

# Transition from forest to agriculture in the Brazilian Amazon from 1985 to 2021

Hugo Tameirão Seixas<sup>1, 2</sup>, Hilton Luis Ferraz da Silveira<sup>2</sup>, Alan Falcão<sup>2</sup>, Fabiana Da Silva Soares<sup>2</sup>, and Ramon Bicudo<sup>1</sup>

<sup>1</sup>Center for Environmental Studies and Research, University of Campinas, Rua dos Flamboyants 155, Brazil

<sup>2</sup>Embrapa Territorial, Av. Soldado Passarinho 303, Brazil

**Correspondence:** Hugo Tameirão Seixas (seixas.hugo@protonmail.com)

**Abstract.** Land use and land cover changes in the Amazon biome are a main process that influences many aspects at local, national, and global levels. A large quantity of studies already relied on land use classification to analyse this process, drivers and impacts. A new dataset was created by calculating the time necessary for deforested forests to transition to agriculture in the Brazilian Amazon biome. The new data can be useful in interdisciplinary studies about land cover and land use change in Brazil, its drivers and implications. A main innovation is that the dataset links the deforestation year with the year of agriculture establishment, which can provide new information about this process.

. The author's copyright for this publication is transferred to institution/company.

## 1 Introduction

Brazil policies since the 1960s were focused on the expansion of the frontier in the Amazon, specially focused in economic income and land security (Carvalho et al., 2002; McDonald, 2003; Banerjee et al., 2009). Such development model led to the construction of thousands of kilometers of roads, and the settlement of large scale livestock farms (Carvalho et al., 2002; Banerjee et al., 2009). This period was marked with high rates of deforestation of mature forests (Fearnside, 2005). At the same time, cattle and soybean productions started to move to the north direction in the Brazilian territory, in which soybeans cultivation areas followed cattle ranches expansion over the Amazon forest (Simon and Garagorry, 2005; ?; Arima et al., 2011). This pattern of extensive livestock occupation after deforestation, followed by the establishment of annual crops is very characteristic in the Amazon biome, and persists nowadays. This process can take several decades to be accomplished, or even less than one year, in which it may be considered as a direct transition from forest to agriculture.

Land cover transitions are known to cause impacts on different scales. Deforestation and land use changes can affect hydrological processes in large basins (Arias et al., 2018); reduce the forest resilience to extreme events and other sources of perturbation (Boulton et al., 2022); deforestation and farming practices can reduce convective rainfall and increase surface temperature (Maeda et al., 2021); increase carbon emissions (Gatti et al., 2021); cause important impacts on fauna and flora

diversity, soil properties and carbon stocks (Nunes et al., 2022); and even negatively impact public health (Ellwanger et al., 2020).

Data on land use and land cover (LULC) classification are evolving rapidly in the last decade. Initiatives such as MapBiomass (Souza et al., 2020), launched in 2015, which provides high resolution, annual classifications for the Brazilian territory. Such type of data are essential to analyse LULC change processes, make causal inferences, and understand what drives and what are the impacts of the transformation of the landscape in Brazil. In this context, this project aims to characterize and quantify the length of the transitions from forest formations to agriculture in the Amazon. The availability of this data can be useful to the development of interdisciplinary research involved with LULC changes.

## **2 Methods**

### **2.1 Transition length calculation**

The estimations of transition from forest to agriculture were performed for the Amazon biome region, as defined by the Brazilian Institute of Geography and Statistics (IBGE), in 2019. Transitions were calculated using land use and land cover classification data from MapBiomass, collection 7, which ranges from 1985 to 2021, at a spatial resolution of approximately 30 meters.

The MapBiomass data was downloaded from Google Earth Engine platform (Gorelick et al., 2017). The pixels of the Amazon biome were filtered to contain only those that were occupied by forest and agriculture at some period, and that are not considered as water, according to the Global Surface Water product provided by Copernicus (Pekel et al., 2016). For the download, the data was divided in tiles, to allow local processing of a large quantity of pixels. Two sets of data were downloaded with the same spatial dimensions, one with the LULC classifications for each year, and another with binary values, representing whether that pixels was valid for processing or not.

The first part of the processing was to create a table from the binary values data, and create unique identification for each pixel, their coordinates, calculate the area, and also address the municipality in which each pixel was inside. In this part, a table was also generated with the spatial information of each tile, so that it is possible to convert the generated tables back to raster format.

The second part of the processing was to load each tile separately, convert it to a table and calculate every possible transition from forest to agriculture. The transitions were calculated pixel by pixel, by performing the following steps:

1. Load raster and extract valid values into a table;
2. Calculate the year of first occurrence of any agriculture class for each pixel;
3. Calculate the first year of “Forest Formation” LULC class after the year calculated in step 2. This step identifies if there are more than one transition in a pixel;

4. Classify rows as “before” or “after” the occurrence of the year calculated in step 3. This is the identification of periods before and after the recurrence of forest after a first transition to agriculture;
5. Calculate the last year of “Forest Formation” within the rows classified as “before”, and add 1 year to represent the deforestation year;
6. Calculate the first year of any agriculture type class within the rows classified as “before”, for each pixel;
7. Calculate the difference between years from items 5 and 6 to get the LULC transition length in years, for each pixel;

The steps 2 to 7 are performed recursively to identify multiple transitions, in case they are present. In addition to the transition length values and the years of the transition, transitions are also qualified by the type of agriculture that were established after deforestation, if the transition occurred from primary or secondary forests, and the number of recurrence of transitions in a single pixel. The LULC classes within the transition and until 5 years after the transitions were also stored.

