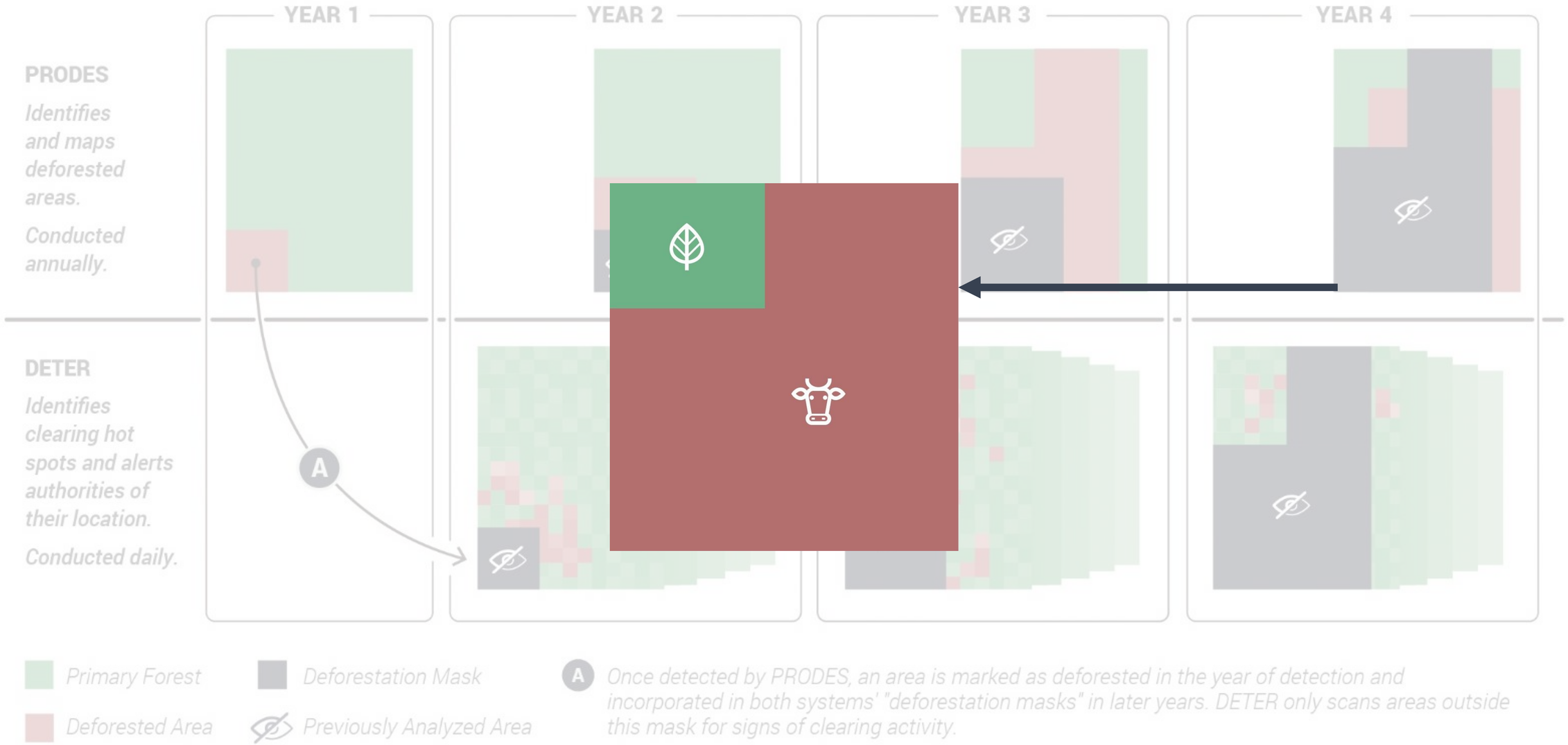



***Source:*** *Climate Policy Initiative/ PUC-Rio (2020).*

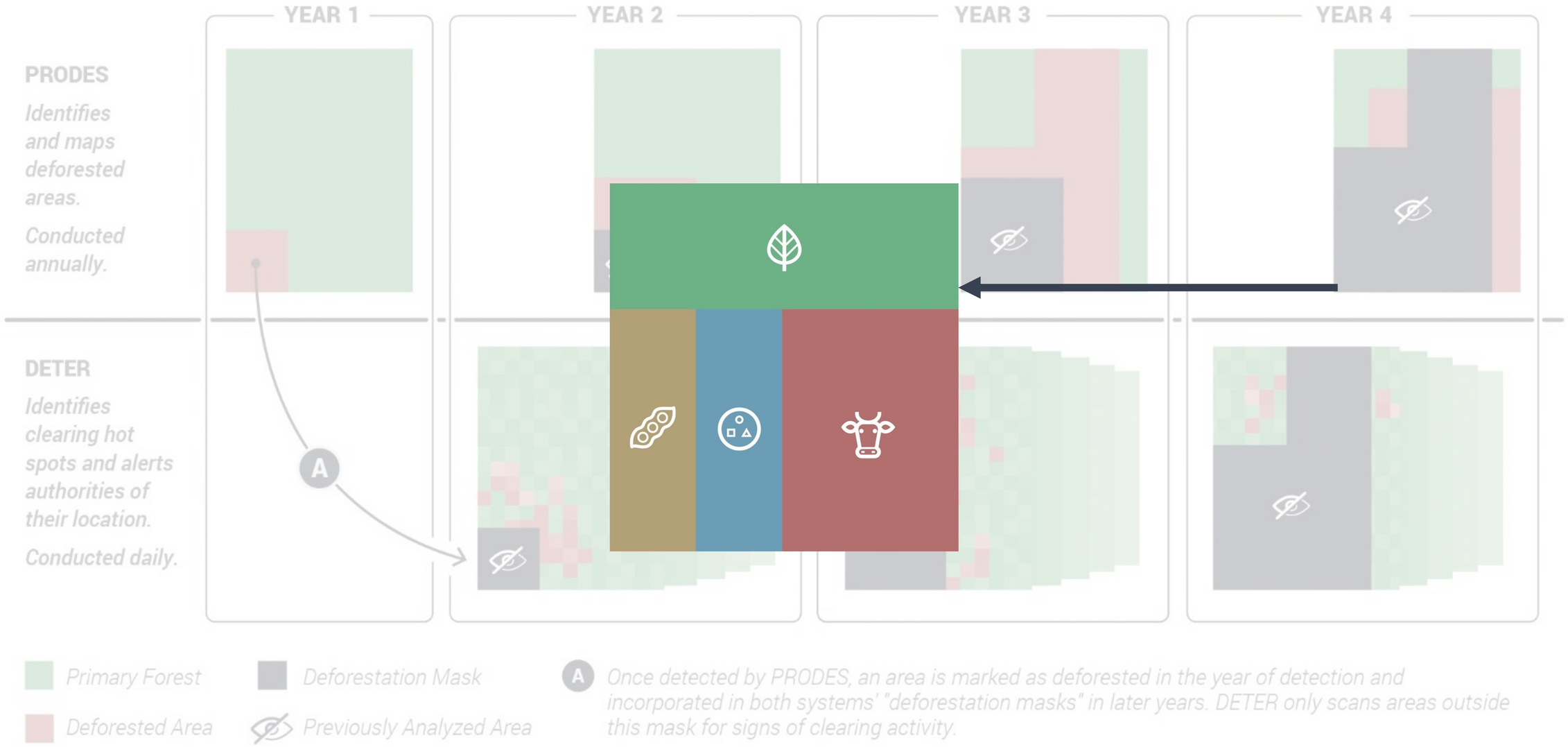
# MONITORING REGENERATION (OR LACK THEREOF…)



# MONITORING REGENERATION (OR LACK THEREOF…)



# MONITORING REGENERATION (OR LACK THEREOF…)



# DATA

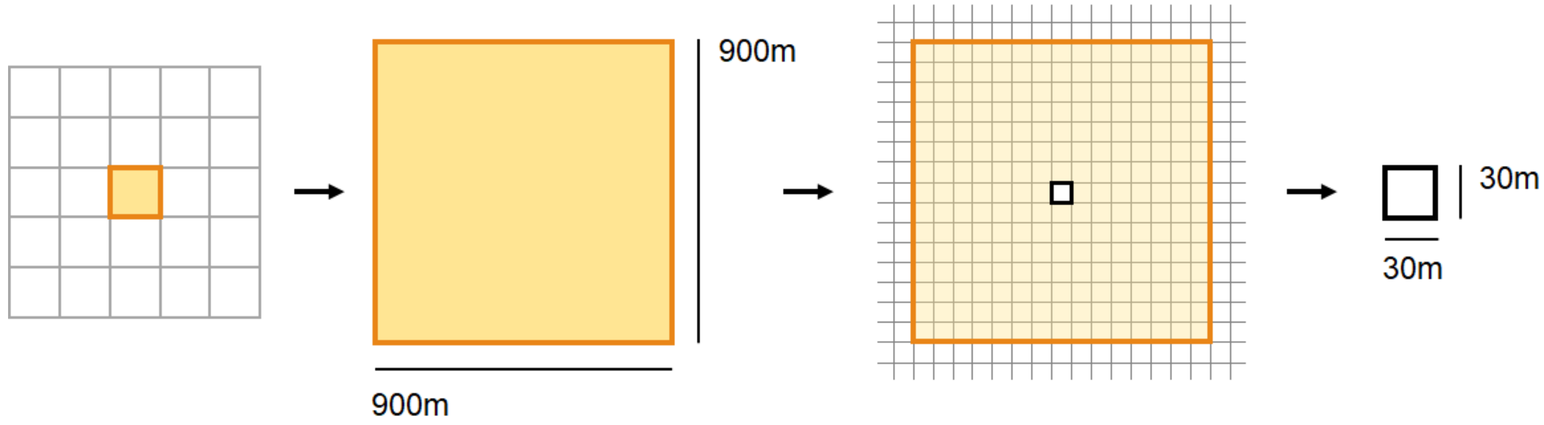
