

Land use change analysis of the flooded area in the Guaíba Hydrographic Region in southern Brazil 2024

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Abstract: The impact of extreme weather events is largely influenced by land cover, as demonstrated by the catastrophic flood in Rio Grande do Sul (RS), Brazil, in May 2024. Over 200mm of rain fell daily in numerous municipalities, displacing 2.3 million people. Although forests cannot entirely mitigate such extreme rainfall, they can help reduce runoff and related damages. We conducted a geospatial analysis to assess land use changes from 1985 to 2022 in the Guaíba Hydrographic Region, applying a three-step raster analysis using GIS tools. We classified pixels as natural or anthropogenic to monitor vegetation changes over four periods. Data processing efficiency improved significantly with a PostgreSQL approach, reducing query time from 20 hours to five minutes after a lengthy initial pre-processing. Our findings indicated a higher long-term anthropogenic influence in flooded areas, with vegetation loss in Pampa Grasslands (PP) at 33.2%, compared to 18.1% for the Atlantic Forest (AF) and 16.8% in flooded areas. Between 1985 and 2022, we observed a fluctuating conversion rate of natural forests, with an overall loss in grasslands at an increasing annual rate. Soybean cover rose dramatically during these years, growing 430% until 2022, diminishing natural pastures in the Pampa biome. Our analysis emphasizes the effectiveness of forest protection policies while revealing that grassland areas remain poorly managed despite their crucial role in mitigating flood impacts.

Keywords: Natural Vegetation, Watershed, Extreme Weather Event, Forest Cover

1. Introduction

The impact of extreme weather events is largely depended on land cover. Rio Grande do Sul (RS), the southernmost state of Brazil, experienced a catastrophic flood in May 2024. Over 200mm/day of rain was recorded in 265 out of 497 municipalities, with some cities experiencing 500mm/day. This unprecedented rainfall led to the highest recorded flood levels, displacing 2.3 million people, 420,000 of whom were rendered homeless (Laipelt et al., 2025). Although no forest can mitigate the full effects of this extreme rainfall, they can help reduce run-off and damages. Analyzing changes in land use over time using GIS helps understand how the environment influences these events' devastating effects and its relation to public policies.

Brazil's land base spans 850 million hectares, of which natural forest cover exceeds 57%. The country has five distinct biomes. In RS, 31% of the land lies within the Atlantic Forest biome. It has higher altitudes and is associated with a humid tropical climate. The remaining

69% is in the Pampa, which features diverse natural landscapes consisting mainly of grasslands. Livestock farming has been the primary economic activity in the Pampa for a long period, contributing to the conservation of natural fields. In 2022, Atlantic Forest's natural cover stood at 30%, and the Pampa's at 50% (MapBiomias Project, 2023). Notably, the Guaíba Hydrographic Region (**Figure 1**), intersecting both biomes, experienced the greatest impact from the flooding and supports the largest human population within RS. The Guaíba Hydrographic Region comprises nine watersheds: Alto Jacuí, Pardo, Vacaraí, Baixo Jacuí, Taquari-Antas, Caí, Sinos, Gravataí and Guaíba.

Countries must consider territorial location, national environment, and policy shifts for effective integration. Aligning forest information with traditional territories, ecological protection areas, and recovery efforts can enhance sustainable forest management. Public policies shape land use practices, forest coverage, and climate change awareness. Mitigation actions guided by robust

policies are essential for maintaining healthy forests and combating climate change.

The MapBiomias project in Brazil uses spatially explicit models to estimate land use changes, including forest areas. These changes depend on a mix of global factors like GDP growth and local factors such as land use planning and ecological constraints. Brazil's forest policy, including the New Forest Code (Law No. 12.651/2012), is crucial for balancing economic development with environmental protection. Understanding land use dynamics can help Brazil enhance forest resilience to climate change and promote sustainable practices.