The transition results are stored in a data set of tabular files, where data can be queried for further analysis. After the calculations, data was also converted back to raster format, with the aim to expand the accessibility of the data set.

## **2.2 Accuracy assessment**

An accuracy assessment was performed by visual inspection of annual composites of Landsat images from MapBiomias. We selected 100 random points to be analysed. An area of approximately 4 squared kilometers around the sample point was used in the visual inspection of satellite images.

The visual inspection used several variables derived from the Landsat historical collection. The median of Red, Green, Blue, Near Infrared (NIR) and Short Wave Infrared (SWIR1) from dry and wet season were used, and also the annual amplitude of the Normalized Difference Vegetation Index (NDVI). The process of accuracy assessment was performed in a Shiny app, and was conducted without any consultation to the transition length results. In the validation app, we estimated, by visual inspection, the year of deforestation and the year of agriculture establishment. The observed transition length was obtained by subtracting both dates.

To evaluate the accuracy, we calculated the Mean Absolute Error (MAE), the Bias (BIAS), and the Percent Bias (PBIAS). We also analysed the results by plotting the errors as frequency bars, and scatter plots between observed and estimated values.

After the completion of the analysis of the 100 sample points, we also conducted a qualitative assessment, where we compared our results with the satellite images.

## **3 Description of data collection**

After the calculation of transitions, the results are stored in three different types of tables, organized in a folder structure and stored as Apache Parquet files.

- Tables that contains the spatial information (longitude, latitude) of each pixel, its unique id and the code of the municipality which contains the pixel. It is named as “mask\_cells”;
- Tables with transition length values, the first and last year of the transition, the resulting agriculture type, and the number of the transition cycle. They also contain the unique id of each pixel (related to the table above);
- Table with the LULC classes of all years within the transition, and also the first 5 years after the transition.

The three tables are related to each other and can be used altogether, and are separated by tiles. Another table containing the metadata of each tile is also created, and holds the spatial characteristics of the tiles. With this spatial information, it is possible to convert the tabular data back to spatial raster, with identical spatial properties as the MapBiomass classification data.

## 4 Results and discussion

The transition calculations shows that between 1985 and 2021, 64874 squared kilometers of forests were converted to agriculture, in the Brazilian Amazon biome. The length of the transitions can go from 0 to 35 years, in which transitions closer to 0 year are considered as fast transitions, and transitions closer to 35 years are considered as slow transitions. Transitions of 0 year are considered as “direct” transitions, where there were no presence of pasture before the establishment of agriculture, our estimations shows that around 9.2 % of the transitions are considered as “direct”.

Our transitions calculations found pixels that presented up to six transitions from forest to agriculture since 1985, as these numbers are unlikely to happen (they are distributed as sparse pixels, and do not show patterns of real transitions, being common at borders), we proceeded the results analysis only in the first transitions found in each pixel.

Although we named as deforestation the last years identified as forest before classification of antropic cover, we acknowledge that it is not a direct measurement of deforestation (such as PRODES), it is however a proxy to deforestation.

### 4.1 Transition patterns

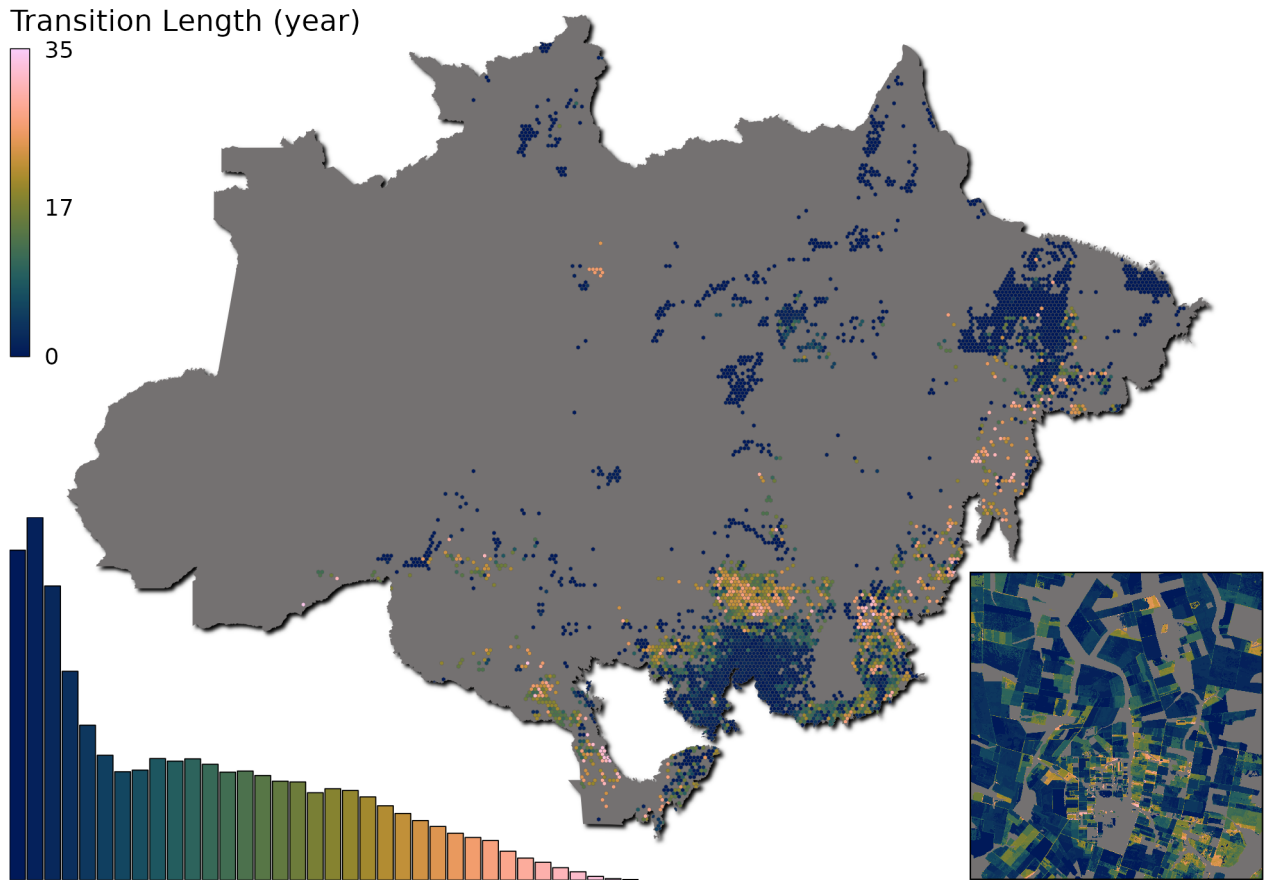
Transitions from forest to agriculture can be found in almost every region in the Amazon, but is mostly concentrated in clusters, specially in the south and east of the biome, in the states of Mato Grosso, Pará and Maranhão (Figure 1).