# DATA

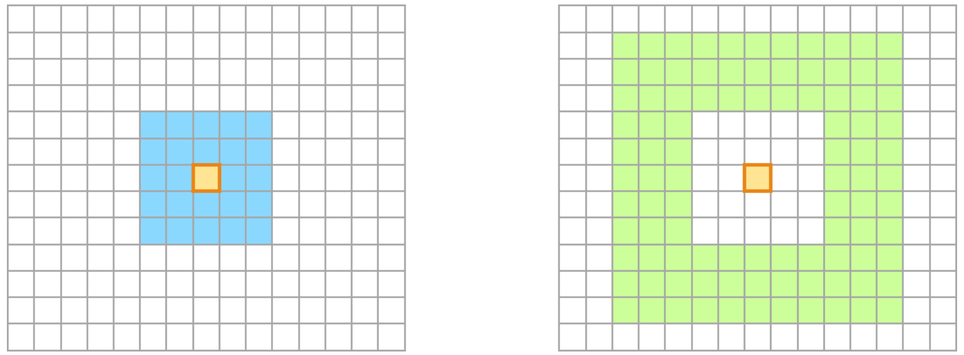
- satellite-based land cover and land use
  - deforestation: PRODES / Inpe
  - land use in deforested areas: TerraClass / Inpe and Embrapa
    - years: 2004, 2008, 2010, 2012, 2014
  - forest disturbance alerts: DETER / Inpe

