Reflections on Land Cover and Land Use Change Studies in the Large Scale Biosphere Atmosphere Experiment in Amazonia (LBA) or *Long Bloody Arguments*

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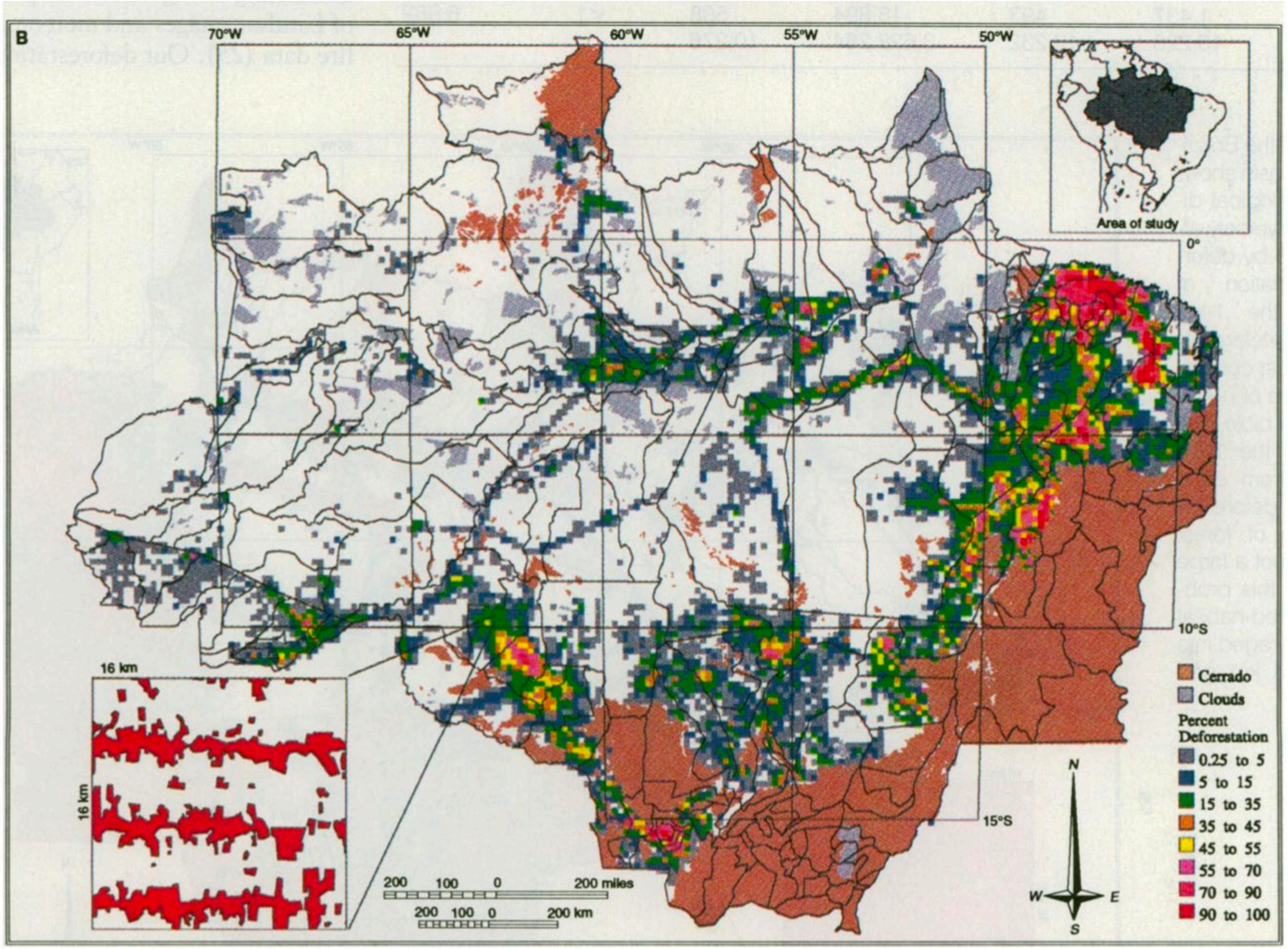
NASA LCLUC 25th Anniversary Meeting
October 18, 2022

Contributions from …

- Ane Alencar, Eugenio Arima, Greg Asner, Mateus Batistella, Richard Bilsborrow, Ruth DeFries, Frank Merry, Emilio Moran, Douglas Morton, Alex Pfaff, Wilfrid Schroeder, David Skole, Adriano Venturieri, Robert Walker

Landsat records 15,000 km^2 y^{-1} deforestation between 1978 and 1988 in the Brazilian Amazon



Skole & Tucker *Science* 1993

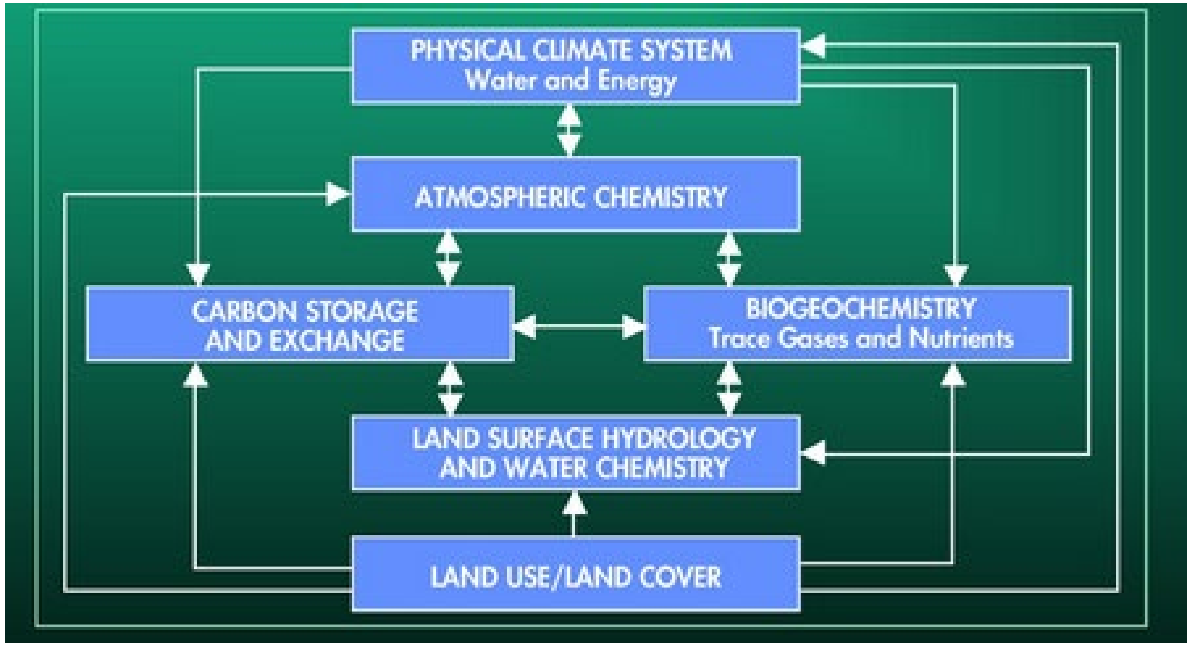
"Landsat satellite imagery covering the entire forested portion of the Brazilian Amazon Basin was used to measure, for 1978 and 1988, deforestation, fragmented forest, defined as areas less than 100 square kilometers surrounded by deforestation, and edge effects of 1 kilometer into forest from adjacent areas of deforestation. Tropical deforestation increased from 78,000 square kilometers in 1978 to 230,000 square kilometers in 1988 while tropical forest habitat, severely affected with respect to biological diversity, increased from 208,000 to 588,000 square kilometers. Although this rate of deforestation is lower than previous estimates, the effect on biological diversity is greater."

The Large Scale Biosphere-Atmosphere Experiment in Amazonia

<u>The LBA questions</u>

1) How does Amazonia currently function as a regional entity?

2) How will changes in land use and climate affect the biological, chemical, and physical functions of Amazonia, including the sustainability of development in the region and the influence of Amazonia on global climate?



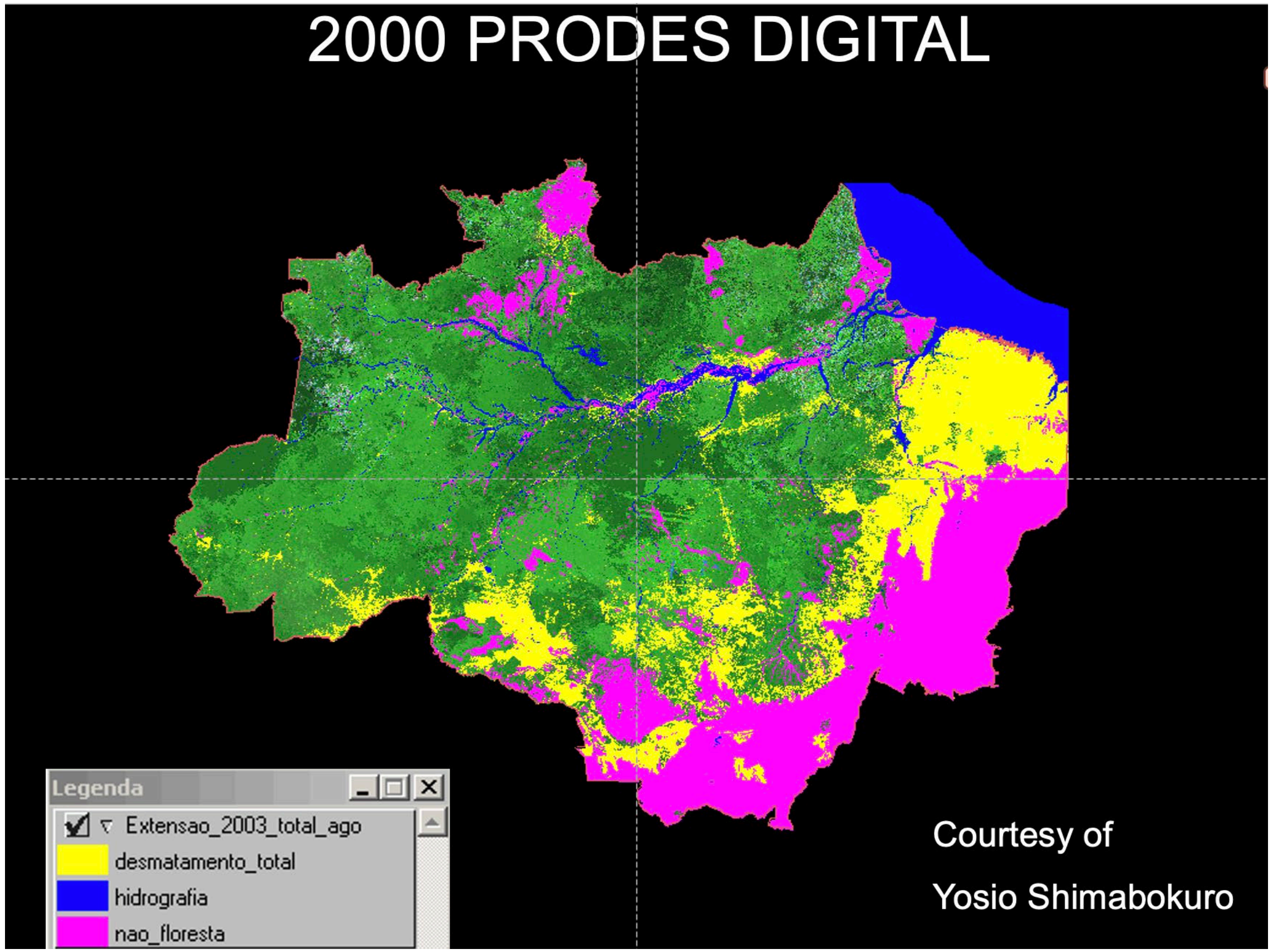
LBA ECO -- A NASA Contribution to LBA

- **How do tropical forest conversion, regrowth, and selective logging influence carbon storage, nutrient dynamics, trace gas fluxes, and the prospect for sustainable land use in the Amazon region?**

LCLUC Questions

1. What are the rates and mechanisms of forest conversion to agricultural land uses, and what is the relative importance of these land uses?
2. At what rate are converted lands abandoned to secondary forests; what is the fate of these converted lands, and what are the overall dynamic patterns of land conversion and abandonment?
3. What is the area of forest that is affected by selective logging each year? How does the intensity of selective logging influence forest ecosystem function, thus altering forest regrowth and flammability?
4. What are plausible scenarios for future land-cover change in Amazonia?