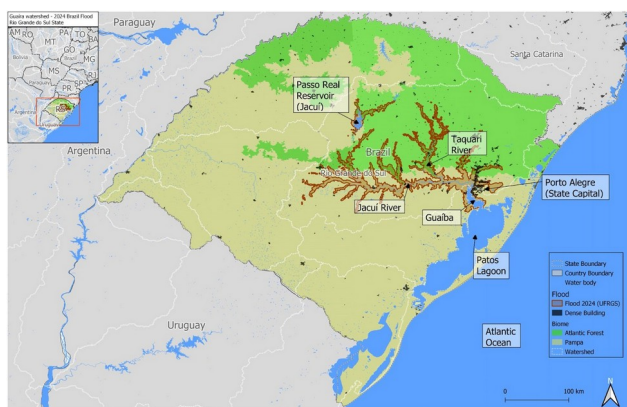


Figure 1: Map showing the distribution of the Atlantic Forest and Pampa biomes in the Guaíba watershed and the estimated flood area.

The Atlantic Forest biome section of the Guaíba Hydrographic Region is situated north (**Figure 1**). The Jacuí River, in the centre of this region, lies mainly in the Pampa to the south with tributary rivers running from the forest. The river receives water from tributaries from both regions and flows south to the Guaíba Lake near Porto Alegre, then to the Patos Lagoon and the Atlantic Ocean. Guaíba is an Indigenous word meaning "Meeting of the Waters." It is classified as a lake but has the characteristics of a River (Andrade et al., 2019).

Understanding land cover dynamics is crucial for practical flood risk assessment and mitigation, especially in contemporary climate unpredictability and ongoing urbanization. Furthermore, exploring the causal relationship between land use change and government policies provides valuable insight into the relationship between land use management regimes, natural disasters and other phenomena that can cause human suffering on a massive scale. In this paper, we use open remote sensed data from the Guaíba Hydrographic Region to examine land use changes in the region over the past 40 years. We use this analysis to explore how land use changes have influenced the extent of the 2024 flooding.

2. Methods

The geospatial classification raster analysis consisted of three steps to assess land use change from 1985 to 2022 in the Guaíba Hydrographic Region, covering 9.5 million hectares, with 1.2 million hectares of flooded areas (MapBiomias, 2024; UFRGS, 2024). In Step 1, we cropped data to the region limits. Step 2 involved grouping natural areas using the QGIS Raster Calculator, assigning a value of 1 to natural areas and 0 to others. In Step 3, we generate a pixel-by-pixel change raster by comparing two time periods with prime number weights like 1, 3, 5, 7, and 17. We get unique values in the raster to compare changes over the evaluated time frames shown in **Figure 2**.

We downloaded the flooded area vector data from the University of Rio Grande do Sul (UFRGS map repository measures the tragedy in RS, 2024). The confirmed flood area was selected and joined with simulated estimates on a 5.5m water rise. We utilized the watershed Otto level 3 number 6796 from the Brazilian Water Agency (ANA), representing the Guaíba Hydrographic Region. We also used the 1985, 1992, 2002, 2012, and 2022 Mapbiomas (land use year by year, 30m resolution) land cover classification. We used a combination of pixel values representing natural classes to visualize changes in land cover. Each pixel in a database point had sample values for each year, and the possible value changes between the classes were grouped (100 million rows). From the aggregate area estimate, we generate a Sankey diagram over time (Biondo, 2024). Next, the flooded areas were selected and compared to the whole region.

2.1 Mapbiomas Land Use Classification

Our geospatial analysis used tools from QGIS and PostGIS. These tools were instrumental in comparing MapBiomias 8 land cover data from different years, enabling us to create images and a database for combinatorial analysis of land use change over time. The processing used a regular gaming notebook computer with an i7-10750H processor, 40GB RAM, and 1TB SSD running Ubuntu 22.10 with QGIS 3.22, PostgreSQL 14.7, PostGIS 3.2.3 and PGAdmin 4 v6.21 without performance adjustments.

This methodology was successfully applied to characterize areas in several municipalities affected by the May 2024 Brazil flooding. The combination of PostgreSQL with Qgis and Geoserver offer a great balance of performance and accessibility using OpenSource tools ready for webportals and services.