- Other variables
  - weather: Matsuura and Willmott, 2015
  - satellite visibility: TerraClass / Inpe and Embrapa
  - protected territory: SNUC / MMA, Funai, ISA
  - priority municipalities: MMA
  - distance to the nearest road, nearest waterway, nearest municipality with pop>20k

- units of observation: 5.2 million cells
- sample period: 2004-2014

# SPATIAL SETUP



# DATA – MEASURING SECONDARY VEGETATION

- TerraClass' definition:
  - areas that were once clear-cut and that currently contains trees and/or shrubs
  - contains no pasture nor commercial reforestation

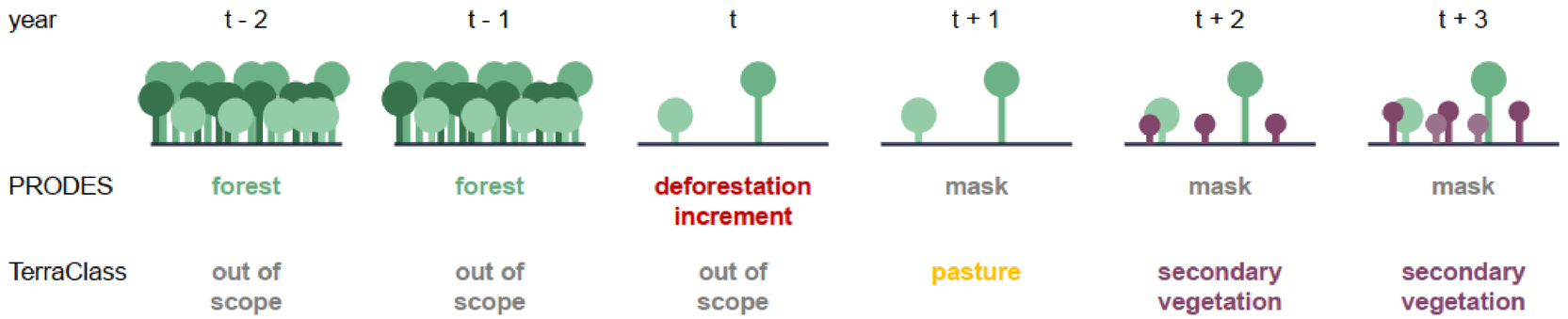
- first main difficulty: regeneration is a time-consuming process
  - may take several years to show up in satellite classification
  - short-term time-series variation is prone to measurement error

    Torchiana, Rosenbaum, Scott, Souza-Rodrigues, 2022; Alix-Garcia and Millimet, 2022
  - *not* fallow land

- second main difficulty: misclassification
  - distinguish degraded primary forest from actual secondary vegetation