- Accomplishments during the LBA era (~1999-2009)
- Reflections on what we have learned since



Reservations

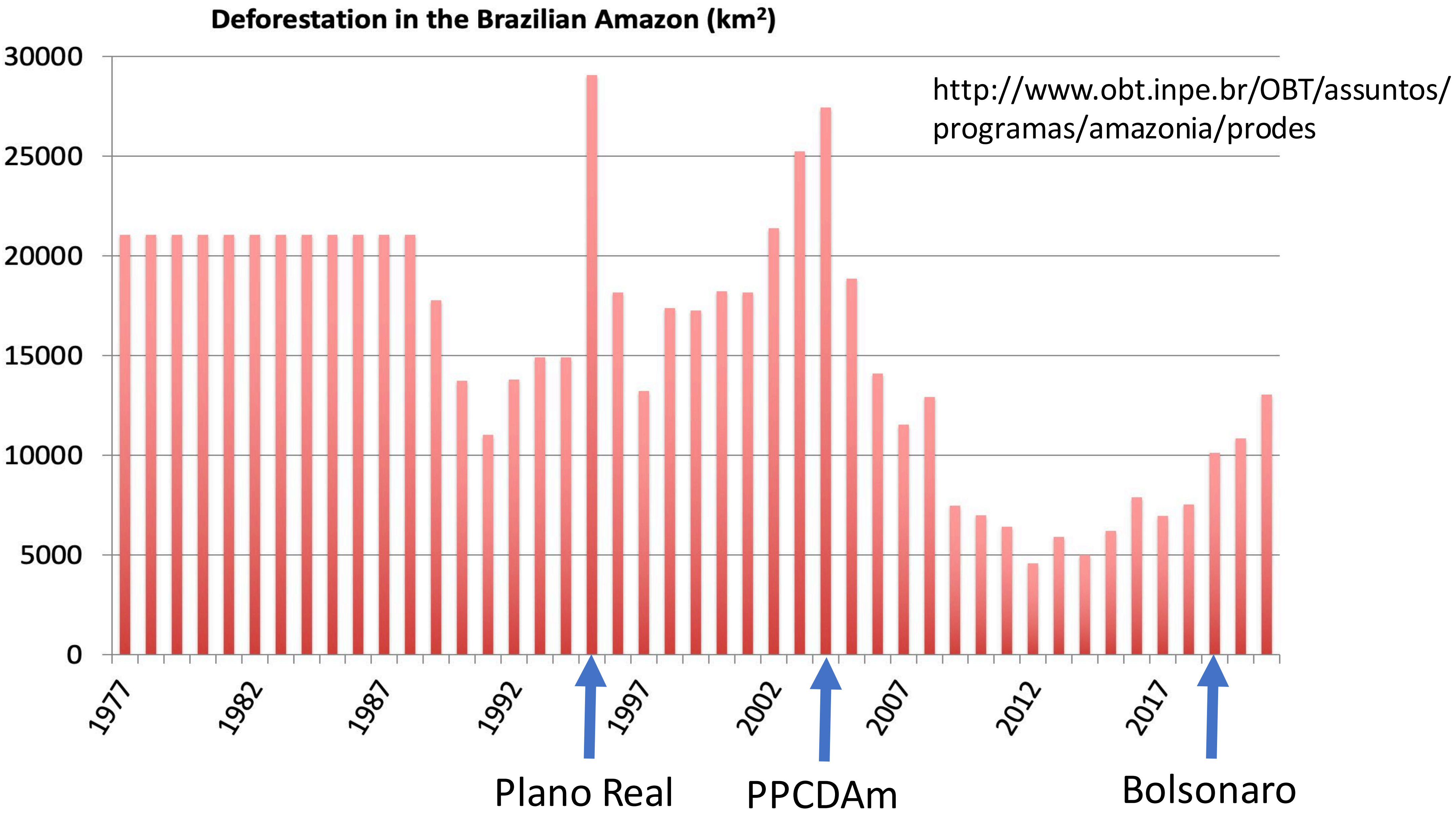
- Reflecting LBA, this presentation biased towards Brazil

- My focus is the collective LBA endeavor and not on our many LBA heroes. Therefore, the selection of papers is only illustrative of a much broader body of work. Please forgive me if I left out your favorite result or author.

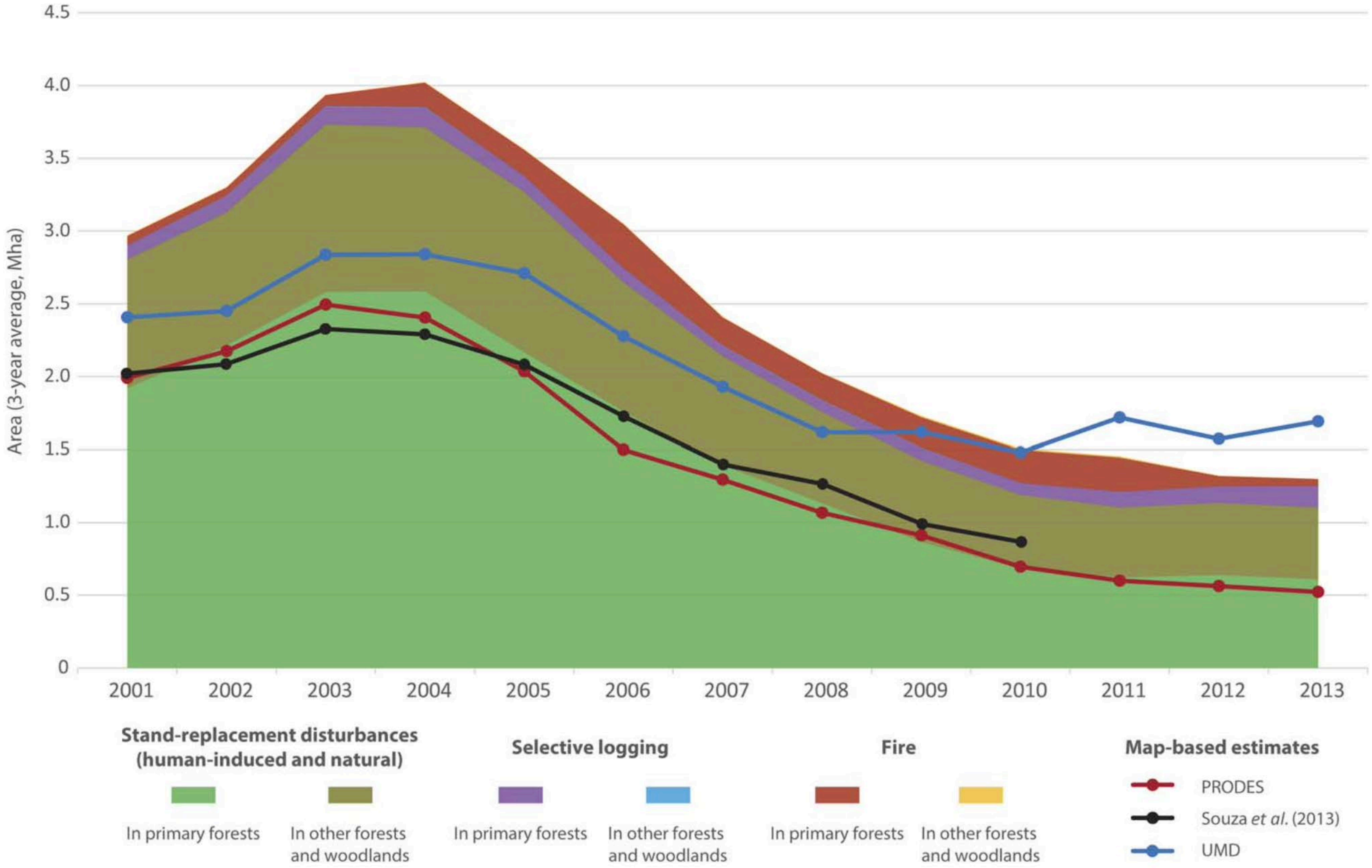
- Time is limited and I chose only a few themes. LCLUC in LBA was much richer than the material that I have time to present.

- While many people contributed ideas to this presentation, you should still blame any distortions or errors on me.

Q1. What are the rates and mechanisms of forest conversion to agricultural land uses, and what is the relative importance of these land uses?