Well defined clusters can be observed in the map created with aggregated transition length data (Figure 1), slow transition areas tend to concentrate in specific regions in the Amazon biome, while fast transitions seem to have a wider distributions, but also tend to form clusters. However, this pattern does not hold completely when observing the data at its original scale (Figure 1), where areas with different transition lengths are mixed between each other. When observing at the original scale, we could not spot any well defined pattern or direction of the occurrence of faster to slower transitions (Figure 1).

Other studies investigating patterns of transitions in the Amazon also found the formation of clusters of patterns, although there is a big heterogeneity at larger scales (Müller-Hansen et al., 2017).

The data can be analysed year by year, and also be separated by primary and secondary forests being converted to agriculture (Figure 2).

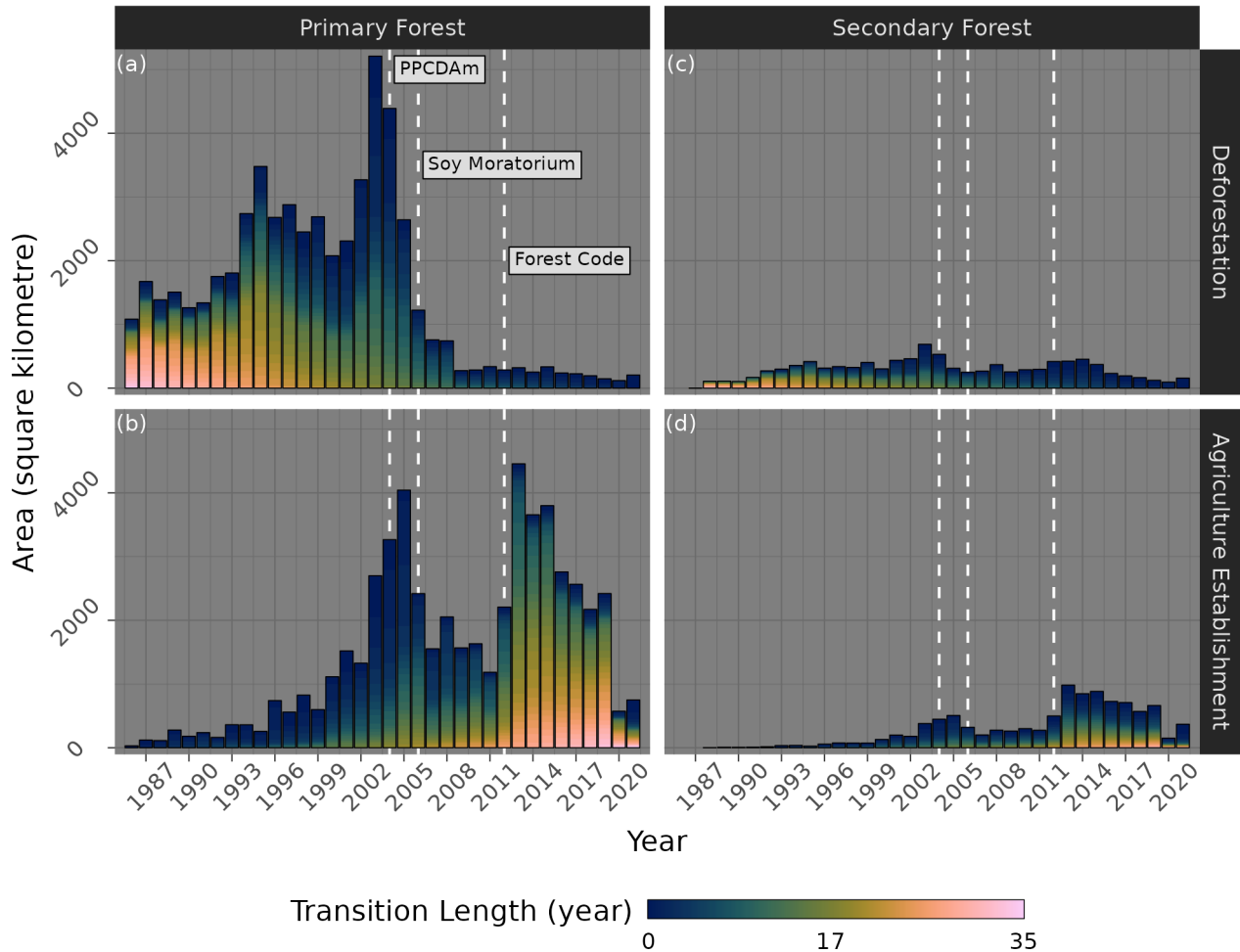
# Distribution of transitions from forest to agriculture in the Amazon



