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Multivariate analysis of the factors influencing soil organic carbon stock (0–30 cm) based on land use and its transitions in the Atlantic Forest Biome

A.A.P.D. Baker[1,*], F.C. Da Silva[1] and A.L. Belém[2]

[1]Fluminense Federal University, Department of Agricultural and Environmental Engineering, Niterói, Rio de Janeiro, BR24210-240, Brazil
[2]Fluminense Federal University, Graduate Program in Ocean and Earth Dynamics, Niterói, Rio de Janeiro, BR24210-240, Brazil
[*]Correspondence: annaamandipdb@gmail.com

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Abstract. Soil organic carbon (SOC) stocks co-vary with land use, land-cover dynamics and their temporal transitions in human-modified biomes such as the Atlantic Forest. This study explores how land-use classes and their annual transitions help to understand the dynamics of SOC variability in the 0–30 cm layer using MapBiomas Soil data and Principal Component Analysis (PCA). This study analyzed total SOC stocks, the areal extent of major land uses (forest, pasture, agriculture, non-vegetated areas, forestry plantations, hydrography and herbaceous vegetation), and their dominant transitions. Correlation analysis indicated positive associations between SOC and pasture, herbaceous vegetation and native forest, whereas agriculture, forestry plantations and non-vegetated areas were negatively related to SOC stocks, in line with recent findings for Brazilian landscapes. In the PCA, the first component (PC1) captured most of the variance and was strongly associated with SOC and transitions between open and vegetated areas, representing a gradient linked to the intensity of landscape conversion. PC2 was mainly associated with transitions involving gains in forestry plantations, corresponding to a gradient of plantation expansion or contraction, while PC3 was associated with transitions affecting water bodies and wetlands, indicating a secondary axis of SOC variation. Overall, the results suggest that both current land use and the direction and intensity of land-cover change are key factors associated with SOC stocks. These patterns are consistent with the importance of conserving vegetation cover and promoting stable, sustainable land management to maintain and enhance soil carbon in agricultural and natural environments across the Atlantic Forest biome.

Key words: land use, MapBiomas, principal component analysis, remote sensing, sustainable management.

INTRODUCTION

Greenhouse gas (GHG) emissions intensified by climate change pose significant challenges to agricultural productivity and food security through the increasing frequency and severity of extreme climatic events. Carbon dioxide (CO_2) is a major GHG, and in its atmospheric form acts as a climate forcing agent, being released

primarily through fossil fuel combustion, deforestation, land-use change and inadequate management in agricultural systems. Soils represent a critical component of the global carbon cycle, as they can store soil organic carbon (SOC) and thus mitigate CO_2 accumulation in the atmosphere. Globally, soils constitute the largest terrestrial carbon reservoir, storing approximately twice as much carbon as the atmosphere and two to three times more than vegetation biomass (Trumbore & Camargo, 2008; Assad et al., 2013).

The elevated concentrations of CO_2, CH_4 and N_2O are associated with rising average global temperatures and more intense climatic extremes, which directly influence natural biogeochemical cycles, including carbon dynamics (IPCC, 2014). During photosynthesis, plants assimilate atmospheric CO_2, yet a portion of captured carbon returns to the atmosphere through plant respiration, organic matter decomposition and biomass combustion. Unsustainable land management practices disrupt this balance by reducing soil carbon sequestration potential, particularly in intensively managed agricultural landscapes and urban areas (Carvalho et al., 2010; Popin et al., 2025).

The Atlantic Forest biome has experienced extensive anthropogenic modification, including urban expansion and land-use intensification, which warrants focused investigation of soil carbon stocks in this region. Remaining native vegetation is highly fragmented, with a large proportion of forest edges, underscoring the biome's vulnerability to further degradation and carbon loss (Ribeiro et al., 2009; Guerrini et al., 2024).

Conservation-oriented management practices, such as agroforestry, crop rotation, no-tillage, sustainable pasture management, integration of livestock with forestry or cropping systems (ILPF), and improved water management, have demonstrated potential to increase SOC stocks. These practices contribute to enhanced soil fertility, reduced erosion, increased microbial activity and strengthened ecosystem services (Lal et al., 2006; Khan et al., 2023; Mir et al., 2023). By contrast, conventional agriculture, monocultures, extensive grazing, biomass burning and deforestation have been linked to greater carbon emissions and reduced SOC retention (Resende & Rosolen, 2013).