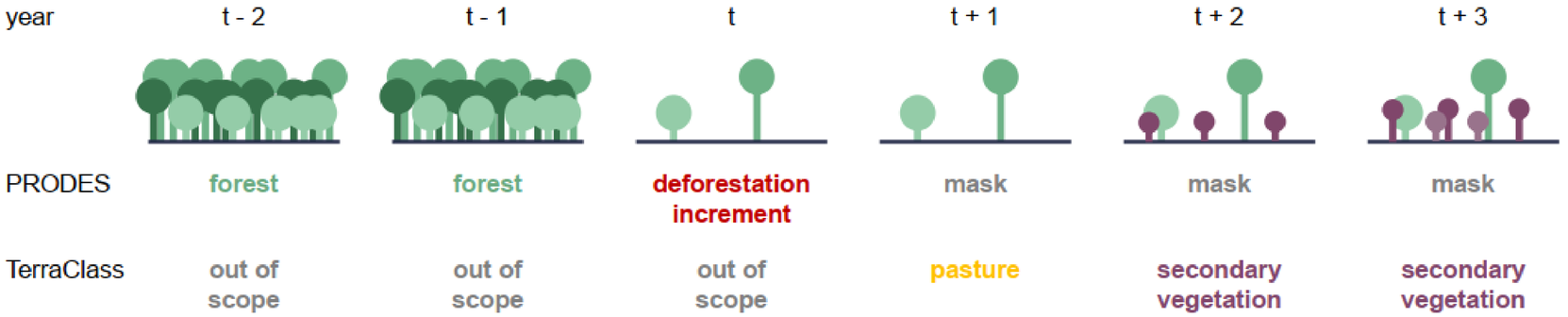
# “NON-DECREASING” SECONDARY VEGETATION

**correct classification**
actual secondary vegetation

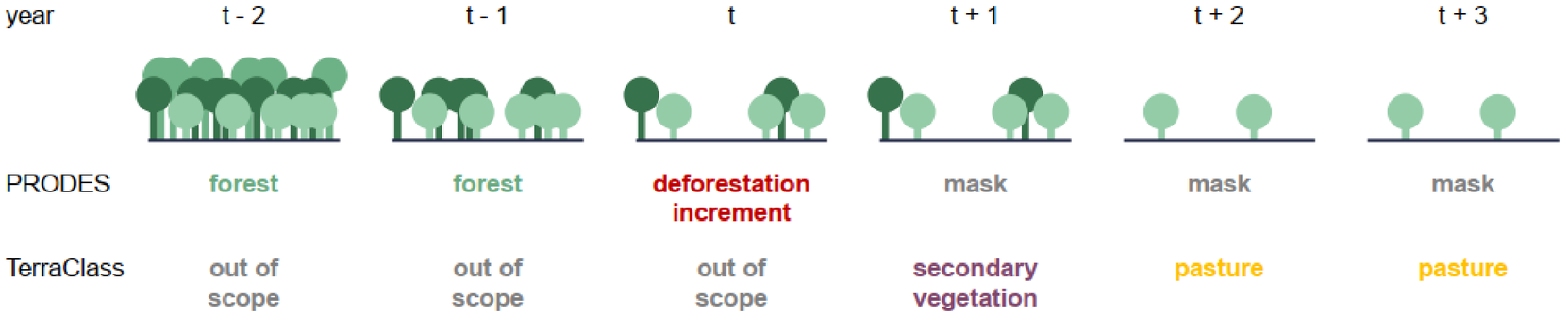


# “NON-DECREASING” SECONDARY VEGETATION

**correct classification**
actual secondary vegetation




**misclassification**
degraded primary vegetation



# DATA – MEASURING SECONDARY VEGETATION

- our (conservative) solution: consider *only* areas that meet two criteria:

a) classified as secondary vegetation for at least two consecutive TerraClass years

b) once classified as secondary vegetation, it never ceases to be classified as secondary vegetation

- we detect *permanence* by using the *full* TerraClass time-series (2004-2014)

# NON-DECREASING SECONDARY VEGETATION

Pixel Classification Algorithm

| TerraClass category | | | | | cell classified as non-decreasing secondary vegetation in … ? | |
|---|---|---|---|---|---|---|
| 2004 | 2008 | 2010 | 2012 | 2014 | 2004 | 2014 |
| sec. veg. | sec. veg. | sec. veg. | sec. veg. | sec. veg. | **yes** | **yes** |
| sec. veg. | sec. veg. | unobserved | unobserved | sec. veg. | **yes** | **yes** |
| forest | forest | sec. veg. | sec. veg. | sec. veg. | no | **yes** |
| forest | sec. veg. | unobserved | unobserved | sec. veg. | no | **yes** |
| forest | sec. veg. | unobserved | unobserved | unobserved | no | **yes** |
| pasture | pasture | sec. veg. | sec. veg. | sec. veg. | no | **yes** |
| sec. veg. | sec. veg. | pasture | pasture | pasture | no | no |
| sec. veg. | sec. veg. | pasture | pasture | sec. veg. | no | no |
| forest | pasture | sec. veg. | sec. veg. | pasture | no | no |
| forest | sec. veg. | unobserved | unobserved | pasture | no | no |
| forest | forest | forest | forest | sec. veg. | no | no |

# DATA – MEASURING CARBON STOCK

## CARBON UPTAKE OF SECONDARY FORESTS

(Yang et al., 2020)

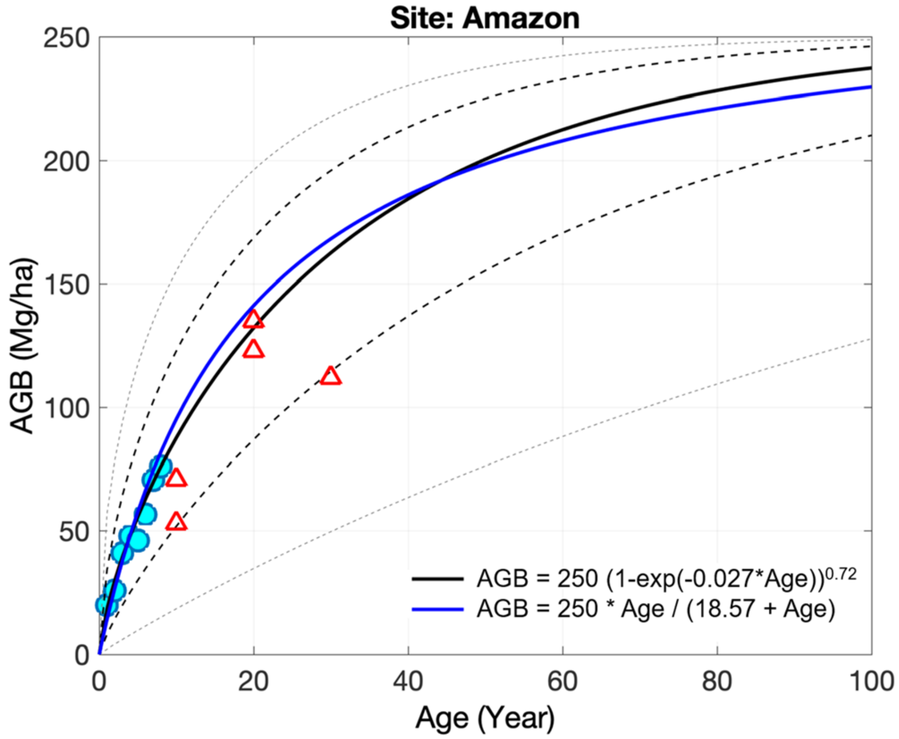
- calculate age of secondary vegetation in every pixel
- relate age to aboveground biomass (AGB)