**Figure 1.** Map of distribution of transitions from forests to agriculture in the Brazilian Amazon biome. The hexagonal cells represent the most common transition length, and do not reflect the amount of area of transitions inside a cell. Transitions are concentrated in the south (Mato Grosso state), and in the east (Pará and Maranhão states). The transition length ranges from 1 (blue tones) to 36 years (pink tones), and clusters of fast transitions (transitions closer to 1 year) can be discerned from clusters of slow transitions (transitions closer to 36 years). The histogram located in the bottom left shows that fast transitions are more common than slower transitions. The zoomed map in the bottom right shows the results in finer resolution, where it is possible to observe different transition lengths between properties.

The deforestation area of primary forests increased largely from 1986 to 2003, which was followed by a steep decrease until 2009, when the deforested areas reached a stable rate (Figure 2.a). From 1986 to approximately 1995, most of deforested areas suffered a slow transition, mostly were higher than 10 years, after this period, fast transitions started to become more common, specially from 2002 to 2004 (Figure 2.a). The peak of deforestation in 2003, according to our results, shows that 12.6% of the

## Transition area per year and transition length



**Figure 2.** Transition area per year and transition length. The bars represent the total amount of area at some state of the transition for each year. The color gradient in each bar represents the transition length related to a deforestation or a agriculture establishment event. Blue tones represents fast transitions (transitions closer to 0 years), pink tones represents slow transitions (transitions closer to 35 years). Transition events were separated by deforestation of primary forests (a) and secondary forests (c), and the subsequent agriculture establishment of primary forests (b) and secondary forests (d).

transitions were a direct conversion from forest to agriculture, estimates by Morton et al. (2006) point to a proportion of 23%. If we include fast transitions (from 0 to 2 years) from our results, the proportion jumps to 48.5 % of all the transitions.

Agriculture establishment over areas of primary forests peaked in 2005 and 2013 (Figure 2.b). Despite similar rates between both years, their transition lengths differ greatly, in 2005 most of the transitions were faster than 10 years, while in 2013 the

great majority of transitions were slower than 10 years (Figure 2.b). The year of 2003 marked a change in the transition length of establishment of agriculture areas, after this year, most of the transitions happened in areas deforested at least 10 years before (Figure 2.b). Even after the decrease of deforestation after 2002, agriculture areas are expanding over lands where deforestation happened before 2002. However, after 2019, a sudden drop of agriculture establishment rate happened (Figure 2.b).

The period between 2001 and 2005 showed a peak of deforestation destined to agriculture (Figure 2.a), and of croplands expansion (Figure 2.b). From 2006 to 2010, we observe a decrease of both variables, a process that were already described by an analysis from 2001 and 2010 by Macedo et al. (2012), which pointed for the decoupling of soybean expansion and deforestation. However, our results shows that after 2011, agriculture areas rapidly expanded in the amazon biome, specially at areas deforested many years before.

The causes of deforestation and agriculture establishment in the Brazilian Amazon are complex and diverse. Political context, public policies, market prices and law enforcement can influence how these processes evolve over time. The end of the 1980s and the 1990s were marked by the development of policies for protection of the environment, with the creation of the National Environmental Policy, and the establishment of the Brazilian Institute of Environment and Natural Resources (IBAMA) and the Ministry of Environment (Banerjee et al., 2009). However, this was not immediately translated as a reduction of deforestation in the Amazon, which remained at high levels. Our results shows that deforestation in this period were mainly occupied by pasture for a long time before being converted to agriculture (Figure 2.a).