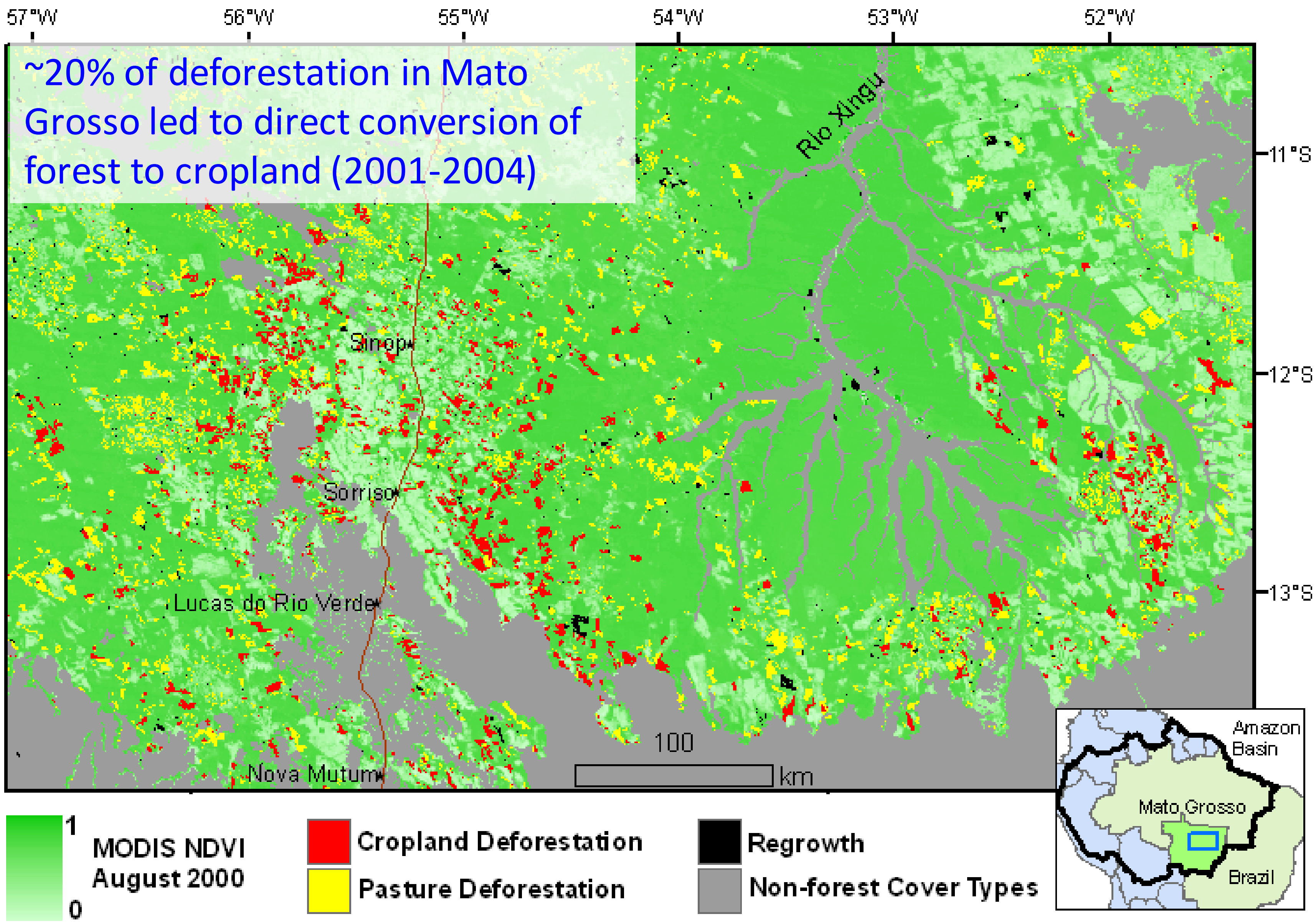


Deforestation Estimates Generally Agree



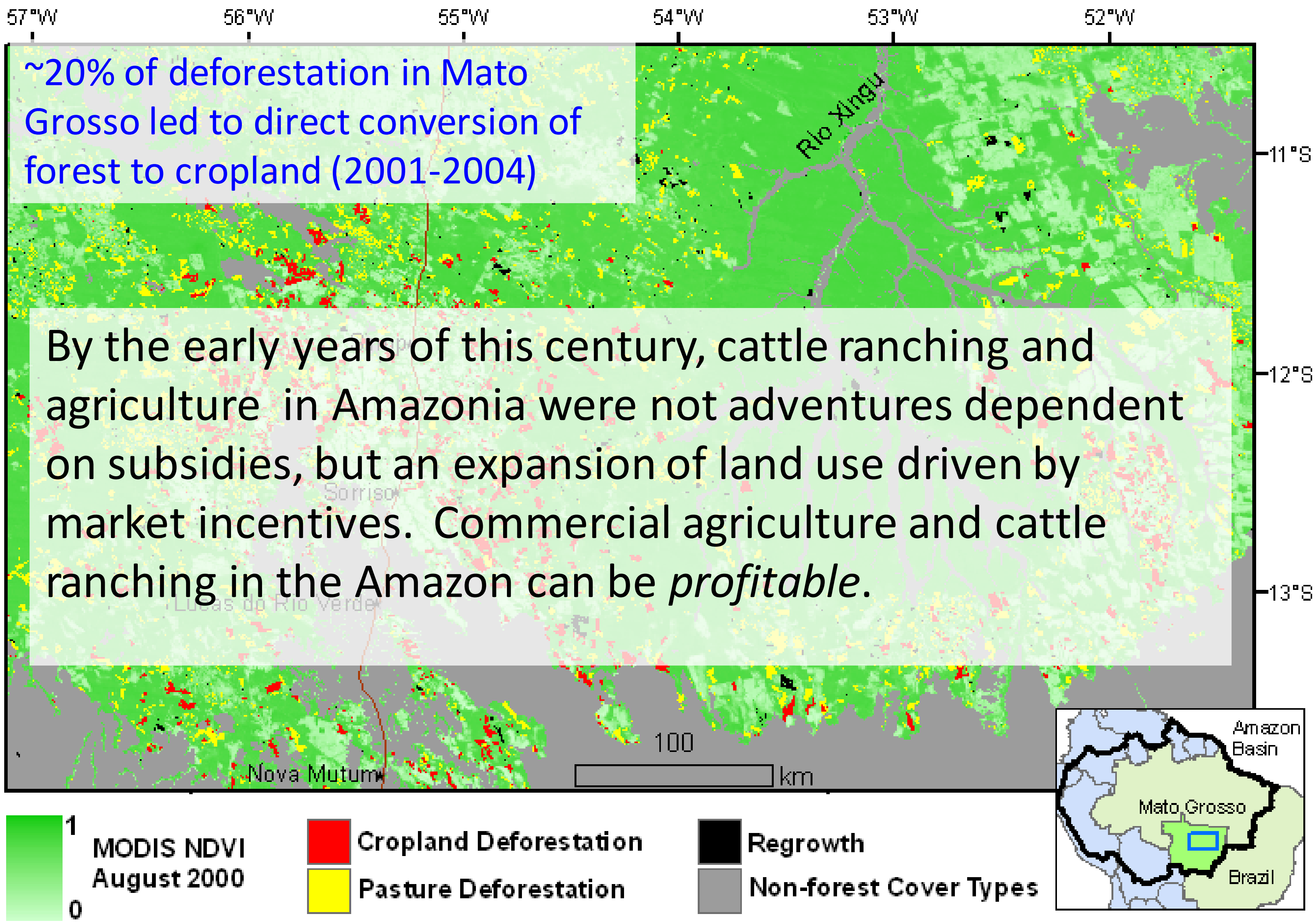
Tyukavina et al. 2015

Fate of deforestation from 2001-04 from MODIS phenology



Morton et al., *PNAS,* 2006

Fate of deforestation from 2001-04 from MODIS phenology



~20% of deforestation in Mato Grosso led to direct conversion of forest to cropland (2001-2004)

By the early years of this century, cattle ranching and agriculture in Amazonia were not adventures dependent on subsidies, but an expansion of land use driven by market incentives. Commercial agriculture and cattle ranching in the Amazon can be *profitable*.

Morton et al., *PNAS*, 2006

Q2. At what rate are converted lands abandoned to secondary forests; what is the fate of these converted lands, and what are the overall dynamic patterns of land conversion and abandonment?

Ecosystems (2006) 9: 609–623
DOI: 10.1007/s10021-006-0001-9

ECOSYSTEMS

Area and Age of Secondary Forests in Brazilian Amazonia 1978–2002: An Empirical Estimate

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Abstract

In quantifying the carbon budget of the Amazon region, temporal estimates of the extent and age of regenerating tropical forests are fundamental. However, retrieving such information from remote-sensing data is difficult, largely because of spectral similarities between different successional stages and variations in the reflectance of forests following different pathways of regeneration. In this study, secondary-forest dynamics in Brazilian Amazonia were modeled for the 1978–2002 period to determine area and age on a grid basis. We modeled the area, age, and age class distribution of secondary forests using empirical relationships with the percentage of remaining primary forest, as determined from large-area remote-sensing campaigns (the Pathfinder and Prodes projects). The statistical models were calibrated using detailed maps of secondary-forest age generated for seven sites in the Brazilian Legal Amazon. The area–age distribution was then specified from mean age by a distribution assumption. Over the period 1978–2002, secondary-forest area was shown to have increased from 29,000 to 161,000 km^2 (that is, by a factor of 5). The mean age increased from 4.4 to 4.8 years. We generated a time series of secondary-forest area fractions and successional stages that provides wall-to-wall coverage of the Brazilian Amazon at a spatial resolution of 0.1 decimal degrees (approximately 11 km). Validation against reference data yielded root mean squared errors of 8% of the total area for estimate of secondary-forest area and 2.4 years for mean secondary-forest age. Using this approach, we provide the first published update on the state of secondary forests in Amazonia since the early 1990s and a time series of secondary-forest area over the 25-year period.

Key words: Amazon; area–age distribution; forest age; land-use model; secondary forest; succession.

Introduction

Largely because of uncertainties about the contribution of Amazonia to the global carbon budget the dynamics of forests and the fate of deforested land in this region have received increasing attention in recent years (Fearnside 1997; Houghton and others 2000; Achard and others 2002, 2004; Houghton 2003). The regrowth of secondary forests has been recognized as one of the major vectors of land-cover change (Neeff and others 2005); therefore, establishing the relative capacity of forests at different stages of re generation to sequester carbon has been

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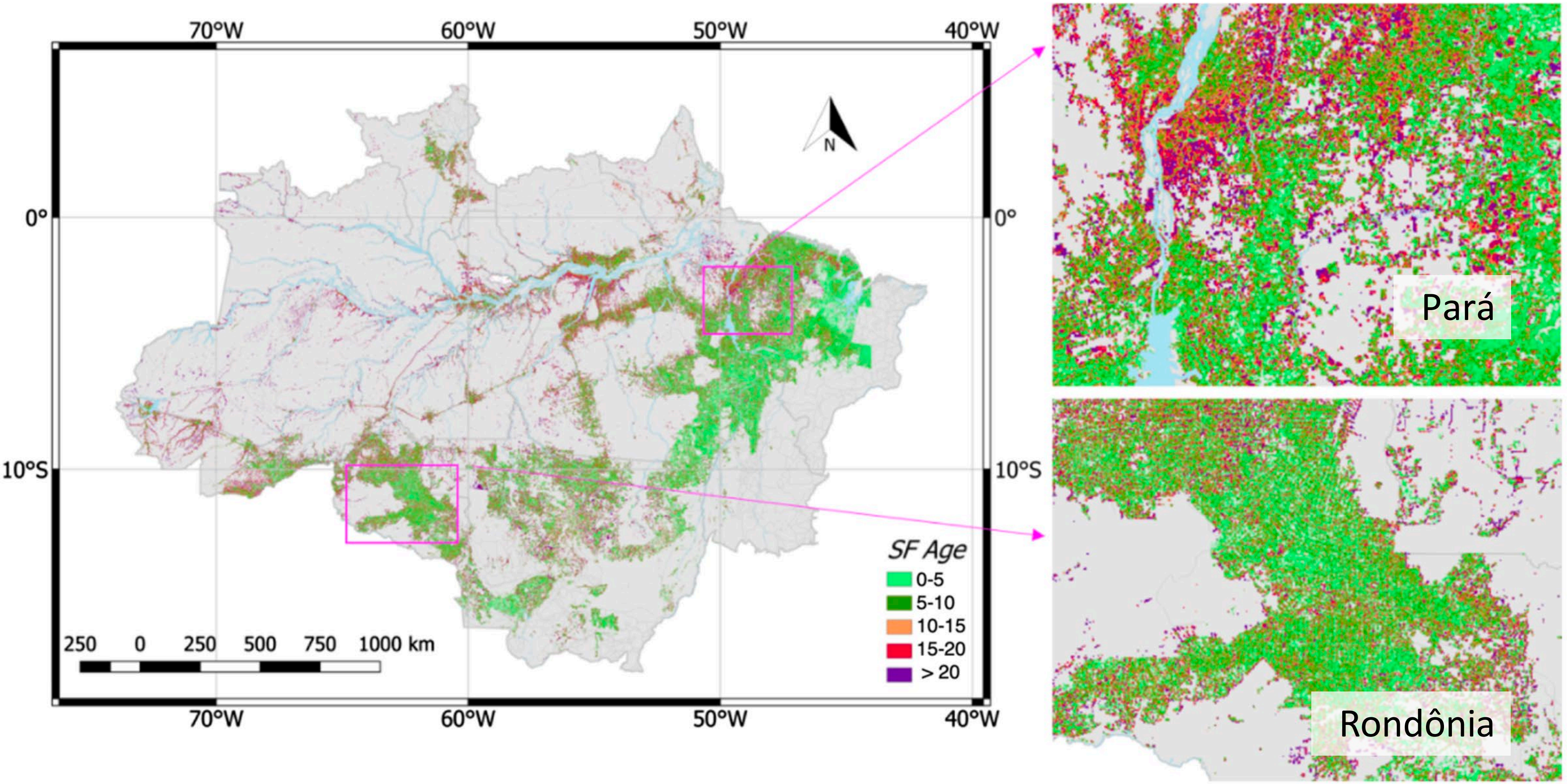
Neef et al. *Ecosystems* 2006

- Secondary-forest dynamics in Brazilian Amazonia were modeled for the 1978–2002 period to determine area and age
- Over the period 1978–2002, secondary-forest area was shown to have increased from 29,000 to 161,000 km^2 (that is, by a factor of 5)
- The mean age increased from 4.4 to 4.8 years (in other words age was nearly constant!).

Secondary forest continues to occupy a relatively small area and remains young in 2014



- Secondary forest area in the Brazilian Amazon increased from approximately 220,000 km^2 in 2004 to 280,000 km^2 in 2014
- Average age of SF remained less than 10 years (age ~8.2 with one standard deviation of 3.2 spatially