$$ABG = 250(1 - \exp(-0.027Age))^{0.72}$$

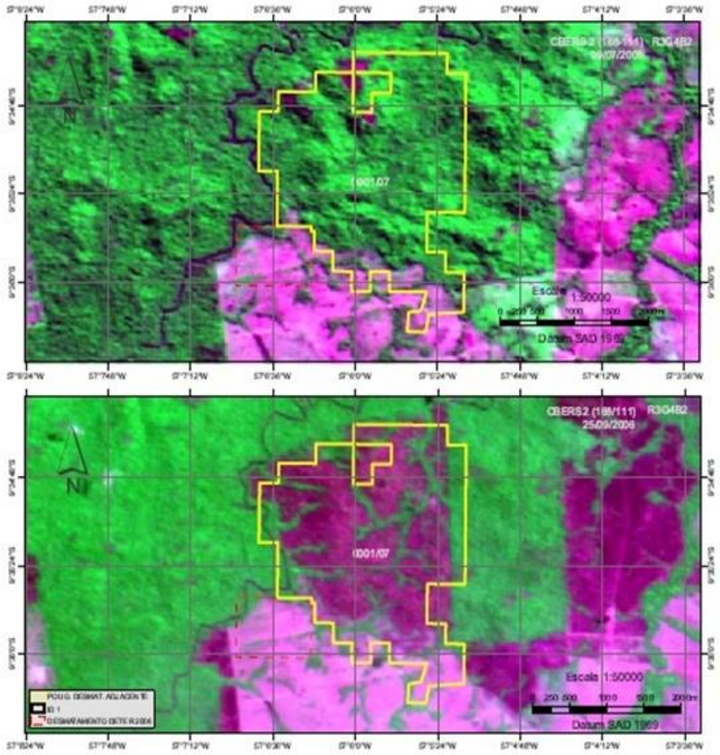
- convert aboveground biomass to total carbon density

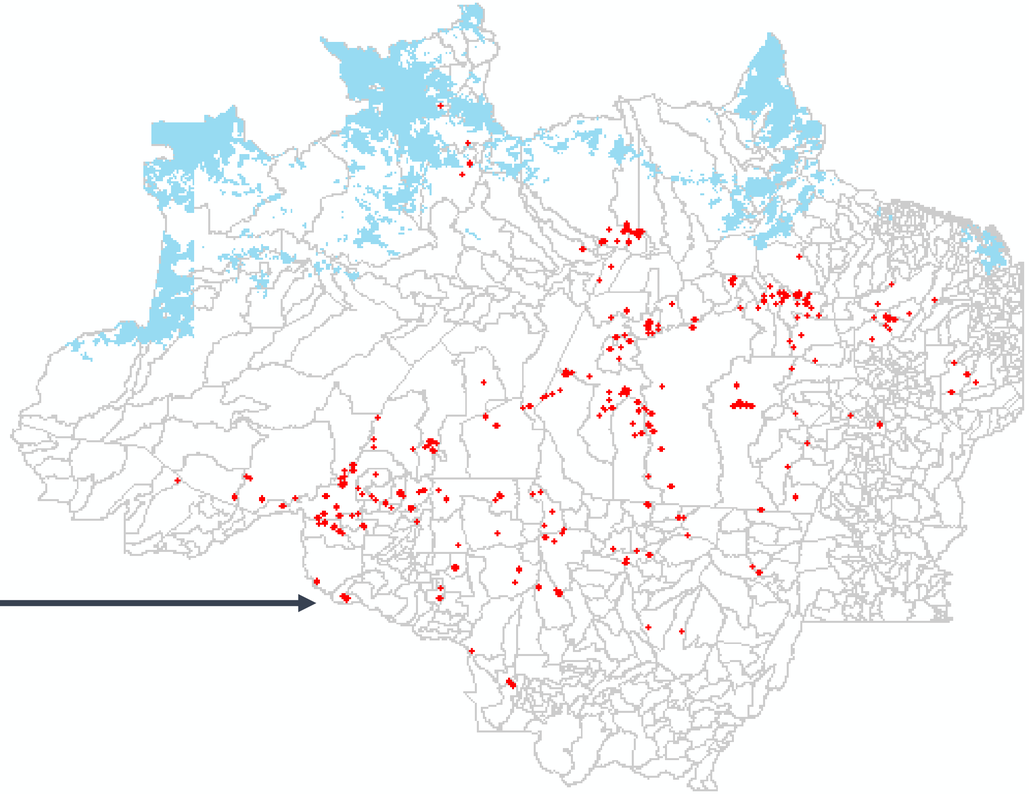
$$TCD = 0.49(ABG + 0.489ABG^{0.72})$$

- Average: 41.5–66.3 tons of carbon per hectare



# MONITORING AND LAW ENFORCEMENT



# DATA – DETER VS PRODES

Recorded Areas in Monitoring and Measuring Systems

| year | detected area DETER (ha) | detected area PRODES (ha) | detection share DETER/PRODES |
|---|---|---|---|
| 2006 | 491,457 | 1,091,857 | 45% |
| 2007 | 816,888 | 1,150,637 | 71% |
| 2008 | 438,735 | 1,336,129 | 33% |
| 2009 | 224,019 | 643,061 | 35% |
| 2010 | 266,439 | 635,751 | 42% |
| 2011 | 204,710 | 574,122 | 36% |
| 2012 | 277,758 | 446,873 | 62% |
| 2013 | 305,376 | 542,452 | 56% |
| **total** | **3,025,380** | **6,420,882** | **47%** |

# DATA – DETER VS PRODES

- differences due to:
  - spatial resolution
  - DETER detects forest degradation too