The Mapbiomas Collection 8, which encompasses 29 distinct classes of land use, was a key resource in our study. We grouped these classes into 13 more relevant categories, seven of which were anthropic or non-natural. This grouping allowed us to apply filters to identify probable natural vegetation or remaining native areas, demonstrating the practical application of our methodology in the context of land use change analysis.

The geospatial analysis process for mapbiomas raster data involved four steps to understand land use change over time. Step 1 included cropping data from 1985 to 2022 within the Guaíba hydrographic region, resulting in a raster with dimensions of 446Km wide and 297Km high, covering 9.5 million hectares. The area of interest, including the flooded areas along the main rivers, covers 1.2 million hectares.

In Step 2, we grouped the natural areas and assigned different weights on a yearly basis. We used the QGIS Raster Calculator to create a TIFF file with values of 1 for natural areas and 0 for other classes. Then we used an extent layer with the Mapbiomas classes, using Virtual@1 as the first raster band (Biondo, 2024).

In Step 3, we generated a pixel-by-pixel change raster using two years or two groupings of years to be compared. We applied a direct method using the masks generated in steps 2 or 3 and used weights of 1 for the first file and 3 for the second to avoid confusion with the value 1 for the natural area of the original masks. The result had pixels assuming values 0, 1, 3, or 4. Value 0 means no natural area in both files, value 1 only in the first, value 3 only in the second, and value 4 indicates natural class in both. Finally, the weighted sum is applied to identify the changes between any natural pixel in the considered dates.

Finally, in step 4, we used prime numbers to create distinct combinations in the data. This procedure helps differentiate the results and identify the origin of the combinations using pixel values. For example, if using 1, 3, and 7, when adding three pixels, the resulting distinct values will indicate the presence and combination of natural areas in the pixels. We did that with five rasters with weights 1-3-5-7-17, so the possible values on the resulting raster files are all unique: 0, 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 17, 18, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 32, 33. The natural classes considered were 1, 3, 4, 5, 6, 10, 11, 12, 13, 23, 25, 29, 33, 49 and 50.

2.2 Analysis of land use changes pixel by pixel using a spatial database.

This methodology is both practical and efficient, we can easily evaluate differences between two overlapped images of any region in Brazil using the "Mapbiomas" land use classification data. There are various faster and more efficient ways to carry out this process, particularly in smaller areas. However, this approach allows for visual or statistical analysis of the images, including pixel count per class, display of colour differences, showing only the changes by classes, or grouping of classes.

Those steps are adaptable and reproducible for different analyses with variations in the application area, grouped classes, sampling period, or combinations between classes for different years of classification. We used raster data from the exact location with overlapping information for other sampling years, looking at different pixel tables of the same size and with data of a similar nature. Additionally, we can store these tabular data files in different ways, initially using TIF files offered by Mapbiomas, which have about 1GB of data per year.

An alternative method is using a raster data storage format in a PostgreSQL database, which maintains the raster's size and facilitates organization and access by different users and systems. This format stacks data in layers with different resolutions, increasing file size but accelerating image display. To reprocess and compare regions and periods, access the class tables in the image files and run relation algorithms between them.

To accelerate the access and processing of vector spatial data, we used the spatial database extension PostGIS for PostgreSQL. This extension efficiently stores, processes, and provides spatial data to applications and users. Polygonizing TIFF images, placing them in this database, and carrying out vector operations can take advantage of spatial indices that speed up geolocation operations.

We polygonized the data to homogenize areas of the same class, creating contour geometries to delineate the original areas. This modification of the original data can make processing more time-consuming and problematic when working with high-resolution files. In the Atlantic Forest section, we used an unconventional method to represent rasters in a PostgreSQL table, each with a unique ID and spatial point coordinates. The only data cleaning was to remove the database records with a classification value of 0 in 1985 and 2020, which were unsampled points, outside the watershed. The table of this clipping then had 105,495,630 rows.