Yang et al. *Global Change Biology, 2020*

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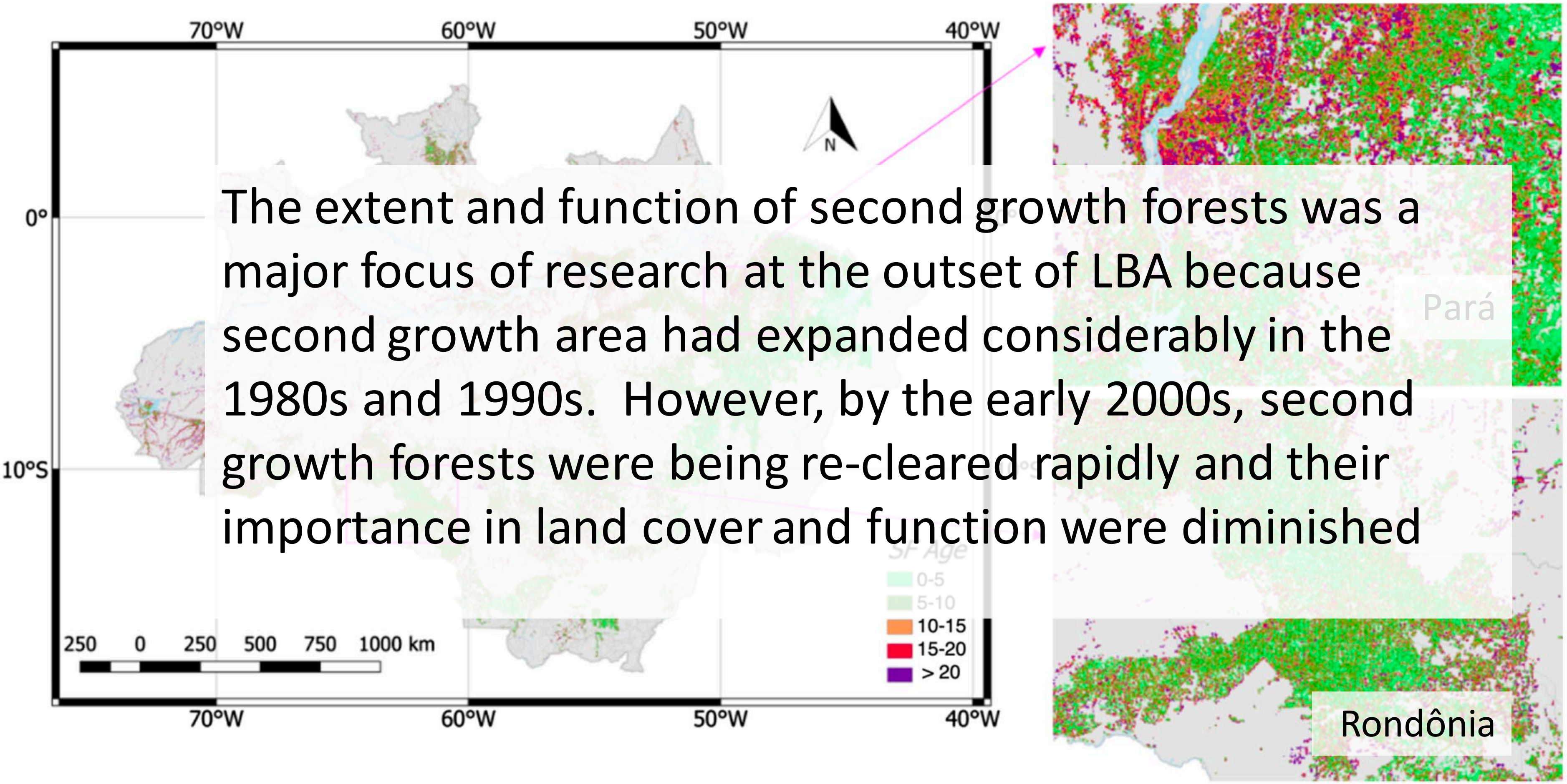
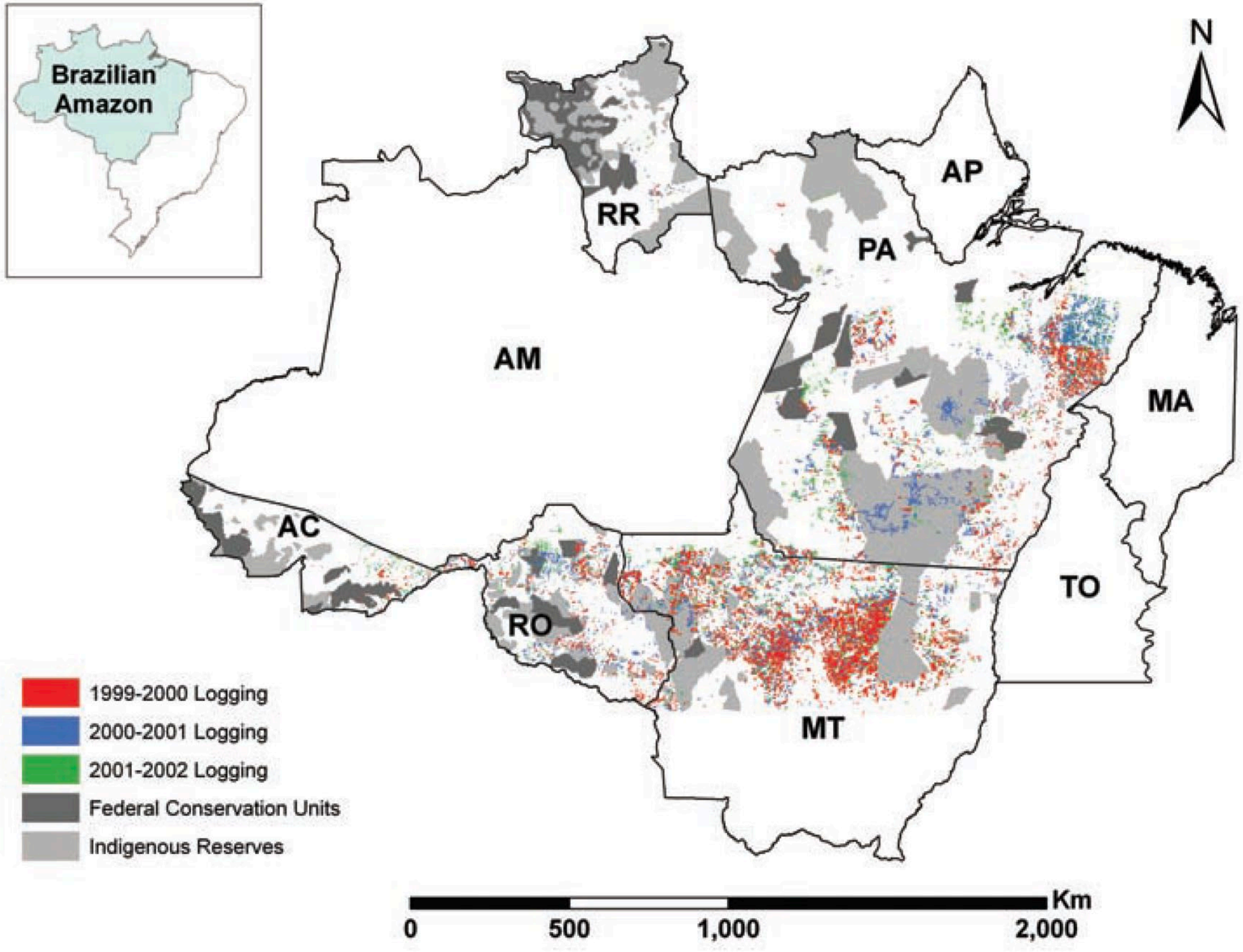


The extent and function of second growth forests was a major focus of research at the outset of LBA because second growth area had expanded considerably in the 1980s and 1990s. However, by the early 2000s, second growth forests were being re-cleared rapidly and their importance in land cover and function were diminished

- Secondary forest area in the Brazilian Amazon increased from approximately 220,000 km^2 in 2004 to 280,000 km^2 in 2014
- Average age of SF remained less than 10 years (age ~8.2 with one standard deviation of 3.2 spatially

Yang et al. *Global Change Biology, 2020*

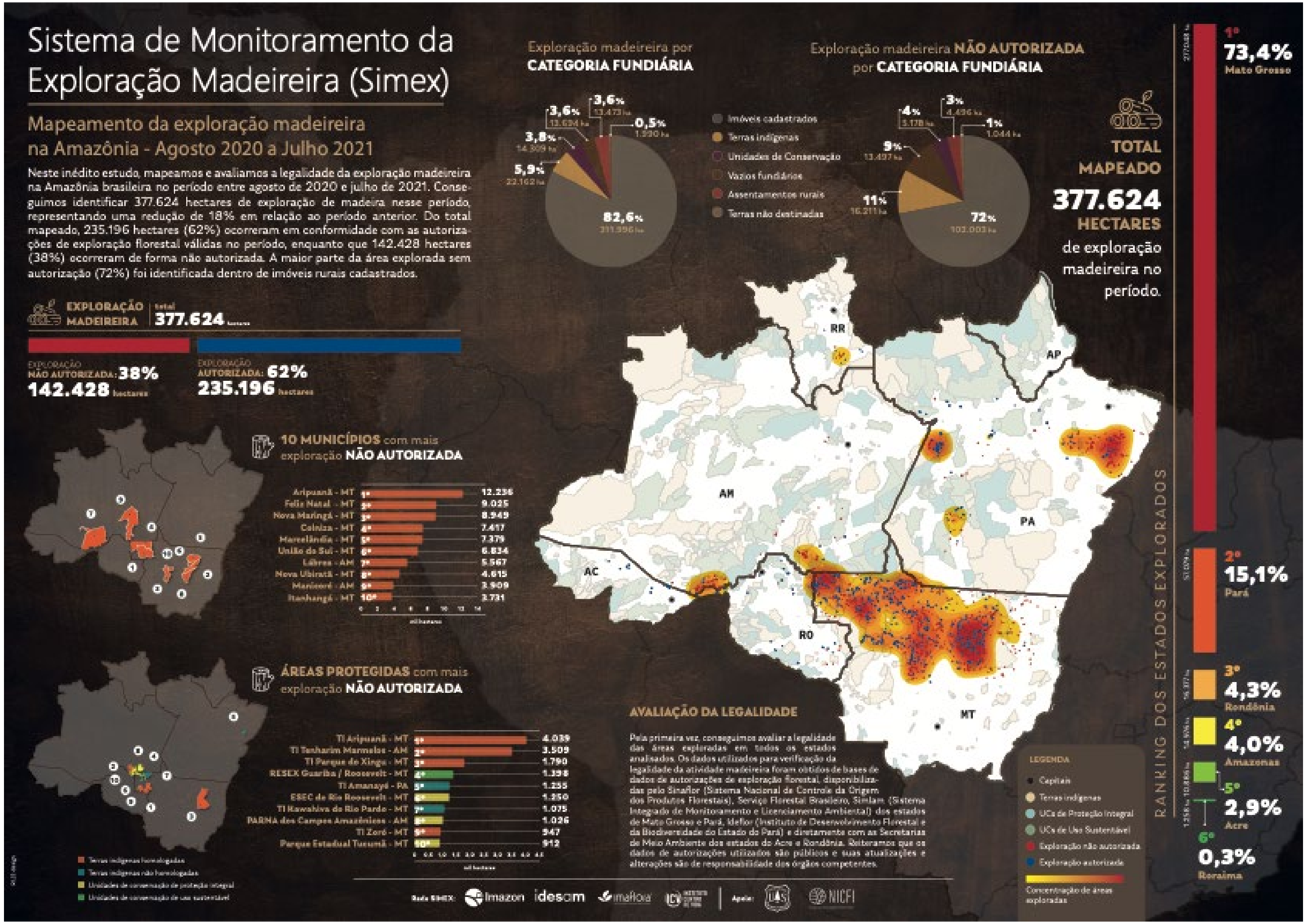
Q3: What is the area of forest that is affected by selective logging each year? How does the intensity of selective logging influence forest ecosystem function, thus altering forest regrowth and flammability?



- Logged areas ranged from 12,075 to 19,823 square kilometers per year (±14%) between 1999 and 2002, equivalent to 60 to 123% of INPE reported deforestation area.

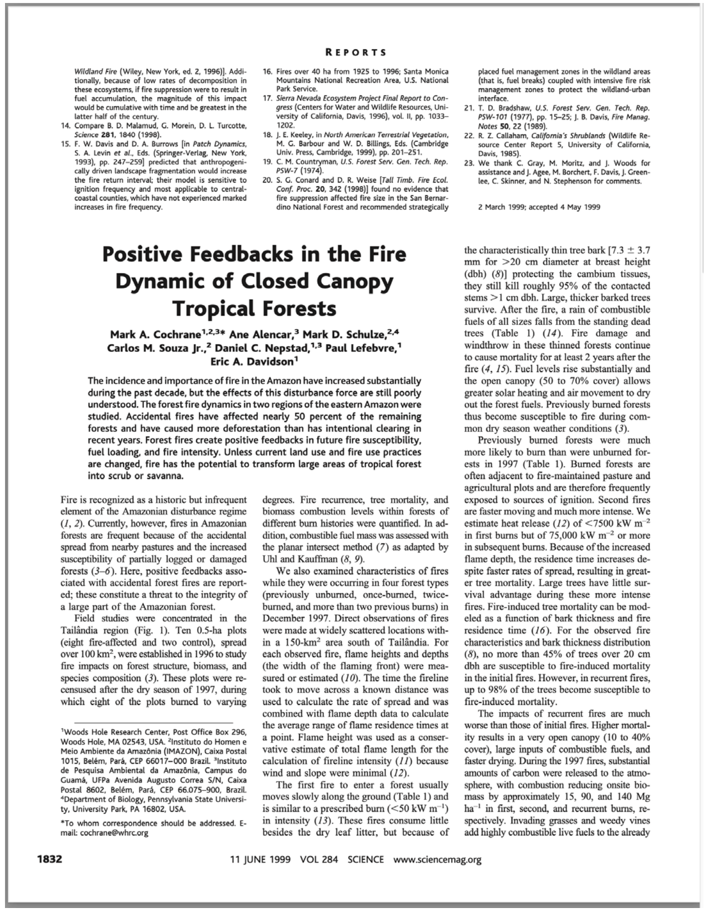
Asner et al. *Science* 2005

SIMEX Brazilian Amazon Logging Monitoring (IMAZON)



- Logging from August 2020 through July 2021 covered 3,774 km^2
- 38% of the logged area had no legal authorization

Q3: What is the area of forest that is affected by selective logging each year? How does the intensity of selective logging influence forest ecosystem function, thus altering forest regrowth and flammability?