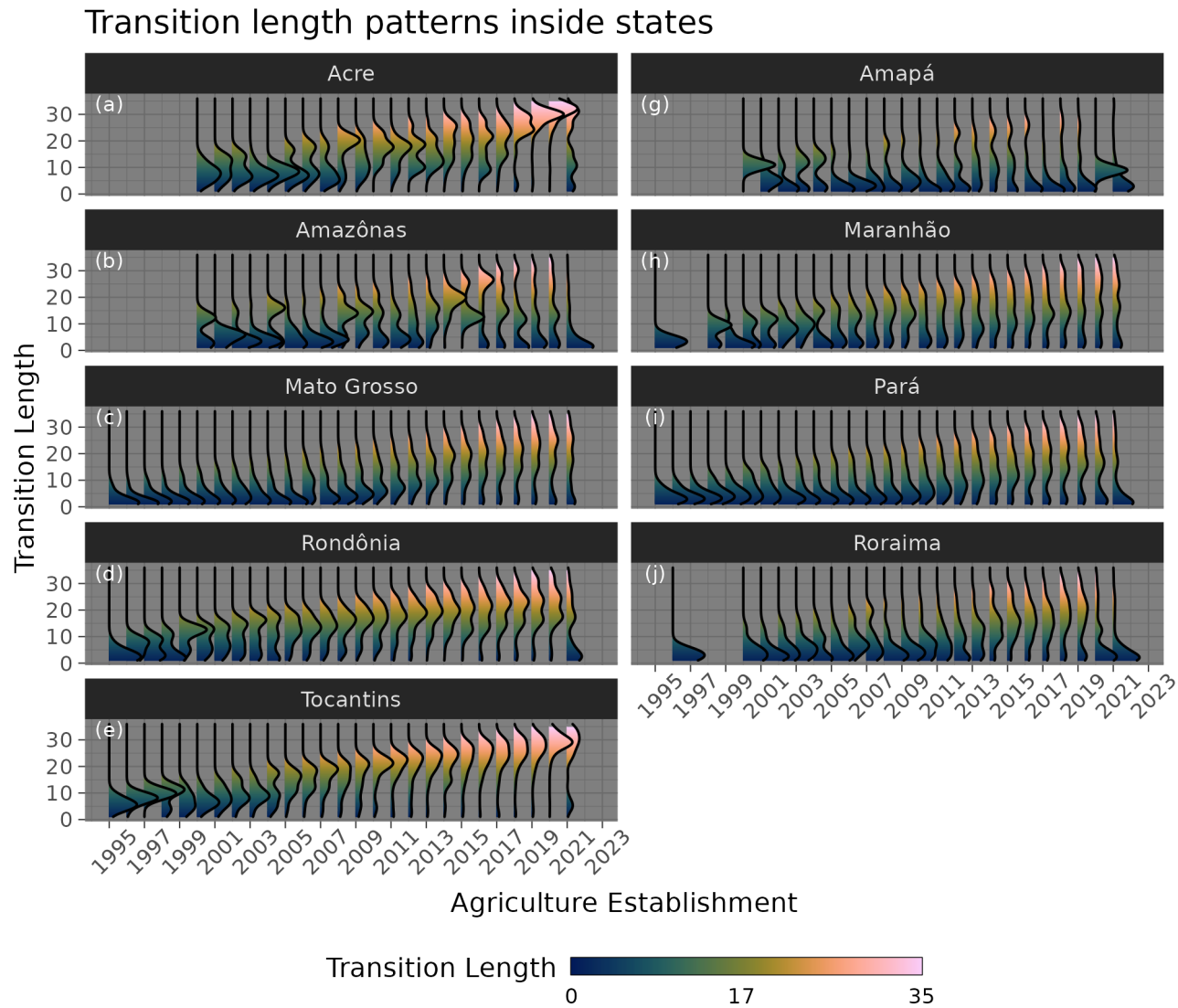
Apart from protectionist policies created in the 1990s, development programs kept pressuring forests in the Amazon. In the late 1990s, the development policies “Brasil em Ação” and “Avança Brasil” (1995 - 2003) accelerated the infrastructure expansion, including in the Amazon (Carvalho et al., 2002). This is a period when the deforestation areas to be converted to agriculture reached the highest values in the time series (Figure 2.a), and also a peak in the establishment of agriculture in the Amazon biome, predominantly with fast transitions (Figure 2.b).

In 2004, the Brazilian Government launched the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), which was composed by many initiatives to curb deforestation (West and Fearnside, 2021). The PPCDAm was considered as a successful policy to slow deforestation rates in Brazil, with international recognition. Our calculations from MapBiomas data reinforces the correlation of the PPCDAm with the reduction of deforestation after 2004, and reduction of the agriculture establishment after 2005 (Figure 2.a).

In 2006, the Brazilian Association of Vegetable Oil Industries (BIOVE) and the National Association of Cereal Exporters (ANEC) committed to avoid commercialization of soy grains harvested from areas deforested after 2006. Our estimates of transitions show a decrease of deforested areas to be converted to agriculture after 2008, where it reached minimal values (Figure 2.a). After 2006, agriculture establishment over deforested primary forests suffered a decrease, which stayed relatively stable until 2012, where a steep increase occurred, however, the new areas being occupied by agriculture were mainly over areas that were cleared more than a decade before (therefore, before 2006) (Figure 2.b) This shows that agriculture expansion did not halt after the soy moratorium, producers started expanding in old cleared areas, which may have indirect impacts on deforestation increase over distant areas (Arima et al., 2011). However, this indirect effect is not always clear when analyzing the Amazon biome as a whole, our data shows that periods of fast agriculture expansion occurred at the same time with minimal

deforestation values, according to PRODES. Expansion of agriculture areas also expanded over cleared areas of secondary forests in 2012, but with an important amount of fast transitions (Figure 3(a)). The causes of the increase of agriculture establishment areas can be numerous, one main driver was the approval of a new Forest Code, in 2012, which is considered to have undermined the environmental protection of forests (Kröger, 2017; Pereira and Viola, 2019).

The transition length patterns across years can change significantly between different states (Figure 3).



**Figure 3.** Transition length patterns inside states that belongs to the Amazon biome. Each year have a density estimate of the transition lengths, represented as colored curves. The peak of the curves represents transition length values with more frequency in one year of one state. Blue tones represents fast transitions (transitions closer to 0 years), pink tones represents slow transitions (transitions closer to 35 years)



The state of Amapá presented fast transitions along all the time series, where slow transitions are not as common. In contrast, Acre shows a majority of slow transitions, in which only 2021 showed more fast transitions. There are three states where the pattern of transitions length across time are alike, Mato Grosso and Pará presented more fast transitions from 1995 to 2005, after this period, slow transitions became more common with time. Rondônia and Tocantins also presented a pattern in which transitions became slower with time, however this pattern started to occur earlier than Mato Grosso and Pará.