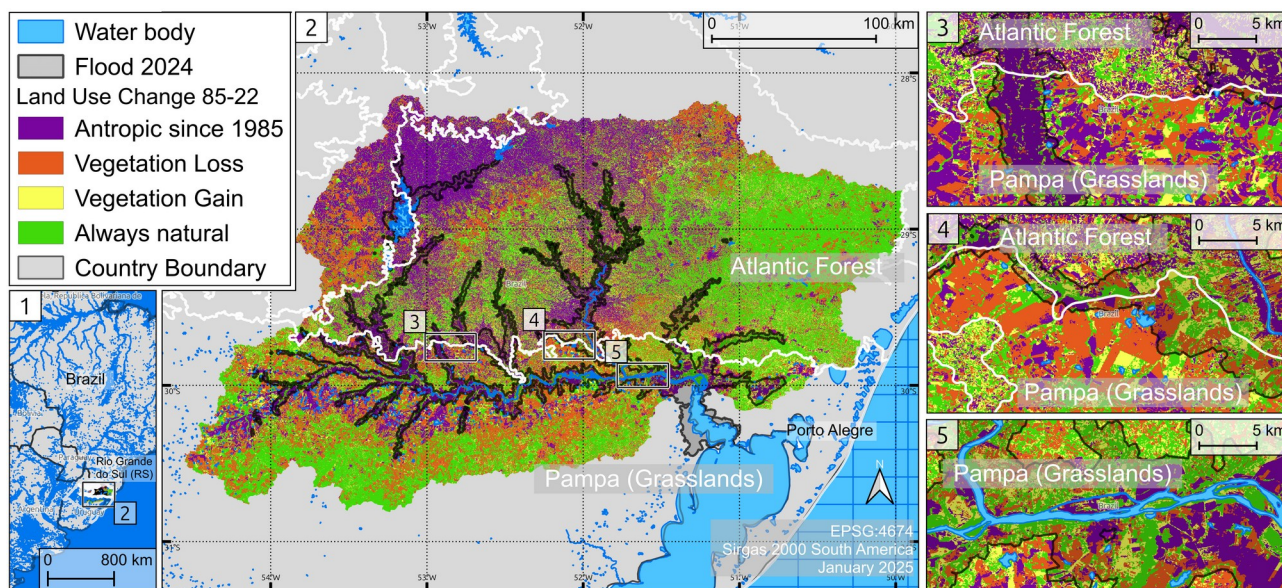


Figure 2: Guaíba watershed with anthropogenic areas since 1985 in purple, always natural between 1985 and 2022 in green, natural vegetation losses in orange and natural vegetation gains in yellow. The northwest anthropic region was colonized earlier by farmers, and the northeast natural area has conservation units. We found higher recovery rates in the Atlantic Forest and losses in the Pampa.

Having a stacked raster file of the 5 years of classification of the mapbiomas, we went for the pre-processing with the "Clip Raster by Extent" tool that clipped every year (explained at the beginning of part 1) and then the "Clip Raster by Extent" tool. We then used the Merge function, checking the option "place each input file into a separate band" by selecting the five rasters placed in ascending order by sampling year. The resulting raster has five bands or layers with the original resolution, which was helpful for the next step, to put the data in the same database table. This procedure samples the raster value for each feature of the input vector and stores it in a column of the output vector. In the case of a raster with more than one layer, the procedure creates a column for each layer. As our sampling vector is a point at the center of each pixel, the result is a table with the same 105 million lines and seven columns that are the unique ID, the spatial point with coordinates at the center of the pixel and 5 years of mapbiomas data for each pixel. Repeating this process on 38 years of data in a single table makes the processing time longer and the necessary space proportionally larger.

The complete table with the data for this test region had a total of 14GB against the original 808MB TIF rasters with "DEFLATE" compression. As the type of data stored in the database was "byte" for all the class information of each attribute of each record, the physical storage space is practically the same as a TIF file without

compression in 8bits (after all, it is also a table that each item is 1 byte).

The first advantage verified in this strange format of storing all rasters was to cross spatial data to filter the processing, which takes advantage of the spatial indexes of the reference layers and the spatial index of the points of the mapbiomas table. The second and most important is the possibility of making different queries at the images pixels' level using aggregation mathematical operations and queries from a structured database.