Wildland Fire (Wiley, New York, ed. 2, 1996)]. Additionally, because of low rates of decomposition in these ecosystems, if fire suppression were to result in fuel accumulation, the magnitude of this impact would be cumulative with time and be greatest in the latter half of the century.
14. Compare B. D. Malamud, G. Morein, D. L. Turcotte, *Science* **281**, 1840 (1998).
15. F. W. Davis and D. A. Burrows [in *Patch Dynamics*, S. A. Levin *et al.*, Eds. (Springer-Verlag, New York, 1993), pp. 247–259] predicted that anthropogenically driven landscape fragmentation would increase the fire return interval; their model is sensitive to ignition frequency and most applicable to central-coastal counties, which have not experienced marked increases in fire frequency.
16. Fires over 40 ha from 1925 to 1996; Santa Monica Mountains National Recreation Area, U.S. National Park Service.
17. *Sierra Nevada Ecosystem Project Final Report to Congress* (Centers for Water and Wildlife Resources, University of California, Davis, 1996), vol. II, pp. 1033–1202.
18. J. E. Keeley, in *North American Terrestrial Vegetation*, M. G. Barbour and W. D. Billings, Eds. (Cambridge Univ. Press, Cambridge, 1999), pp. 201–251.
19. C. M. Countryman, *U.S. Forest Serv. Gen. Tech. Rep. PSW-7* (1974).
20. S. G. Conard and D. R. Weise [*Tall Timb. Fire Ecol. Conf. Proc.* **20**, 342 (1998)] found no evidence that fire suppression affected fire size in the San Bernardino National Forest and recommended strategically placed fuel management zones in the wildland areas (that is, fuel breaks) coupled with intensive fire risk management zones to protect the wildland-urban interface.
21. T. D. Bradshaw, *U.S. Forest Serv. Gen. Tech. Rep. PSW-101* (1977), pp. 15–25; J. B. Davis, *Fire Manag. Notes* **50**, 22 (1989).
22. R. Z. Callaham, *California's Shrublands* (Wildlife Resource Center Report 5, University of California, Davis, 1985).
23. We thank C. Gray, M. Moritz, and J. Woods for assistance and J. Agee, M. Borchert, F. Davis, J. Greenlee, C. Skinner, and N. Stephenson for comments.

2 March 1999; accepted 4 May 1999

Positive Feedbacks in the Fire Dynamic of Closed Canopy Tropical Forests

Mark A. Cochrane[1,2,3]* Ane Alencar,[3] Mark D. Schulze,[2,4] Carlos M. Souza Jr.,[2] Daniel C. Nepstad,[1,3] Paul Lefebvre,[1] Eric A. Davidson[1]

The incidence and importance of fire in the Amazon have increased substantially during the past decade, but the effects of this disturbance force are still poorly understood. The forest fire dynamics in two regions of the eastern Amazon were studied. Accidental fires have affected nearly 50 percent of the remaining forests and have caused more deforestation than has intentional clearing in recent years. Forest fires create positive feedbacks in future fire susceptibility, fuel loading, and fire intensity. Unless current land use and fire use practices are changed, fire has the potential to transform large areas of tropical forest into scrub or savanna.

Fire is recognized as a historic but infrequent element of the Amazonian disturbance regime (*1*, *2*). Currently, however, fires in Amazonian forests are frequent because of the accidental spread from nearby pastures and the increased susceptibility of partially logged or damaged forests (*3*–*6*). Here, positive feedbacks associated with accidental forest fires are reported; these constitute a threat to the integrity of a large part of the Amazonian forest.

Field studies were concentrated in the Tailândia region (Fig. 1). Ten 0.5-ha plots (eight fire-affected and two control), spread over 100 km^2, were established in 1996 to study fire impacts on forest structure, biomass, and species composition (*3*). These plots were recensused after the dry season of 1997, during which eight of the plots burned to varying degrees. Fire recurrence, tree mortality, and biomass combustion levels within forests of different burn histories were quantified. In addition, combustible fuel mass was assessed with the planar intersect method (*7*) as adapted by Uhl and Kauffman (*8*, *9*).

We also examined characteristics of fires while they were occurring in four forest types (previously unburned, once-burned, twice-burned, and more than two previous burns) in December 1997. Direct observations of fires were made at widely scattered locations within a 150-km^2 area south of Tailândia. For each observed fire, flame heights and depths (the width of the flaming front) were measured or estimated (*10*). The time the fireline took to move across a known distance was used to calculate the rate of spread and was combined with flame depth data to calculate the average range of flame residence times at a point. Flame height was used as a conservative estimate of total flame length for the calculation of fireline intensity (*11*) because wind and slope were minimal (*12*).

The first fire to enter a forest usually moves slowly along the ground (Table 1) and is similar to a prescribed burn (<50 kW m^{-1}) in intensity (*13*). These fires consume little besides the dry leaf litter, but because of the characteristically thin tree bark [7.3 ± 3.7 mm for >20 cm diameter at breast height (dbh) (*8*)] protecting the cambium tissues, they still kill roughly 95% of the contacted stems >1 cm dbh. Large, thicker barked trees survive. After the fire, a rain of combustible fuels of all sizes falls from the standing dead trees (Table 1) (*14*). Fire damage and windthrow in these thinned forests continue to cause mortality for at least 2 years after the fire (*4*, *15*). Fuel levels rise substantially and the open canopy (50 to 70% cover) allows greater solar heating and air movement to dry out the forest fuels. Previously burned forests thus become susceptible to fire during common dry season weather conditions (*3*).

Previously burned forests were much more likely to burn than were unburned forests in 1997 (Table 1). Burned forests are often adjacent to fire-maintained pasture and agricultural plots and are therefore frequently exposed to sources of ignition. Second fires are faster moving and much more intense. We estimate heat release (*12*) of <7500 kW m^{-2} in first burns but of 75,000 kW m^{-2} or more in subsequent burns. Because of the increased flame depth, the residence time increases despite faster rates of spread, resulting in greater tree mortality. Large trees have little survival advantage during these more intense fires. Fire-induced tree mortality can be modeled as a function of bark thickness and fire residence time (*16*). For the observed fire characteristics and bark thickness distribution (*8*), no more than 45% of trees over 20 cm dbh are susceptible to fire-induced mortality in the initial fires. However, in recurrent fires, up to 98% of the trees become susceptible to fire-induced mortality.

The impacts of recurrent fires are much worse than those of initial fires. Higher mortality results in a very open canopy (10 to 40% cover), large inputs of combustible fuels, and faster drying. During the 1997 fires, substantial amounts of carbon were released to the atmosphere, with combustion reducing onsite biomass by approximately 15, 90, and 140 Mg ha^{-1} in first, second, and recurrent burns, respectively. Invading grasses and weedy vines add highly combustible live fuels to the already

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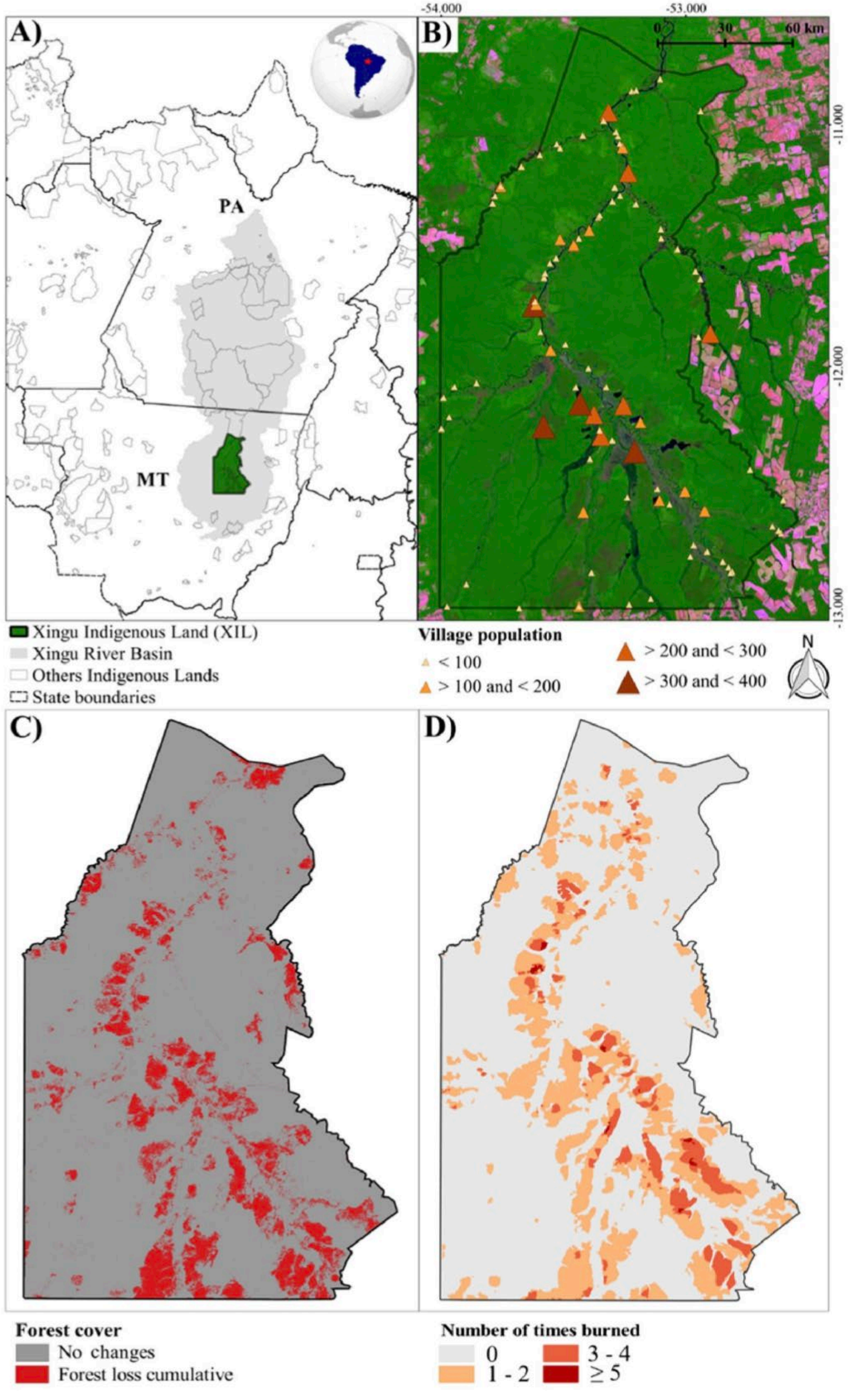
Cochrane et al. *Science 1999*