- accuracy:
  - $\Pr(deforestation\ or\ degradation \mid alert) \cong 89\%$
  - Negligible errors for areas > 10 has

    INPE, 2008 | Ferreira, 2023

# DATA

- alert intensity:
  - total number of alert cells over 2006-2013 as a share of total neighborhood area
- neighborhood rings:
  - 5km, 10km, 20km, 50km, and 100km
- sample selection:
  - cells with strictly positive shares of deforestation
- benchmark sample: cells containing at least 50% primary forest cover in 2004
  - proximity to remaining primary vegetation affects regeneration

    Crouzeilles et al., 2016 | Latawiec et al., 2016 | Uriarte and Chazdon, 2016

# DATA – SUMMARY STATISTICS

| | Brazilian Amazon | | benchmark sample | |
|---|---|---|---|---|
| | mean | std. dev. | mean | std. dev. |
| 2004 secondary vegetation (% cell area) | 0.0220 | 0.0865 | 0.0611 | 0.0862 |
| 2004 non-decreasing secondary vegetation (% cell area) | 0.0109 | 0.0565 | 0.0345 | 0.0663 |
| 2014 secondary vegetation (% cell area) | 0.0366 | 0.1167 | 0.1056 | 0.1274 |
| 2014 non-decreasing secondary vegetation (% cell area) | 0.0243 | 0.0887 | 0.0735 | 0.1009 |
| | | | | |
| d=1 if 2004-2014 $\Delta$ secondary vegetation $\geq$ 0.1 cell area | 0.0630 | 0.2430 | 0.2031 | 0.4023 |
| 2004-2014 $\Delta$ secondary vegetation | 0.0146 | 0.0919 | 0.0445 | 0.1181 |
| 2004-2014 $\Delta$ non-decreasing secondary vegetation (% cell area) | 0.0133 | 0.0605 | 0.0390 | 0.0785 |
| | | | | |
| alerts 5km neighborhood ring (% ring area) | 0.0590 | 0.1920 | 0.1809 | 0.3067 |
| alerts 10km neighborhood ring (% ring area) | 0.0590 | 0.1576 | 0.1608 | 0.2372 |
| alerts 20km neighborhood ring (% ring area) | 0.0589 | 0.1327 | 0.1429 | 0.1881 |
| alerts 50km neighborhood ring (% ring area) | 0.0583 | 0.1039 | 0.1173 | 0.1321 |
| alerts 100km neighborhood ring(% ring area) | 0.0572 | 0.0819 | 0.0962 | 0.0985 |
| | | | | |
| 2004 primary forest (% cell area) | 0.7656 | 0.3853 | 0.7958 | 0.1512 |
| | | | | |
| total annual rainfall (mm) | 2326.69 | 448.39 | 2182.20 | 368.65 |
| average annual temperature (Celsius) | 26.41 | 0.98 | 26.28 | 1.06 |
| 2004 unobservable TerraClass (% cell area) | 0.0108 | 0.0820 | 0.0137 | 0.0553 |
| 2014 unobservable TerraClass (% cell area) | 0.0070 | 0.0581 | 0.0146 | 0.0682 |
| baseline accumulated deforestation (% cell area) | 0.1318 | 0.3040 | 0.1742 | 0.1435 |
| alert intensity (year average) | 0.0590 | 0.3152 | 0.2216 | 0.5766 |
| d=1 if protected | 0.4879 | 0.4999 | 0.1922 | 0.3941 |

# ECONOMETRIC STRATEGY & RESULTS

# EMPIRICAL STRATEGY

- benchmark specification: $\Delta regeneration_i = \sum_{n \in \partial i} \beta_n enforcement_{n,i} + X'_i \theta + \varepsilon_i$

- time-consuming natural process: collapse panel into ten-year cross-sectional difference

  Aide et al., 2000 | Chazdon, 2008 | Alves et al., 1997

- identification: alerts in *n* do not correlate with unobservable factors affecting regeneration in *i*
  - regeneration invisible to monitoring
  - OVB
    - cell-level controls: location (municipality, saturated longitude/latitude)
      weather (temperature, rainfall)
      satellite visibility (2004 and 2014)
      baseline deforested area
      observed conservation policy (protection, local law enforcement)

# RESULTS: AREA

Catchment Area for Law Enforcement Spillover on Regeneration

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| *Panel B: Δ non-decreasing secondary vegetation (% cell area)* | | | | | |
| alerts 5km | 0.0035*** | -0.0001 | 0.0001 | 0.0001 | 0.0001 |
| | (0.0006) | (0.0008) | (0.0008) | (0.0008) | (0.0008) |
| alerts 10km | | 0.0068*** | 0.0030** | 0.0030** | 0.0030** |
| | | (0.0010) | (0.0012) | (0.0012) | (0.0012) |
| alerts 20km | | | 0.0076*** | 0.0075*** | 0.0077*** |
| | | | (0.0014) | (0.0016) | (0.0016) |
| alerts 50km | | | | 0.0002 | -0.0004 |
| | | | | (0.0022) | (0.0023) |
| alerts 100km | | | | | 0.0038 |
| | | | | | (0.0036) |
| R-squared | 0.1403 | 0.1404 | 0.1404 | 0.1404 | 0.1405 |
| number of observations | 403,191 | 403,191 | 403,191 | 403,191 | 403,191 |
| controls | | | | | |
| municipality | yes | yes | yes | yes | yes |
| coordinates (lon, lat, $lon^2$, $lat^2$, lon*lat) | yes | yes | yes | yes | yes |
| weather | yes | yes | yes | yes | yes |
| satellite visibility | yes | yes | yes | yes | yes |
| baseline accumulated deforestation | yes | yes | yes | yes | yes |
| observed conservation policy | yes | yes | yes | yes | yes |

Table notes omitted from slides, but included in document.