While all previous processing took about 20 hours of machine time, querying all records that have not changed in 5 decades and grouping pixel counts by land use class across the entire region took 5 minutes. Other test operations proved quick and easy to change and reprocess since years are fields in a table and images are records. We would recommend raster processing with python for just building a diagram, and this method to further investigate the multivariate transitions and their significance. Example query for change combinations:

```
CREATE TABLE changes AS SELECT x.y1985,
x.y1992, x.y2002, x.y2012, x.y2022, count(*) FROM
mapbiomas x GROUP BY x.y1985, x.y1992, x.y2002,
x.y2012, x.y2022;
```

2.3 Sankey diagrams for temporal visualization

With the grouped land classes, we estimated the area for each year, each pixel being approximately 900 square

meters. We then created a Sankey diagram from each year to the next using Sankeymatik software online. The diagram is a proportional flow chart that facilitates seeing the regional coverage transitions over the years. We built one change chart for the initial and end dates of Mapbiomas data (1985 and 2022 – **Table 1**) and another chart comparing all analyzed periods (85-92, 92-02, 02-12 and 12-22). This data generated the SankeyMatic.com diagrams shown in **Figure 3**.

leading to decreased natural pastures in the Pampa biome until 2022. Our analysis suggests that forest and environmental policies have effectively protected tree cover but fail to maintain grassland areas, equally important for mitigating significant flooding events.

We used Mapbiomas data from 1992 to 2022 in 10-year increments and the oldest available 1985 classification in the Guaíba Hydrographic Region. We compared pixel-by-pixel changes to identify areas with consistent natural

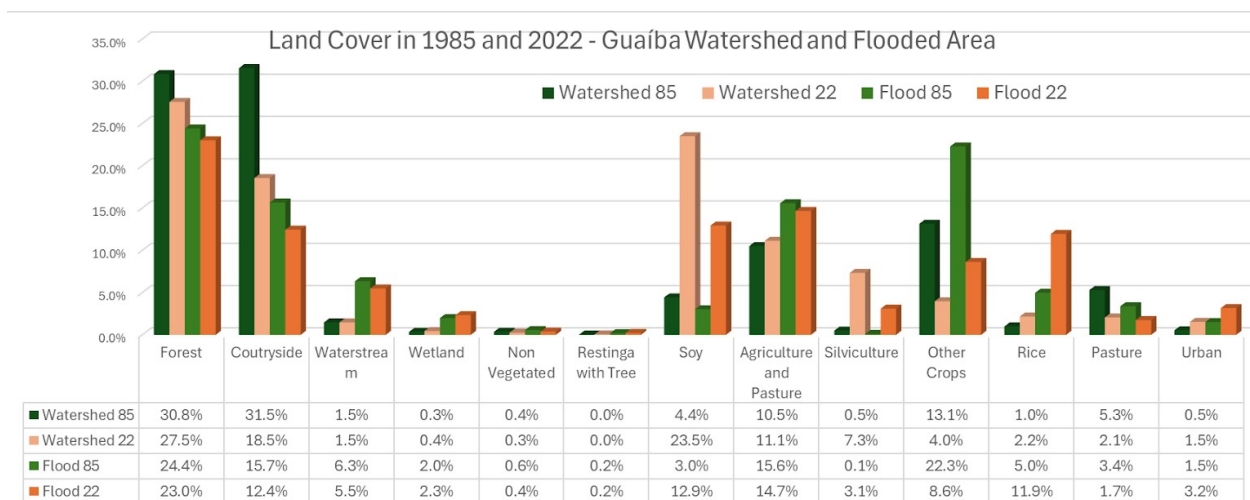


Table 1: Land cover percentages by class in the hydrographic region and in the flooded areas in 1985 and 2022.

Rio Grande do Sul comprises two significant biomes, the Pampa Grasslands (PP) and the Atlantic Forest (AF). Using the region values of 2022 natural vegetation, we classified each pixel as being "Natural" or "Anthropogenic" and aggregated change in natural vegetation as "gain" and "loss" areas using four periods: 1985 to 1992 (limited by existing data), 1992 to 2002, 2002 to 2012 and 2012 to 2022. The flooded area had a higher long-term stable anthropogenic portion, as more people live near the rivers. The vegetation loss was higher in the PP (33.2%) compared to the AF (18.1%) and lower in the flooded area (16.8%). The difference may be related to two reasons: the strict land use protection policies for the AF (Law 11.428/2006) and the vertical structure of grassland vegetation that makes its conversion easier compared to that of the Atlantic forest.