The great majority of transitions are from forests to Soybeans and “Other Temporary Crops”, which represents 95% of the transitions in the Amazon biome (14% of Soybean and 81% of “Other Temporary Crops”). When analyzing what happened after 5 years since the transition, Soybean farms are persistent, 79% of these areas remained as Soybean, 14% is converted to “Other Temporary Crops” and 7% in occupied by Pasture. “Other Temporary Crops” are less persistent, 27% of these areas remains as the same use, 56% is converted to Soybean, and 15% to Pasture. Conversions from Soybean and “Other Temporary Uses” to other covers and uses (apart from the already cited) are negligible. Sugar Cane, Cotton and Perennial Crops also appears, but in a negligible proportions.

## 4.2 Validation

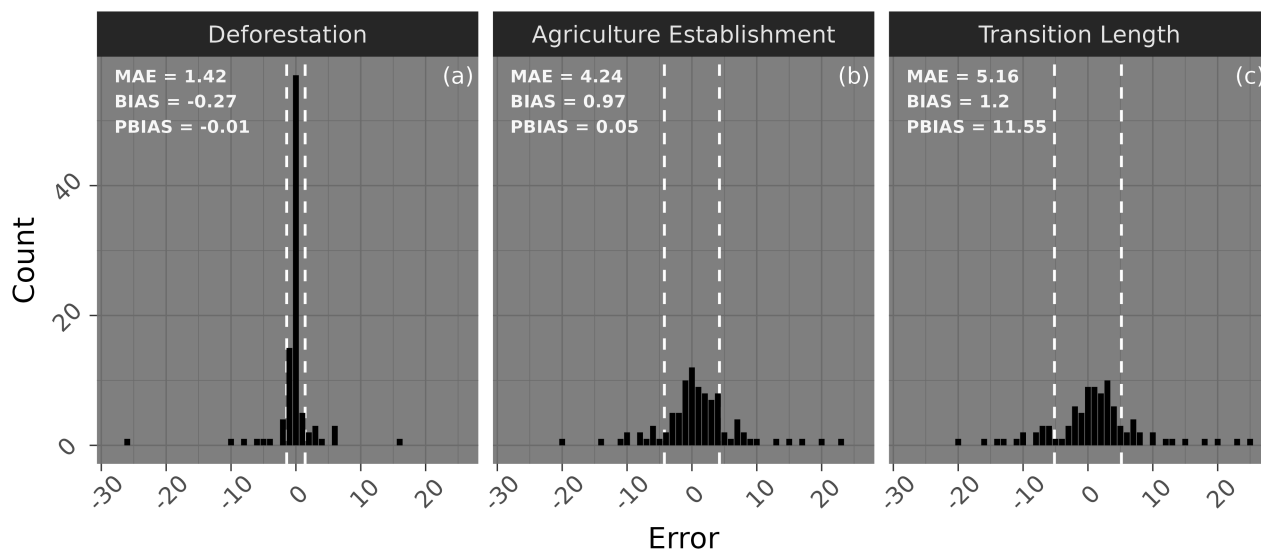
From the 100 random sample points used in the results validation, 1 point (sample 21) was not considered as a transition from our estimations, however, the visual inspection pointed to a likely event of transition from forest to agriculture. Also, there were 6 points (sample 6, 7, 55, 56, 78, 97) which the visual inspection did not found a transition from forest to pasture, although our estimations pointed as transitions. Therefore, 7% of the sample were completely misclassified by our estimates, and the rest of the accuracy assessment was performed over the remaining 93 sample points.

When analyzing the errors from the transition length estimates, we observe that the year of deforestation shows the least amount of errors (Figure 4). The MAE of the deforestation year is of 1.42 years, and the error shows a bias towards underestimation. The year of the agriculture establishment and the transition length estimates showed larger errors when comparing with visual inspection.

The dispersion of observed and estimated values shows no clear pattern of errors (Figure 5). Transition length values are more concentrated in smaller values, which also shows higher errors (Figure 5.c). However, this is expected since faster transitions are more common (Figure 1).

According to accuracy assessment from MapBiomias, the collection 7 presents a global accuracy of 96.6% for the Amazon biome, which is the proportion of pixels that were classified correctly. For the Forest class, MapBiomias showed small errors of inclusion (proportion of pixels misclassified as other classes, but the real class were Forest), which fluctuated around 1%. The omission errors for Forests are also small (proportion of pixels misclassified as Forests, but the real class were not Forest), which fluctuated around 2%. The Agriculture class presented more errors, the inclusion errors ranged from 22% to 5%, and were mostly composed by Forests pixels (forest pixels misclassified as agriculture). The omission errors of Agriculture ranged from 22% to 8%, and were also mostly composed by Forests pixels (agriculture pixels misclassified as Agriculture).

## Distribution of the errors of transition estimates.



**Figure 4.** Bar with the count of error values (difference between observed and estimated values). Positive values indicate underestimation of the variable (estimations were lower than observations), negative values indicates overestimation (estimations higher than observations). Error metrics (Mean Absolute Error, Bias and Percent Bias) are displayed in the top right position of each box. The white dashed lines represents the MAE values of each variable.