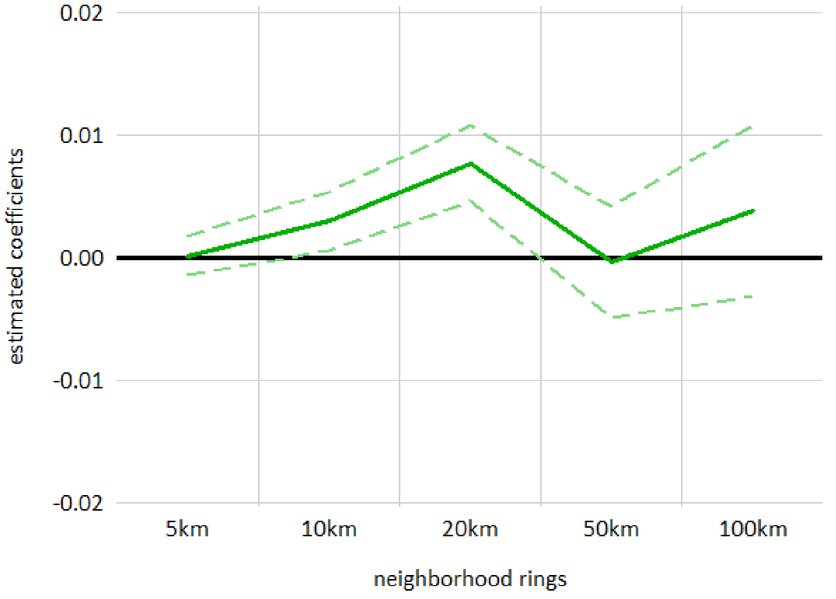
# RESULTS: AREA

## Law Enforcement Spillover on Regeneration

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| *Panel B: Δ non-decreasing secondary vegetation (% cell area)* | | | | | | |
| alerts 5km | -0.0063*** | -0.0058*** | -0.0058*** | -0.0041*** | -0.0021*** | 0.0001 |
| | (0.0007) | (0.0007) | (0.0007) | (0.0007) | (0.0007) | (0.0008) |
| alerts 10km | 0.0026** | 0.0036*** | 0.0036*** | 0.0037*** | 0.0038*** | 0.0030** |
| | (0.0013) | (0.0012) | (0.0012) | (0.0012) | (0.0012) | (0.0012) |
| alerts 20km | 0.0095*** | 0.0095*** | 0.0093*** | 0.0091*** | 0.0075*** | 0.0077*** |
| | (0.0016) | (0.0016) | (0.0016) | (0.0016) | (0.0016) | (0.0016) |
| alerts 50km | -0.0012 | 0.0042* | 0.0028 | 0.0037 | -0.0005 | -0.0004 |
| | (0.0021) | (0.0023) | (0.0023) | (0.0023) | (0.0023) | (0.0023) |
| alerts 100km | 0.0058*** | 0.0039 | 0.0022 | 0.0064* | 0.0035 | 0.0038 |
| | (0.0020) | (0.0036) | (0.0036) | (0.0036) | (0.0036) | (0.0036) |
| R-squared | 0.0005 | 0.0741 | 0.0744 | 0.1164 | 0.1404 | 0.1405 |
| number of observations | 403,191 | 403,191 | 403,191 | 403,191 | 403,191 | 403,191 |
| controls | | | | | | |
| municipality | no | yes | yes | yes | yes | yes |
| coordinates (lon, lat, $lon^2$, $lat^2$, lon*lat) | no | yes | yes | yes | yes | yes |
| weather | no | no | yes | yes | yes | yes |
| satellite visibility | no | no | no | yes | yes | yes |
| baseline accumulated deforestation | no | no | no | no | yes | yes |
| observed conservation policy | no | no | no | no | no | yes |

Table notes omitted from slides, but included in document.

## Benchmark Specification

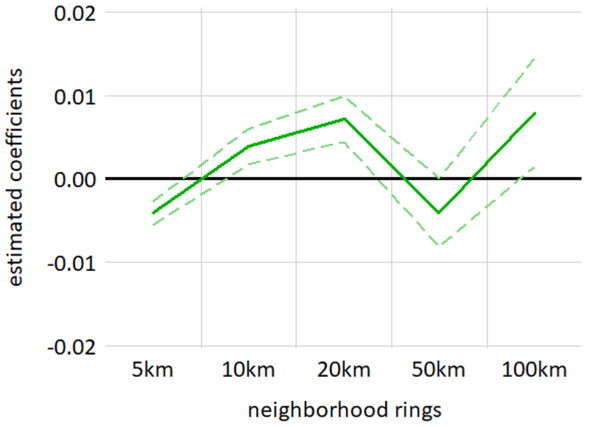



Dashed lines indicate 95% confidence interval.