3. Discussion

Forests and native grasslands are crucial for ecological services like water run-off reduction, biodiversity, and ecological balance (Lyons, K. G. et al., 2023). Our findings show a reduction in net forest loss until 2012, followed by an increase in 2022. We also observed an increasing rate of agricultural expansion at the expense of natural grasslands. In particular, the data show an increase in soybean cultivation (430% greater area),

vegetation, consistent anthropogenic land cover, and partial combinations where natural formations were present in at least one decade (**Table 2**). Mapbiomas Collection 8 (Souza et al., 2020) provides land cover and use maps and annual data in Brazil from 1985 to 2022 with 30x30m resolution and 29 classes. The data is public, open, and accessible under a CC-BY-SA license.

The spots classified as natural cover in the past but not in 2022 are anthropogenic vegetation losses, while locations classified as natural in 2022 but not in all the decades are natural cover gains. The points with natural vegetation in all the years were always natural, as those always anthropogenic were never natural.

We analyzed land cover classes in two main subdivisions: the whole hydrographic region and the estimated flooded areas near local rivers. We also did some estimates using both local biomes.

The guaíba hydrographic region had 64.6% of natural cover in 1985, while the flooded region had 49.1%. After 37 years, the watershed had, in 2022, 48.3% of natural land use coverage, while the flooded area had 43.9%. These variations point to a loss of 1.55 million hectares of native vegetation in the basin and 59,757 hectares inside the affected area. If we detail the actual fragments

of each class over time, it is worse from a conservancy point of view, the forest class itself lost 713Kha and received 402Kha of forestry recover from other uses. As shown in the **Figure 3** diagram, the 2.6 million hectares in 2022 are composed of only 2.2 from 1985 areas; when looking at conversions between Natural and Anthropogenic sectors, we found an increase of 1.55Mha in anthropogenic areas but a total loss of 2.06Mha in 1985 natural classes, the difference being restored secondary vegetation.

The natural land use area decreased from 6.1Mha to 4.1Mha with an additional 0.5Mha gain from 1985 anthropogenic points. Comparing 1985 and 2022 the original natural cover went from 64.6% to 42.9% plus a recovered 5.4%.

Year	2022			
	Land Use	Anthropogenic	Natural	Total
1985	Anthropogenic	2,842,288	517,235	3,359,523
	Natural	2,064,652	4,070,432	6,135,084
	Total	4,906,940	4,587,667	9,494,607

Table 2: Transition matrix in hectares for Natural and Anthropogenic classes between 1985 and 2022 in the Guaíba Hydrographic Region.

The Brazilian Pampa Biome has seen a 26% decrease in natural pastures from 1975 to 2006 due to the expansion of cultivated forests and temporary crops. The loss may led to implications for biodiversity, landscape fragmentation, and soil degradation. Overgrazing and low productivity may have contributed to the loss of natural grasslands, despite the economic potential for sustainable beef production. Initiatives like the Alianza del Pastizal aim to protect Pampa's grasslands by certifying beef produced in conserved areas. Monitoring land use changes and promoting sustainable practices are crucial for maintaining the ecological value of this unique biome, as noted in the agricultural census (Oliveira et al., 2017).

We noticed a similar trend in Mapbiomas data, with the Pampa losing 41.2% of its area in the Guaíba Hydrographic Region from 1985 to 2022. The 2022 Soybean areas (2.2Mha) expanded from 0.4Mha of Soybeans in 1985. The increase originated from other Crops, including pastures (1.1Mha) and natural Grasslands in the Pampa (0.7Mha). Natural forests (2.9Mha) were converted mainly to Sylviculture (0.3Mha), agriculture and pastures (0.2Mha), and Soybeans (0.1Mha).