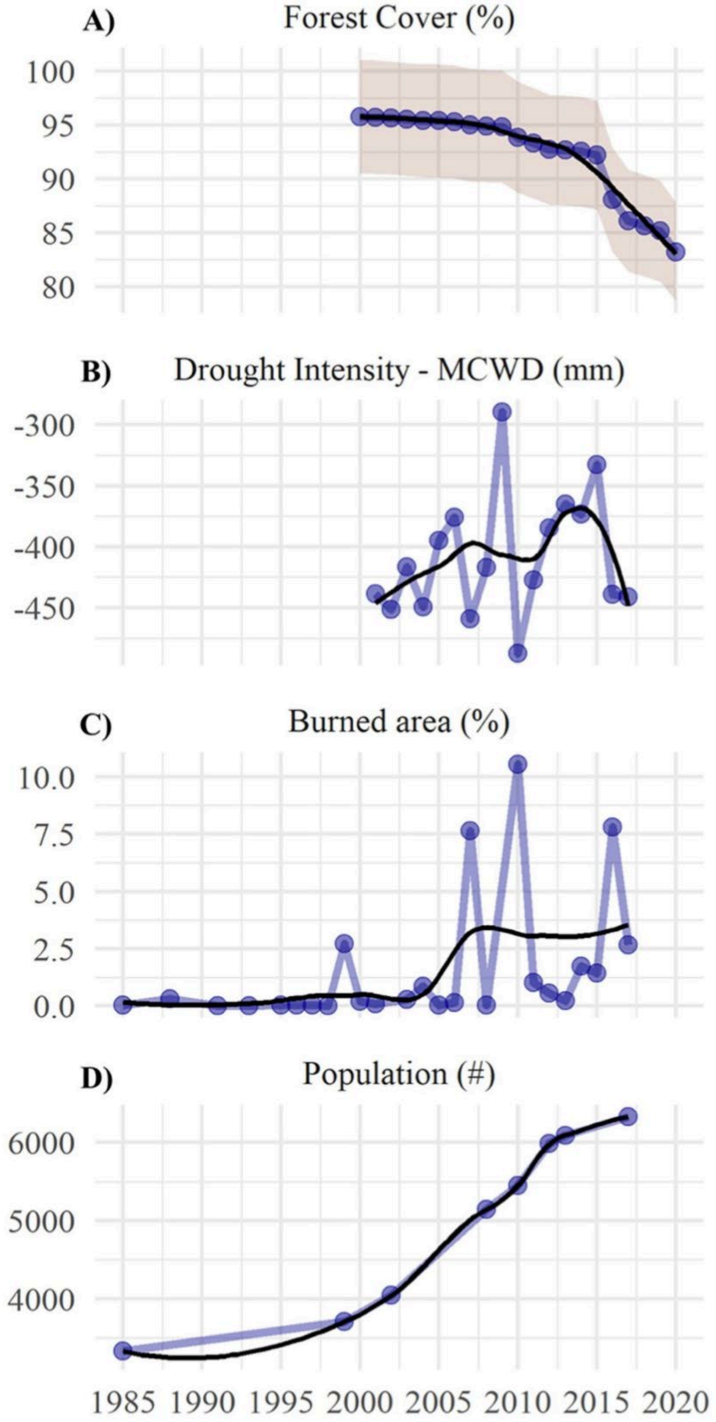
- Why was fire de-emphasized at the beginning of LBA?
  - In the 1990s while we were planning LBA, the consensus was that Amazon forests only became flammable when they were disturbed. This is reflected on the LBA-ECO question.
  - As LBA progressed, we increasingly studied fire and considered it perhaps the most important threat to the integrity of the Amazon forests.



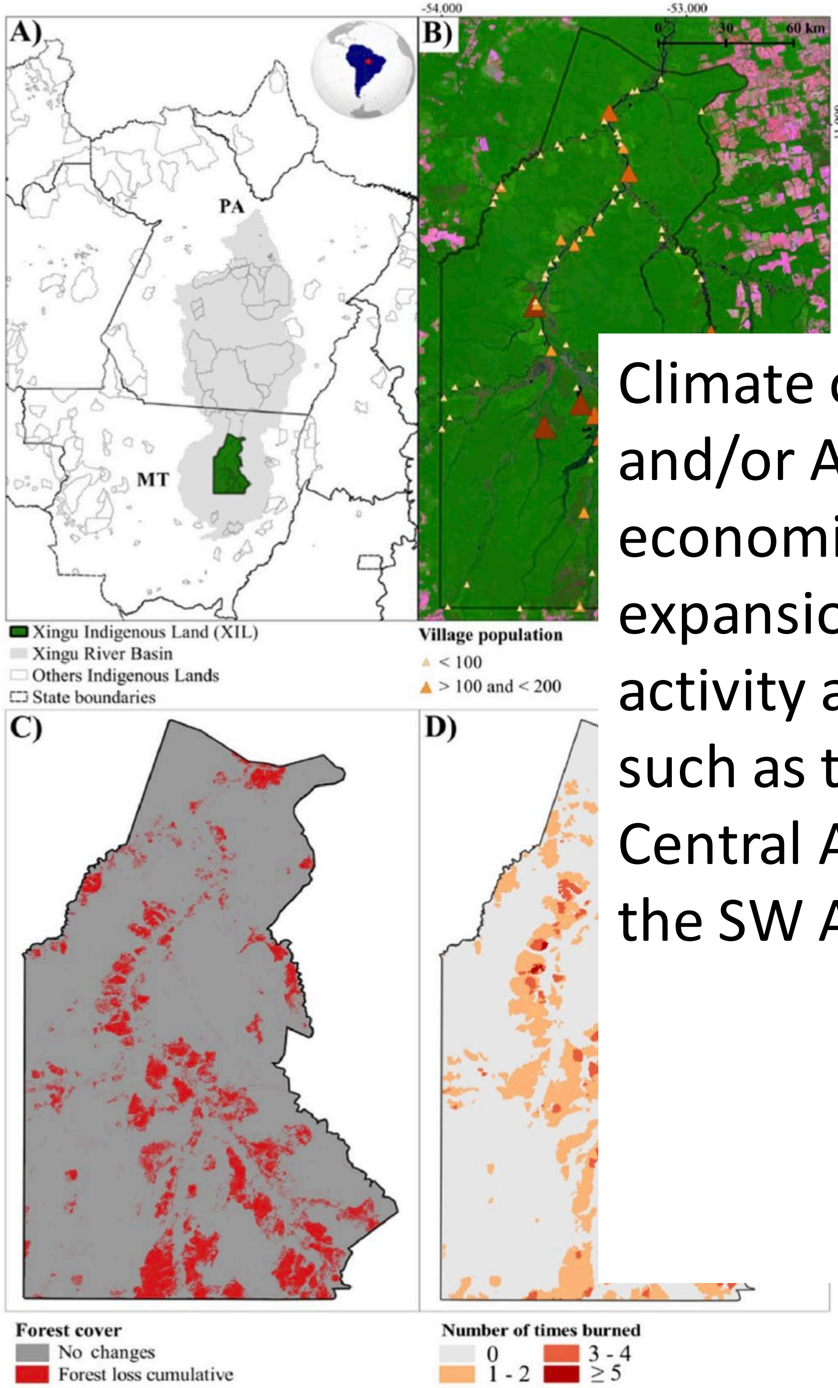
The Amazon has changed

"In one of the most culturally diverse Indigenous lands of the Amazon, in a landscape highly threatened by deforestation, our findings demonstrate that climate change may have already exceeded the conditions to which the system has adapted."

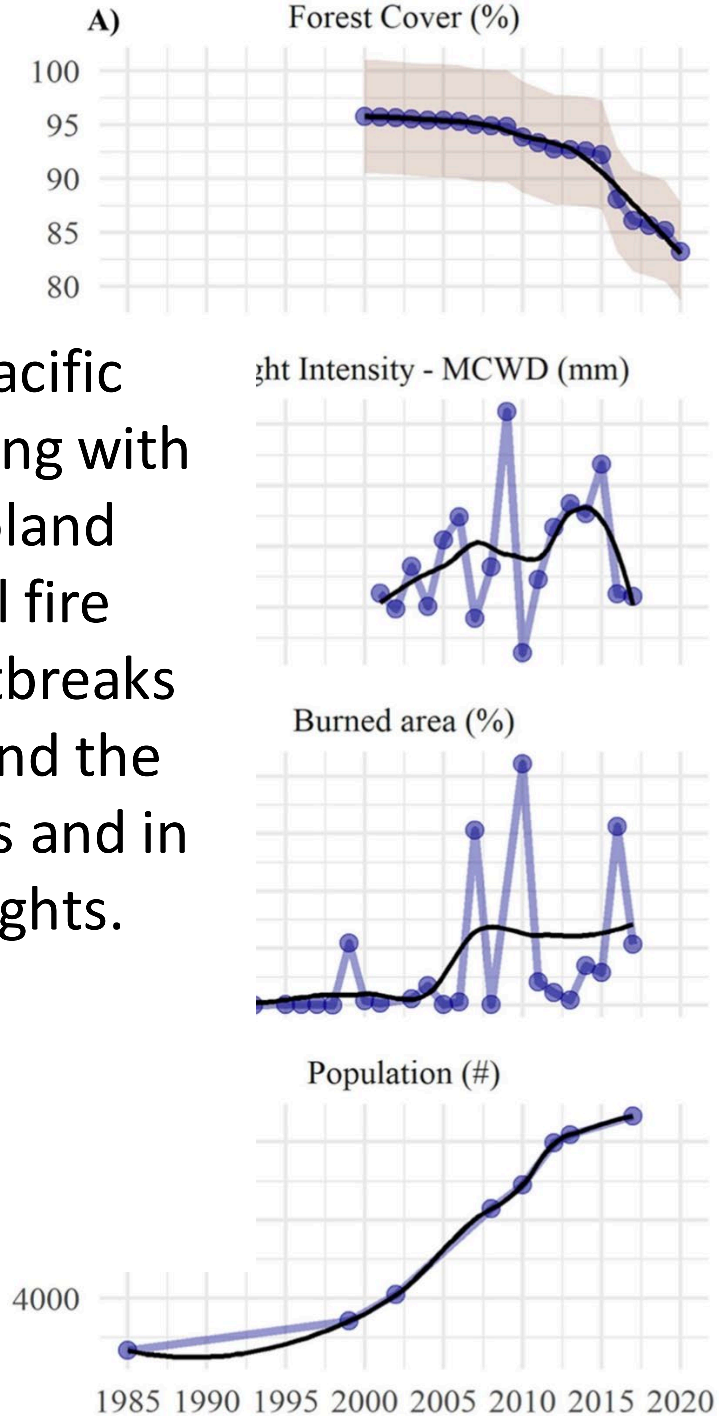
Silverio et al. *ERL* 2022



The Amazon has changed

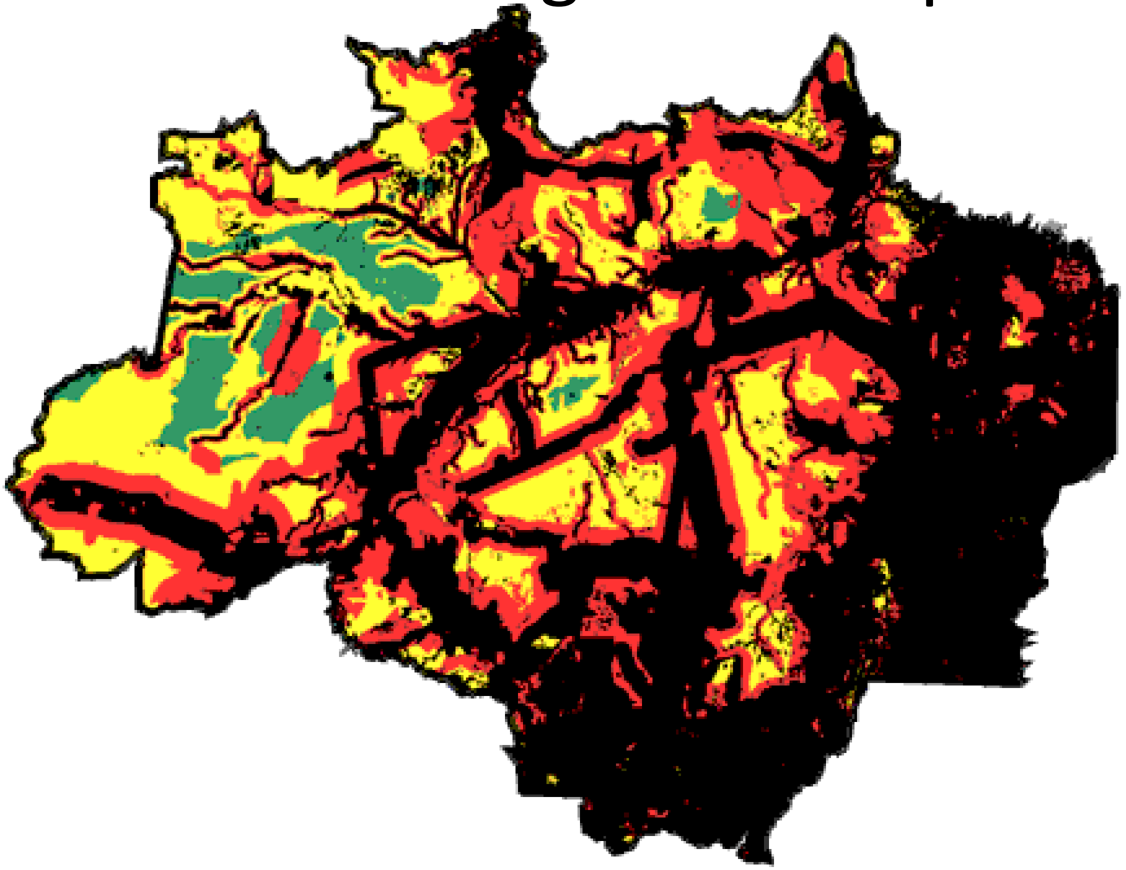


Climate oscillations marked by changes in Pacific and/or Atlantic sea surface temperature along with economic changes such as pasture and cropland expansion have a marked effect on seasonal fire activity and can lead to catastrophic fire outbreaks such as the forest fires in Roraima in 1999 and the Central Amazon (2015-2016) during El Niños and in the SW Amazon during 2005 and 2010 droughts.