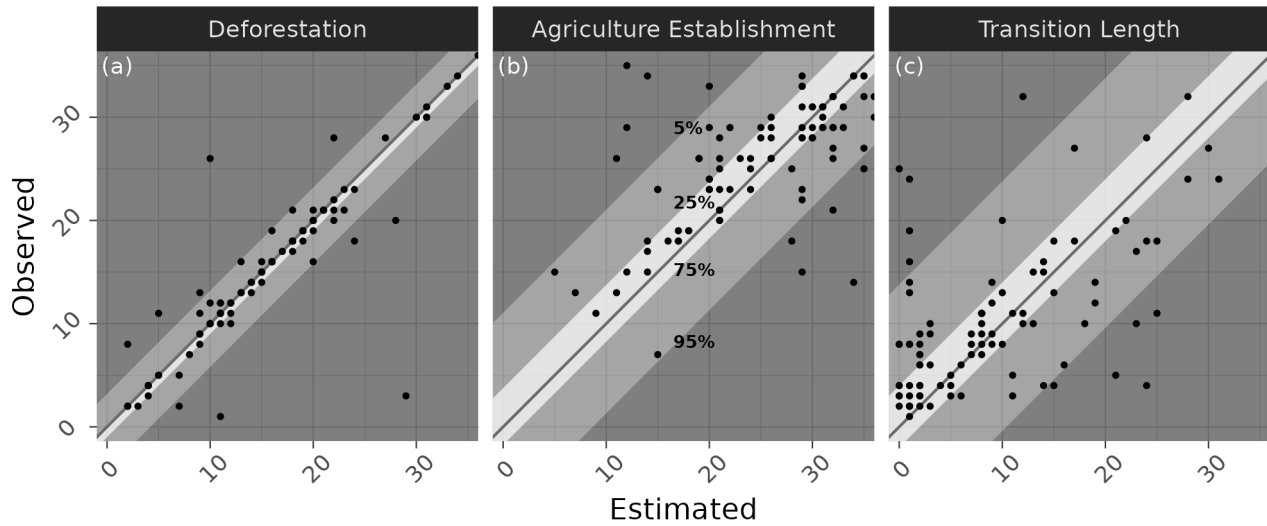
### 4.3 Qualitative assessment

High heterogeneity inside agriculture plots (sample 56), caused by both year of deforestation or year of agriculture establishment. Roads being considered as agriculture (sample 2). Omissions were detected, specially agriculture plots not being considered as a transition as a whole, parts of a plot that were clearly a transition were not considered as a transition (sample 16, 30, 75). Inclusions were detected, areas that clearly showed no agriculture were considered as transitions (sample 10, 98). Effect of border on results (sample 25, 56, 84, 92). Areas with sparse forest vegetation presented large error of deforestation year (sample 33).

Patterns of agriculture areas are roughly well represented (sample 25, 43, 56, 84). Some locations presents a better homogeneity of transitions inside agriculture plots (sample 84).

Interference due to atmospheric conditions and lack of image availability clearly shaped spatial patterns of transitions at some locations. Quality of composites trough the time series affected accuracy of results. Regions of the North part of the Amazon presents lower quality than regions in the South of the Amazon biome.

## Dispersion between observed and estimated transitions.



**Figure 5.** Scatter plot between paired values of estimated and observed Deforestation and Agriculture Establishment years, and their respective Transition Length. Translucid white areas represent quantile ranges (5%, 25%, 75% and 95%) of the errors. The area between 5% and 95% quantiles includes 90% of points. The area between 25% and 75% quantiles includes 50% of points.

## 5 Conclusions

. The authors declare no competing interests.

## References

- Arias, M. E., Lee, E., Farinosi, F., Pereira, F. F., and Moorcroft, P. R.: Decoupling the effects of deforestation and climate variability in the Tapajós river basin in the Brazilian Amazon, *Hydrological Processes*, 32, 1648–1663, <https://doi.org/10.1002/hyp.11517>, 2018.
- Arima, E. Y., Richards, P., Walker, R., and Caldas, M. M.: Statistical confirmation of indirect land use change in the Brazilian Amazon, *Environmental Research Letters*, 6, 024 010, <https://doi.org/10.1088/1748-9326/6/2/024010>, 2011.
- Banerjee, O., Macpherson, A. J., and Alavalapati, J.: Toward a Policy of Sustainable Forest Management in Brazil, *The Journal of Environment and Development*, 18, 130–153, <https://doi.org/10.1177/1070496509333567>, 2009.
- Boulton, C. A., Lenton, T. M., and Boers, N.: Pronounced loss of Amazon rainforest resilience since the early 2000s, *Nature Climate Change*, 12, 271–278, <https://doi.org/10.1038/s41558-022-01287-8>, number: 3 Publisher: Nature Publishing Group, 2022.
- Carvalho, G. O., Nepstad, D., McGrath, D., del Carmen Vera Diaz, M., Santilli, M., and Barros, A. C.: Frontier Expansion in the Amazon: Balancing Development and Sustainability, *Environment: Science and Policy for Sustainable Development*, 44, 34–44, <https://doi.org/10.1080/00139150209605606>, publisher: Routledge \_eprint: <https://doi.org/10.1080/00139150209605606>, 2002.
- Ellwanger, J. H., Kulmann-Leal, B., Kaminski, V., Valverde-Villegas, J., Veiga, A. B. G. D., Spilki, F. R., Fearnside, P. M., Caesar, L., Giatti, L. L., Wallau, G. L., Almeida, S. E. M., Borba, M. R., Hora, V. P. D., and Chies, J.: Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health, *Anais da Academia Brasileira de Ciências*, 92, <https://doi.org/10.1590/0001-3765202020191375>, publisher: Academia Brasileira de Ciências, 2020.
- Fearnside, P. M.: Deforestation in Brazilian Amazonia: History, Rates, and Consequences, *Conservation Biology*, 19, 680–688, <https://doi.org/10.1111/j.1523-1739.2005.00697.x>, \_eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1523-1739.2005.00697.x>, 2005.
- Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L. G., Tejada, G., Aragão, L. E. O. C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A. H., Corrêa, S. M., Anderson, L., Von Randow, C., Correia, C. S. C., Crispim, S. P., and Neves, R. A. L.: Amazonia as a carbon source linked to deforestation and climate change, *Nature*, 595, 388–393, <https://doi.org/10.1038/s41586-021-03629-6>, number: 7867 Publisher: Nature Publishing Group, 2021.
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R.: Google Earth Engine: Planetary-scale geospatial analysis for everyone, *Remote Sensing of Environment*, 202, 18–27, <https://doi.org/10.1016/j.rse.2017.06.031>, 2017.
- Kröger, M.: Inter-sectoral determinants of forest policy: the power of deforesting actors in post-2012 Brazil, *Forest Policy and Economics*, 77, 24–32, <https://doi.org/10.1016/j.forpol.2016.06.003>, 2017.
- Macedo, M. N., DeFries, R. S., Morton, D. C., Stickler, C. M., Galford, G. L., and Shimabukuro, Y. E.: Decoupling of deforestation and soy production in the southern Amazon during the late 2000s, *Proceedings of the National Academy of Sciences*, 109, 1341–1346, <https://doi.org/10.1073/pnas.1111374109>, 2012.
- Maeda, E. E., Abera, T. A., Siljander, M., Aragão, L. E. O. C., Moura, Y. M. d., and Heiskanen, J.: Large-scale commodity agriculture exacerbates the climatic impacts of Amazonian deforestation, *Proceedings of the National Academy of Sciences*, 118, e2023787 118, <https://doi.org/10.1073/pnas.2023787118>, publisher: Proceedings of the National Academy of Sciences, 2021.
- McDonald, M.: Environment and security: Global eco-politics and Brazilian deforestation, *Contemporary Security Policy*, 24, 69–94, <https://doi.org/10.1080/13523260312331271919>, publisher: Routledge \_eprint: <https://doi.org/10.1080/13523260312331271919>, 2003.