When evaluating the decadal flow between land use classes, we found an initial higher conversion rate from natural forests in 85-92 (-5.2%), then -3.8% in 92-02, recovering +1.1% in 02-12 and back to -3.0% annual rate to 22. The Pampa grasslands lost areas in all periods with increasing annual rates of -4.6%, -10.3%, -16.7% and -17.6%. Notably, the Soy crops steadily increased, growing 106.7% in 85-92, then 39.9%, 44.6% and 27.1% until 2022.

In 1988, the constitution put the Atlantic Forest as a national heritage; in 1992, the Rio convention did not do much; the 2006 law protected the Atlantic forest; and in 2012, the new forest code; in 2019, the State removed many protection rules from their evolution after the new code. That may explain why we found reduced forest loss and some areas even recovered forest vegetation. They turned to new areas in the Pampa and, since 2019, have been trying to remove protection from the grassland as a whole, knowing that effort probably made farmers use them upfront.

Permanent Protection Areas (APP) are protected by the "New Brazilian Forest Code Law" covered or not by native vegetation, with the environmental function of preserving water resources, the landscape, geological stability, biodiversity, the gene flow of fauna and flora, protecting the soil and ensuring the well-being of human populations.

Legal Reserve (RL) is "an area located within a property or rural possession, except for permanent preservation, necessary for the sustainable use of natural resources, the conservation and rehabilitation of ecological processes, the conservation of biodiversity and shelter and protection of native fauna and flora" (Brazil, 2012). The competent government body approves the management plan in these areas, allowing for sustainable forest management to produce goods and services. This Law determines the protection of at least 20% of the property area as a Legal Reserve on rural properties located in forest areas or other forms of native vegetation located outside the Brazilian Legal Amazon;

The native vegetation helps by reducing the speed at which runoff reaches riverbeds, increasing the amount of water infiltrated into the soil, and protecting the soil by reducing the amount of sediment that silts up the region's rivers. The Rio Grande do Sul Secretariat for the Environment (Sema) has stated that it took action to protect and restore areas of native vegetation in the State, with reforestation and restoration of natural environments included in the State's priority projects. The ruling on the

matter can vary for each municipality, with unclear large-scale directives for its definition in RS state.

Riparian vegetation is crucial for protecting river ecosystems, as it helps improve water quality, reduce erosion, and support biodiversity. Annual flooding is essential for maintaining these forests, as the trees have

forest (19.1%) and even lower in the flooded area (16.8%), mainly inside the Pampa. That can indicate that the protection rules for the Atlantic Forest and protected areas near rivers reduced human expansion there or forced it to the Pampa. Similar behaviour happened with the natural gains, with the flooded area recovering 13.2% against the 9.5% average in the Pampa.