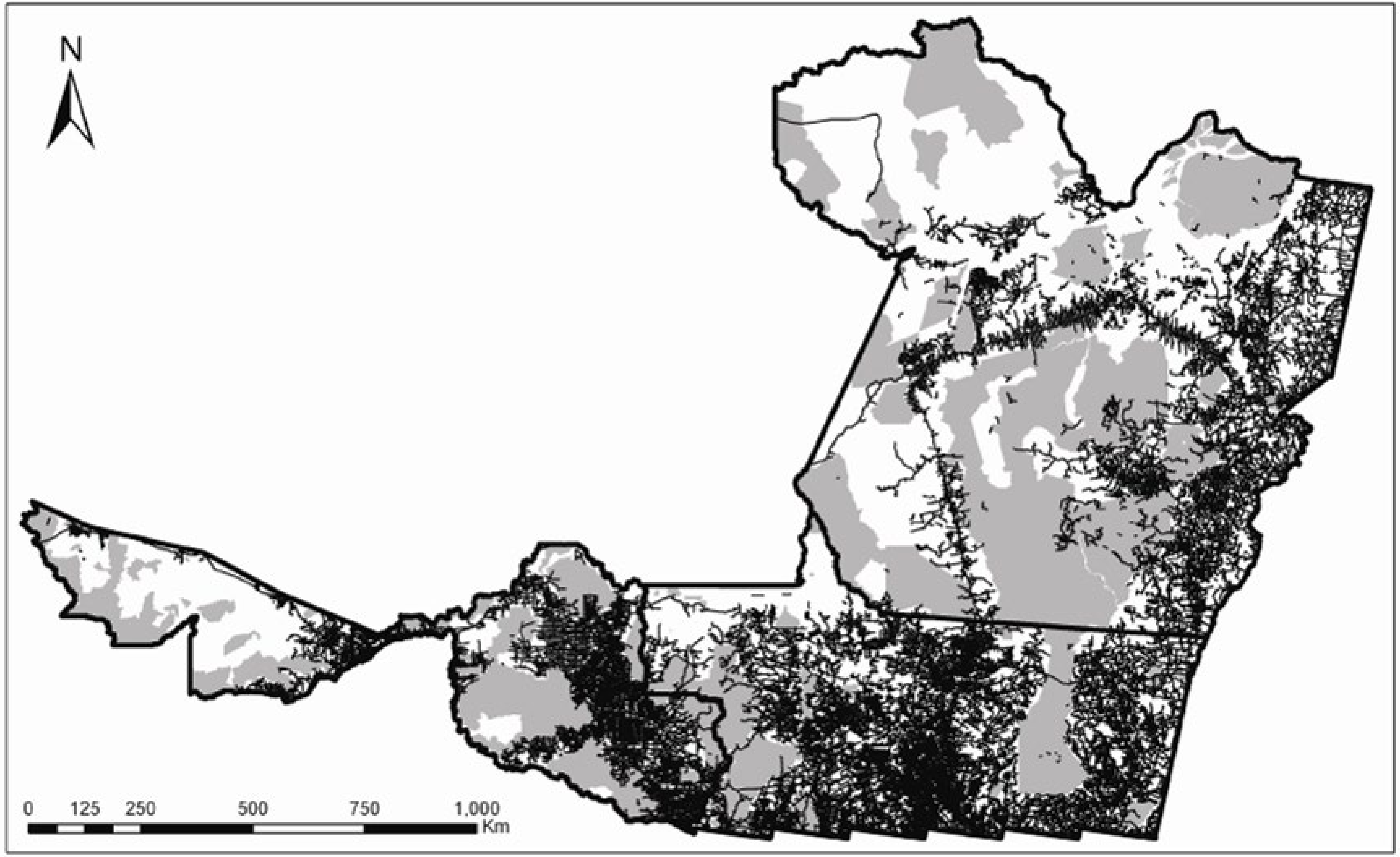
Q4: What are plausible scenarios for future land-cover change in Amazonia?

What is wrong with this picture?



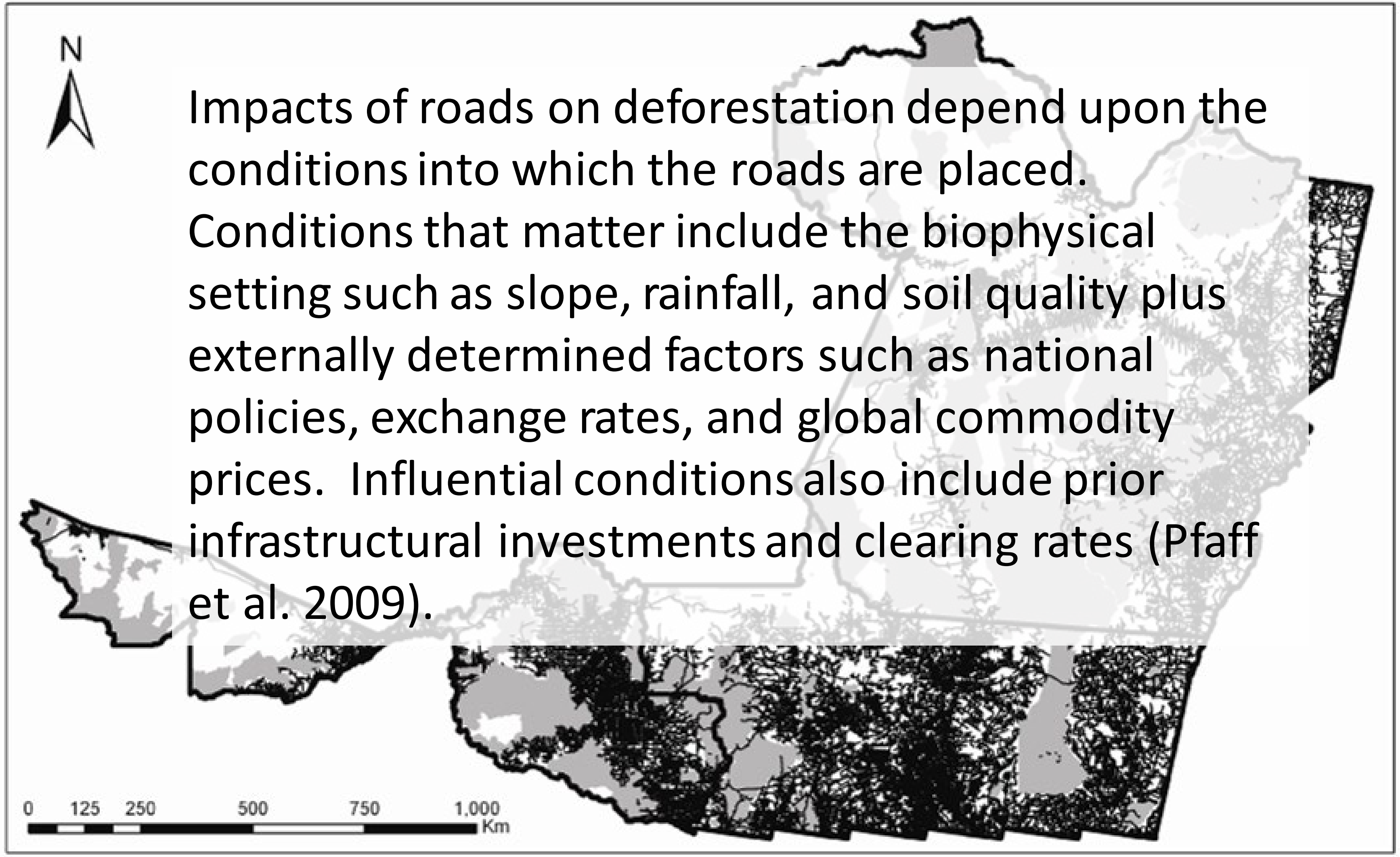
Prediction for 2020 by Laurance et al. 2001

Road Network



Data from IMAZON Circa 2015

Road Network



Impacts of roads on deforestation depend upon the conditions into which the roads are placed. Conditions that matter include the biophysical setting such as slope, rainfall, and soil quality plus externally determined factors such as national policies, exchange rates, and global commodity prices. Influential conditions also include prior infrastructural investments and clearing rates (Pfaff et al. 2009).

Data from IMAZON Circa 2015

Public policies can reduce tropical deforestation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Public policies can reduce tropical deforestation: Lessons and challenges from Brazil

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ABSTRACT

Reducing carbon emissions from deforestation and forest degradation now constitutes an important strategy for mitigating climate change, particularly in developing countries with large forests. Given growing concerns about global climate change, it is all the more important to identify cases in which economic growth has not sparked excessive forest clearance. We address the recent reduction of deforestation rates in the Brazilian Amazon by conducting a statistical analysis to ascertain if different levels of environmental enforcement between two groups of municipalities had any impact on this reduction. Our analysis shows that these targeted, heightened enforcement efforts avoided as much as 10,653 km^2 of deforestation, which translates into 1.44×10^{-1} Pg C in avoided emissions for the 3 y period. Moreover, most of the carbon loss and land conversion would have occurred at the expense of closed moist forests. Although such results are encouraging, we caution that significant challenges remain for Brazil's continued success in this regard, given recent changes in the forestry code, ongoing massive investments in hydro power generation, reductions of established protected areas, and growing demand for agricultural products.

Introduction

Although tropical deforestation and degradation have long been a concern of the academic community and the general public for a wide variety of reasons, attention has begun to focus increasingly on carbon emissions because of their contribution to global warming (Myers et al., 2000; Wright, 2005). Land use changes for 2000–2007, primarily tropical deforestation, account for an estimated 1.10 ± 0.70 Pg C y^{-1}, or 14–20% of global greenhouse gas emissions (Pan et al., 2011), and will probably remain substantial in coming decades (Sitch et al., 2005). As a consequence, the United Nations has spear-headed an initiative to reduce emissions from deforestation and forest degradation (REDD), and numerous efforts are underway worldwide to achieve such forest-based reductions. Countries like Norway have donated millions of dollars to support REDD+ forest conservation projects, which altogether now account for 9% of voluntary carbon offsets (BNDES, 2013; Peters-Stanley and Hamilton, 2012).

Given growing investment in REDD/REDD+ activities, and their importance to climate change mitigation, it is important to identify situations where REDD-oriented policies appear to be successful but not at the expense of human welfare. That said, developing sustainable relationships between natural and human systems are not easily achieved, and successful cases are few and far between (Nunes et al., 2012). Brazil, which made deforestation reduction a central piece of its climate change policy in 2009 (Brasil, 2009), appears to present one such success story. Thus, the article's objective is to examine the impact of recent environmental policy applications in Brazil, in the interest of finding a pathway to sustainable development for countries with large extents of native vegetation.