- Morton, D. C., DeFries, R. S., Shimabukuro, Y. E., Anderson, L. O., Arai, E., del Bon Espirito-Santo, F., Freitas, R., and Morisette, J.: Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon, *Proceedings of the National Academy of Sciences*, 103, 14 637–14 641, <https://doi.org/10.1073/pnas.0606377103>, publisher: Proceedings of the National Academy of Sciences, 2006.
- Müller-Hansen, F., Cardoso, M. F., Dalla-Nora, E. L., Donges, J. F., Heitzig, J., Kurths, J., and Thonicke, K.: A matrix clustering method to explore patterns of land-cover transitions in satellite-derived maps of the Brazilian Amazon, *Nonlinear Processes in Geophysics*, 24, 113–123, <https://doi.org/10.5194/npg-24-113-2017>, 2017.
- Nunes, C. A., Berenguer, E., França, F., Ferreira, J., Lees, A. C., Louzada, J., Sayer, E. J., Solar, R., Smith, C. C., Aragão, L. E. O. C., de Lima Braga, D., de Camargo, P. B., Cerri, C. E. P., de Oliveira, R. C., Durigan, M., Moura, N., Oliveira, V. H. F., Ribas, C., de Mello, F. V., Vieira, I., Zanetti, R., and Barlow, J.: Linking land-use and land-cover transitions to their ecological impact in the Amazon, *Proceedings of the National Academy of Sciences*, 119, <https://doi.org/10.1073/pnas.2202310119>, 2022.
- Pekel, J., Cottam, A., Gorelick, N., and Belward, A. S.: High-resolution mapping of global surface water and its long-term changes, *Nature*, 540, 418–422, <https://doi.org/10.1038/nature20584>, number: 7633 Publisher: Nature Publishing Group, 2016.
- Pereira, J. C. and Viola, E.: Catastrophic Climate Risk and Brazilian Amazonian Politics and Policies: A New Research Agenda, *Global Environmental Politics*, 19, 93–103, [https://doi.org/10.1162/glep\\_a\\_00499](https://doi.org/10.1162/glep_a_00499), citation Key: pereira2019, 2019.
- Simon, M. F. and Garagorry, F. L.: The expansion of agriculture in the Brazilian Amazon, *Environmental Conservation*, 32, 203–212, <https://doi.org/10.1017/S0376892905002201>, publisher: Cambridge University Press, 2005.
- Souza, C. M., Shimbo, J. Z., Rosa, M. R., Parente, L. L., Alencar, A. A., Rudorff, B. F. T., Hasenack, H., Matsumoto, M., Ferreira, L. G., Souza-Filho, P. W. M., de Oliveira, S. W., Rocha, W. F., Fonseca, A. V., Marques, C. B., Diniz, C. G., Costa, D., Monteiro, D., Rosa, E. R., Vélez-Martin, E., Weber, E. J., Lenti, F. E. B., Paternost, F. F., Pareyn, F. G. C., Siqueira, J. V., Viera, J. L., Neto, L. C. F., Saraiva, M. M., Sales, M. H., Salgado, M. P. G., Vasconcelos, R., Galano, S., Mesquita, V. V., and Azevedo, T.: Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine, *Remote Sensing*, 12, 2735, <https://doi.org/10.3390/rs12172735>, 2020.
- West, T. A. P. and Fearnside, P. M.: Brazil’s conservation reform and the reduction of deforestation in Amazonia, *Land Use Policy*, 100, 105 072, <https://doi.org/10.1016/j.landusepol.2020.105072>, 2021.