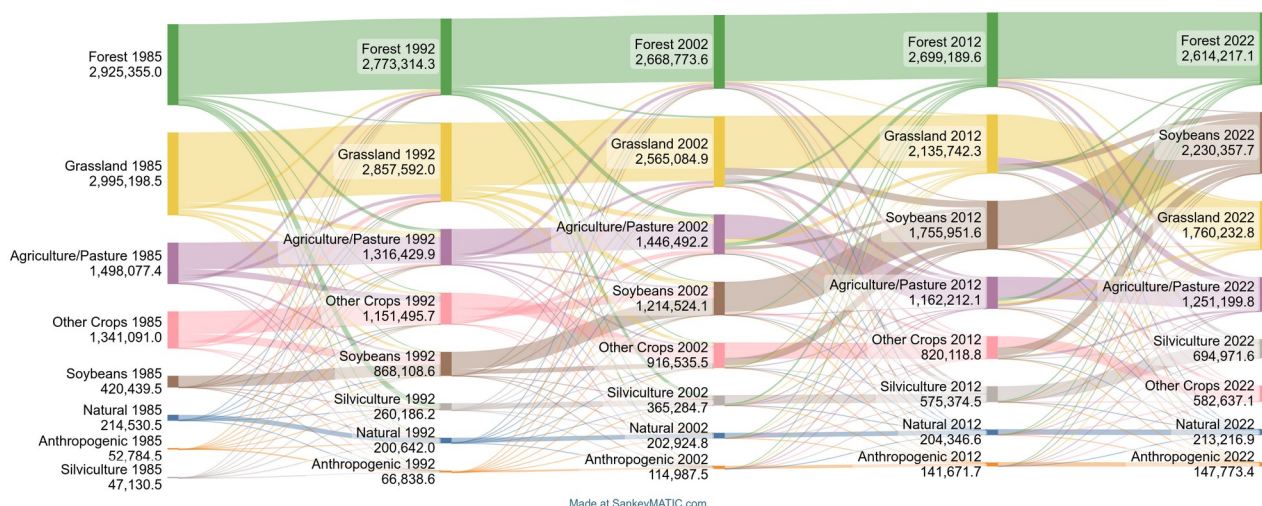


Figure 3: Sankey diagram of estimated land use classes for the four periods with area in hectares. The bars represent the portion from the left transition to right over time. From the top we have Forest in green, Grasslands in Yellow, Agriculture/Pasture in Purple, Other Crops in Pink, Soybean in Brown, Natural in Blue, Anthropogenic in Orange and Silviculture in Grey.

adapted to survive and reproduce during flood periods. Morphological adaptations, such as exaggerated pores on stems and the development of soft tissues with air channels, allow these trees to thrive even during inundation. Dam construction and changes to river hydrology can negatively impact riparian forests. (Swanson & Bohlman, 2021) Protecting soil is also vital for ecosystem health and sustainable agriculture. Soil erosion, compaction, and contamination degrade soil quality. Conservation practices such as crop rotation, cover cropping, and reduced tillage help maintain healthy soil. Policies and awareness campaigns promote soil conservation efforts.

For the whole hydrographic region values of natural vegetation status in 2022, we counted the pixels whose status was always or never natural and the aggregated "gain" and "loss" areas. We then compared the status of the two biomes, including the flooded area, and then for just the flood estimate. The flooded area had a higher long-term stable anthropogenic ratio even though water pixels are natural and concentrated there, with the Pampa biome having the smallest percentage of never-natural spots. As shown in **Table 3**, the loss of natural areas was higher in the Pampa (33.2%) compared to the Atlantic

4. Conclusions

Protecting sensitive areas near rivers, including deforestation reduction and promoting the restoration of natural vegetation, has a significant effect only when neighbouring regions are planned in conjunction. Increasing riparian floodplain coverage is necessary to mitigate the consequences of extreme weather events, however it will not be sufficient by itself. If land cover transformation prioritizes poor natural resource management to expand agricultural areas, it will make the environment more vulnerable to disastrous outcomes.

The Pampa biome had the smallest percentage of anthropogenic spots. The loss of natural areas was higher in the Pampa (33.2%) compared to the Atlantic forest (18.1%) and even lower in the flooded area (16.8%). The protection rules for the Atlantic Forest and protected areas near rivers may have reduced human expansion in those areas and eventually forced it to the Pampa. The flooded area recovered 13.2% against only a 9.5% average in the Pampa.

The study showed a significant increase in soybean cultivation (430% greater area), leading to decreased natural pastures in the Pampa biome from 1985 to 2022. Protecting and restoring native grasslands is crucial for

ecological services, including water runoff reduction, biodiversity, and ecological balance.

	Watershed	Pampa	Atlantic forest	Flooded Area
Anthropogenic	26.5%	21.8%	30.2%	39.3%
Loss	-25.2%	-33.2%	-19.1%	-16.8%
Gain	10.7%	9.5%	11.5%	13.2%
Natural	37.6%	35.6%	39.2%	30.6%

Table 3: Anthropogenic and natural areas persistence, gain and loss on the watershed, the Pampa biome part, the Atlantic Forest biome section and the flooded area.

The following steps include processing the full 38-year dataset. It can be more accurate to process groups of 5 years together to reduce the absence of data having a temporary recovery counted as an actual natural land gain. A lengthy approach is to do 1985-1990 with 1995-2000, 2005-2010, 2015-2022, and in parallel, analyze the groups 1990-1995, 2000-2005, and 2010-2015 to get robust information as all years are available. It will take longer to process and evaluate the whole set.

Another possibility is repeating the analysis from this study in other areas of interest in Brazil or even a full biome or the whole country.

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