The article pursues its objective as follows. First, it considers deforestation rates in the Brazilian Amazon over the past several decades, and addresses the relationship between agricultural expansion in the basin and changes in forest area. Second, it gives an overview of environmental policy directed at Brazil's northern region, particularly its Amazonian Biome, the closed moist forest ecosystem that once covered ~4,000,000 km^2. Next, the article presents statistical analyses that reveal the extent to which

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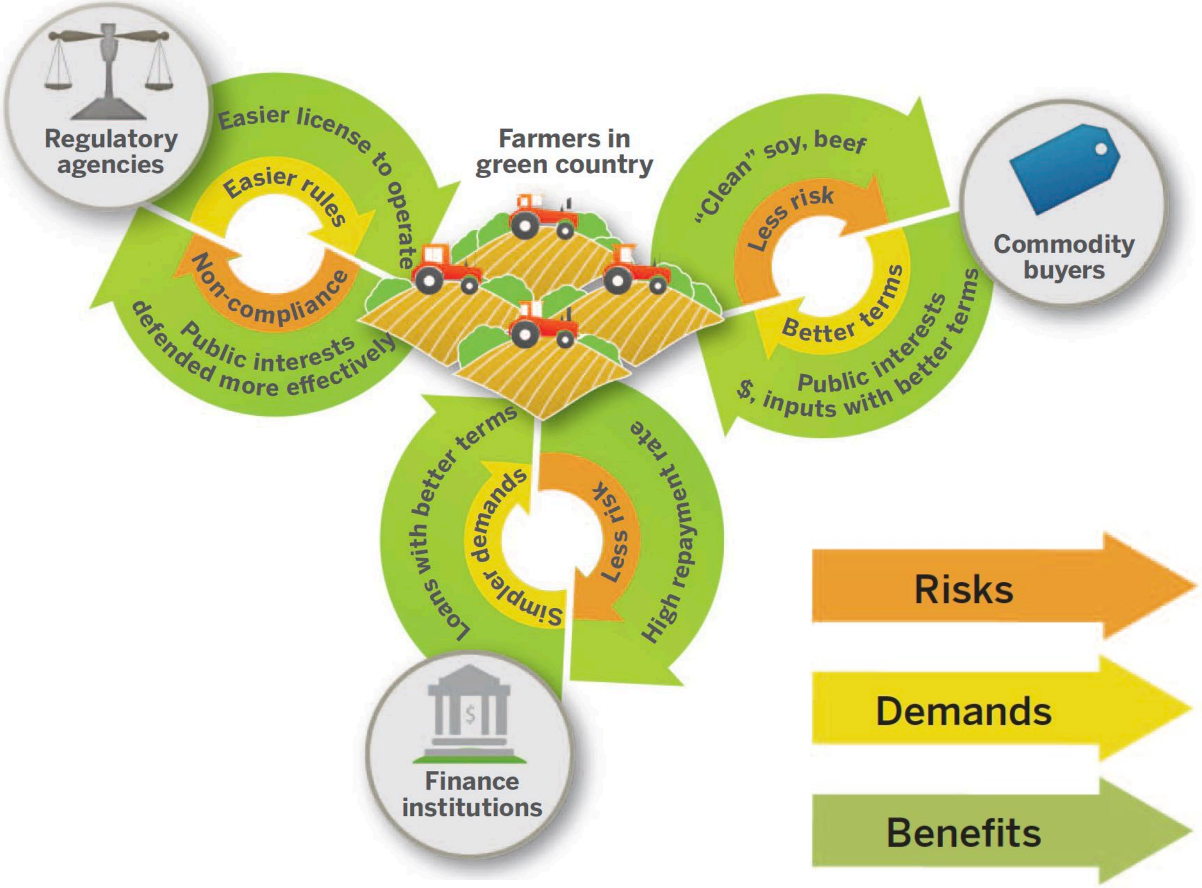
Arima et al. *Land Use Policy* 2014



Nepstad et al. *Science* 2014

We have a more complex appreciation of Amazonian land cover and land use change …

- Neoliberal reforms in the Brazilian macro-economy transformed the land change regime affecting the Amazonian Forest. Specifically, in the late 1990s, engagement in global markets replaced rent capture from infrastructure investments as the primary driver of deforestation. Walker et al., *Geoforum* 2009.
- Agriculture and cattle ranching in Amazonia were not adventures dependent on subsidies, but expansions of land use driven by market incentives. Commercial agriculture and cattle ranching in the Amazon can be *profitable*.
- Impacts of roads on deforestation depend upon the conditions into which the roads are placed. Conditions that matter include the biophysical setting such as slope, rainfall, and soil quality plus externally determined factors such as national policies, exchange rates, and global commodity prices. Influential conditions also include prior infrastructural investments and clearing rates (Pfaff et al. 2009).

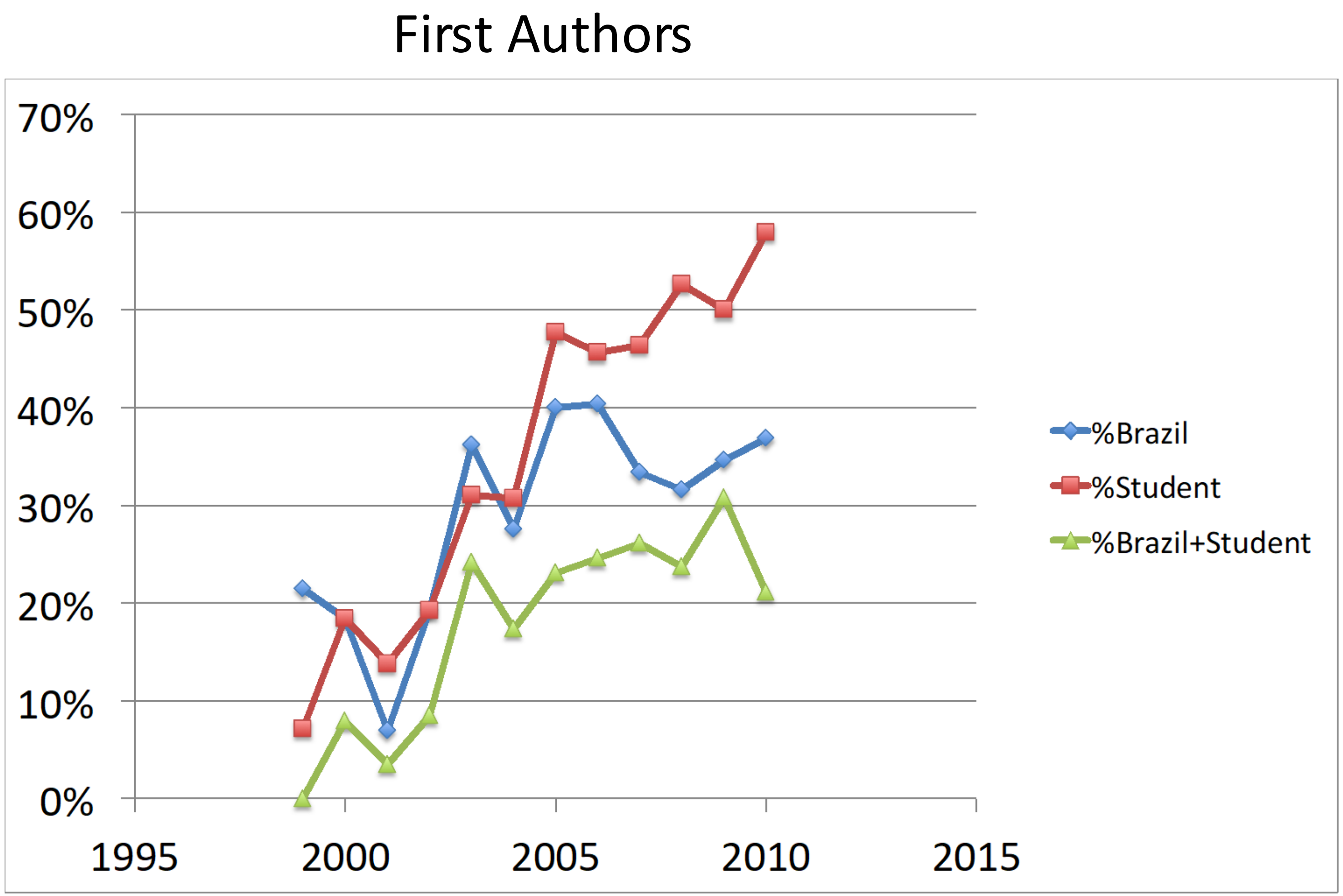
We have a more complex appreciation of Amazonian land cover and land use change …

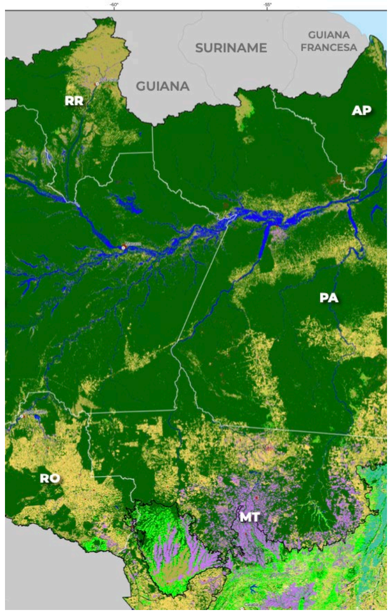
- Profit is not everything. Amazonian deforestation by small holders in colonization frontiers is associated with family size, life history, and market access.
- Climate oscillations marked by changes in Pacific and/or Atlantic sea surface temperature along with economic changes such as pasture and cropland expansion have a marked effect on seasonal fire activity and can lead to catastrophic fire outbreaks such forest fires in Roraima and the Central Amazon during 1997-1998 and 2015-2016 El Niños and in the SW Amazon during 2005 and 2010 droughts).
- Public policies can have profound effects on deforestation.

LBA's Legacy

- Full USA-Brazilian partnership
- True collaboration at PI, institutional and inter-governmental levels
- Emphasis on training and education
- Example for other regional Earth system science programs

667 LBA-ECO publications 1998-2013





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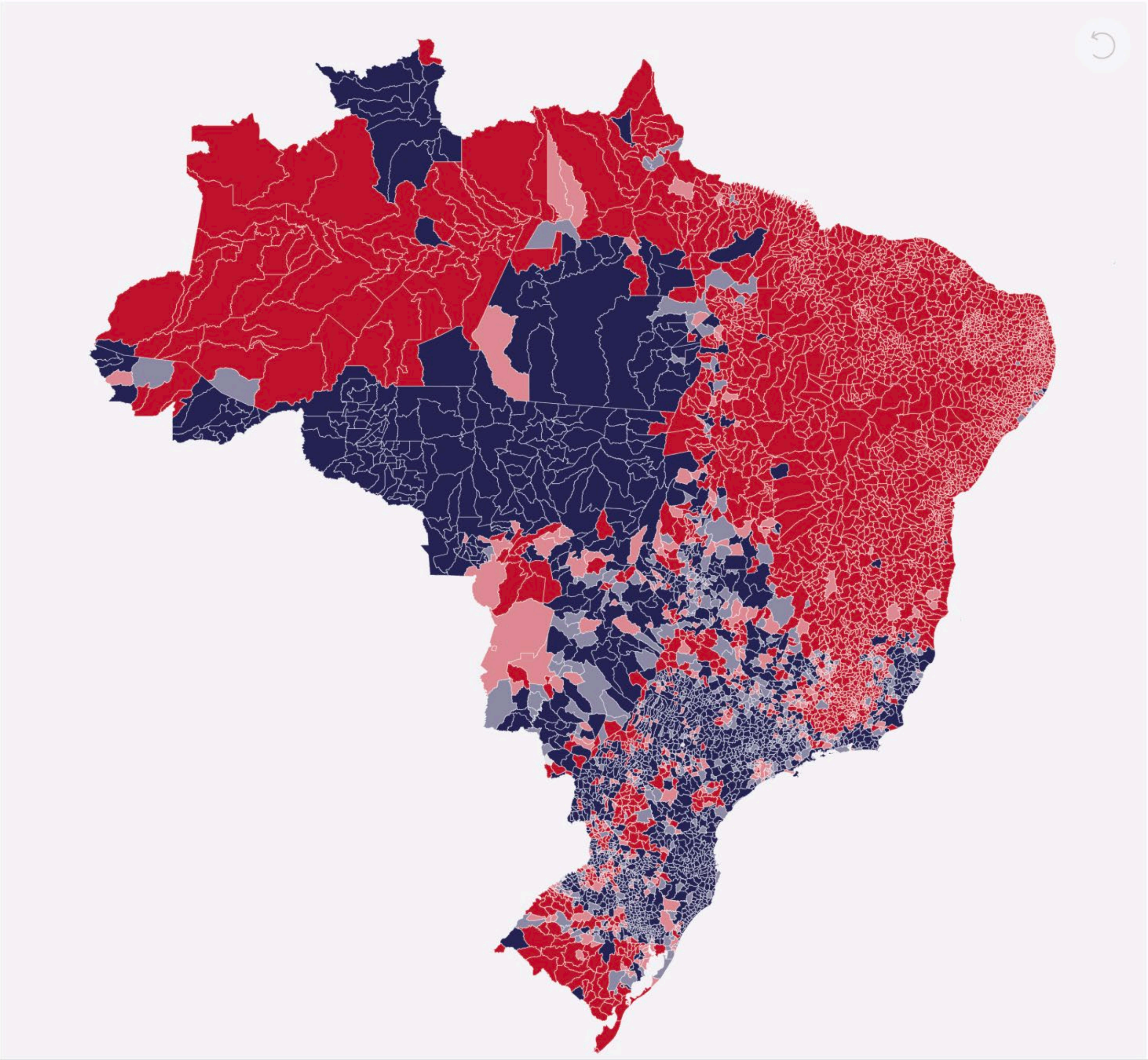
Marcio Henrique Sa

Human Capital
One LBA LCLUC Legacy: MapBiomas

Elections have consequences

- https://especiaisg1.globo/politica/eleicoes/2022/mapas/mapa-da-apuracao-no-brasil-presidente/1-turno/

Results of the first round, October 2, 2022



The fate of the Amazon forest hangs on Brazil's choice?