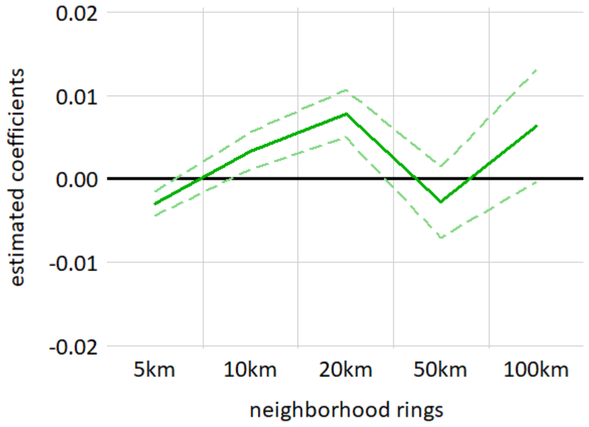
# RESULTS: AREA

## Sample Definition: Alternative Cutoffs

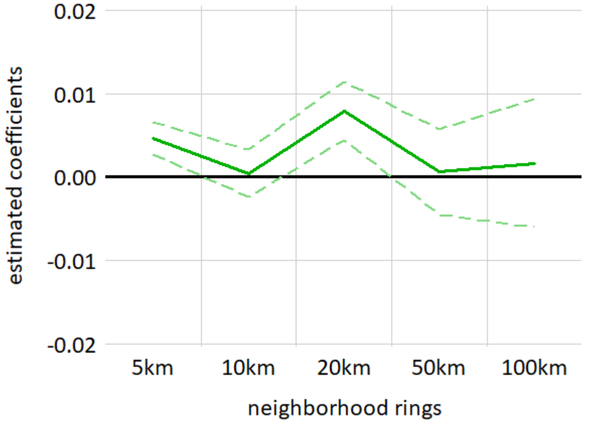
cutoff: 10%



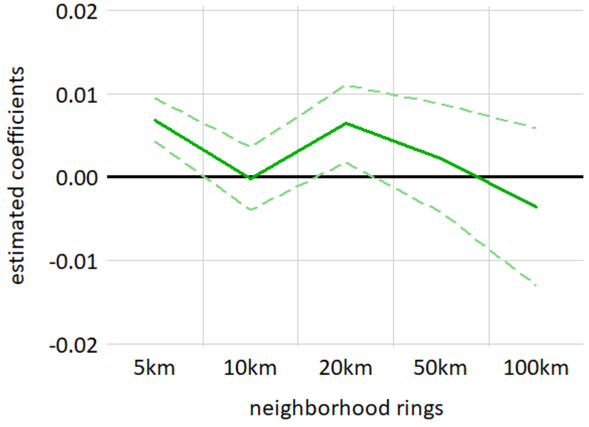

cutoff: 25%




cutoff: 75%

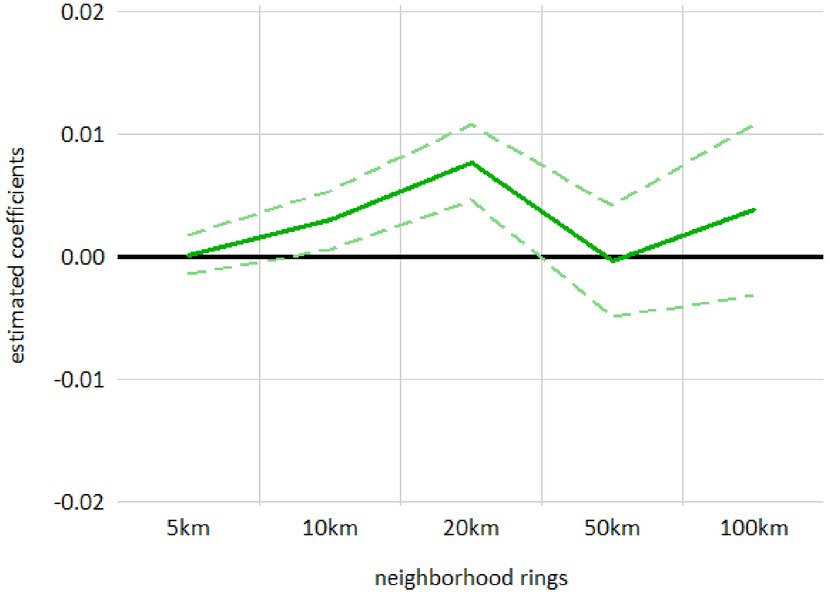



cutoff: 90%




## Benchmark Specification

cutoff: 50%




Dashed lines indicate 95% confidence interval.

# COUNTERFACTUAL EXERCISES

- no monitoring system:
  - almost 100,000 hectares (3%) decrease in extent of secondary vegetation
  - About 4.15—6.63 million tC
  - Social Benefit of $762.5 million – $1.2 billion
    (assuming SCC = $ 50/tCO2)

- improvement to monitoring system: detects all PRODES clearings
  - approx. 300,000 hectares (10%) increase in extent of secondary vegetation
  - About 12—19 million tC
  - Social Benefit of $2.3 billion – $ 3.65 billion

- monitoring costs (IBAMA and INPE – roughly): $60 million per year

# WRAP UP

## (ALWAYS) MORE WORK TO BE DONE

- carbon counterfactual
  - natural (passive) regeneration
  - cost/benefit
    - reduced deforestation (target)
    - increased regeneration (spillover)

- disentangle impact heterogeneity
  - where is regeneration happening? [public x private lands]
  - time for regeneration? [early x late alerts]

# WRAP UP

## POLICY IMPLICATIONS

- policy design & targeting
  - evaluation & cost-effectiveness (impact on social welfare)

- restoration at scale
  - UN development goals
  - UN decade for ecosystem restoration
  - Brazil’s iNDCs: restore/reforest 12 million hectares countrywide

**… information can catalyze promotion and protection of tropical regeneration**

# THANK YOU