Climatic extremes, such as prolonged droughts and intense precipitation events, influence carbon cycling by altering ecosystem carbon sequestration capacity (Piao et al., 2019). Reductions in SOC can, in some cases, become difficult to reverse, with important implications for long-term carbon dynamics and climate mitigation strategies. Recent research in Atlantic Forest landscapes indicates that SOC stocks vary according to environmental conditions and land-use history, highlighting the need for sustainable management and conservation to mitigate greenhouse gas emissions (Guerrini et al., 2024; Silva et al., 2025).

The adoption of sustainable agricultural practices not only helps improve soil fertility and carbon retention but also supports global sustainability goals, including United Nations Sustainable Development Goals (SDG) 2 (Zero Hunger) and SDG 13 (Climate Action). In Brazil, public policies aimed at reducing land-use change emissions and conserving natural carbon stocks emphasise the importance of understanding the relationship between land use and SOC dynamics (Brasil, 2023). Analysing how land-use and land-cover changes (LULC) influence soil carbon stocks is therefore essential for effective mitigation and land-use planning (Leite et al., 2019; Santos et al., 2023; Popin et al., 2025). Activities such as deforestation, burning and pasture

degradation compromise the soil's capacity to retain carbon, whereas sustainable land management can mitigate and potentially reverse these impacts (APIB, 2018).

This study aims to analyse the relationships between soil organic carbon (SOC) stocks and changes in land use and land cover in the Atlantic Forest biome from 1985 to 2023. Using large-scale spatial data integrated through Google Earth Engine and Python, this research identifies the land-use classes and transitions that most strongly co-vary with SOC, thereby supporting a better understanding of the patterns associated with soil carbon dynamics in this critically threatened biome.

MATERIALS AND METHODS

Study area

The Atlantic Forest biome extends along the eastern portion of South America, approximately between latitudes 3°S and 31°S and longitudes 35°W and 60°W, originally covering about 148 million hectares (Ribeiro et al., 2009). In Brazil, it is discontinuously distributed across 17 states, predominantly along the coastal region, with narrower extensions in the Northeast and broader areas in the Southeast and South. The biome forms transition zones with other major ecosystems, including the Pampa to the south, the Pantanal and Chaco to the west-southwest, the Cerrado to the west, and the Caatinga towards the interior of the Northeast.

In this study, the spatial boundaries of the Atlantic Forest were defined using reference maps from MapBiomas Brazil Collection 10[1], which follow the official Brazilian biome limits at a scale of 1:250,000. In addition, a 5-km buffer surrounding the official biome boundary was included to represent ecotonal areas and to reduce edge effects in spatial analyses (MapBiomas, 2025).

Data sources

Soil organic carbon (SOC) data (1985–2023)

Annual soil organic carbon data were obtained from the Google Earth Engine (GEE) platform using the MapBiomas Soil, Collection beta v2 (MapBiomas, 2025; Asset ID: https://code.earthengine.google.com/3c31fa3660f6e70afbee81c2d244e02f). SOC is provided as a gridded product representing soil organic carbon stocks in the 0–30 cm layer (Mg C ha^{-1}) at 30×30 m resolution. For each year, the SOC layer was first clipped to the Atlantic Forest boundary and was then computed the total SOC stock for the biome by summing pixel-level stocks multiplied by pixel area (0.09 ha), yielding annual totals expressed in gigatonnes (Gt C). The analysed time series spans from 1985 to 2023 (39 years). Annual totals were exported as .csv files, merged and processed in Python within the Google Colab environment.

Land use and land cover (LULC) data:

Land-use and land-cover (LULC) data were obtained from the MapBiomas Brazil Collection 10 at 30×30 m resolution for the same period as the SOC dataset (1985–2023), from the MapBiomas platform. For each year, was used the official MapBiomas Brazil Collection 10 legend to compute the area (ha) occupied by each

[1] Available at: https://brasil.mapbiomas.org/. Accessed: 20/01/2026

land-use and land-cover class within the Atlantic Forest biome and to group them into the following categories: Forest, Herbaceous and Shrubby Vegetation, Agriculture, Forest Plantation, Mosaic of Uses (mosaic class as defined by MapBiomas), Pasture, Non-vegetated Area and Water and Marine Environment (coastal and inland water). These categories follow the MapBiomas legend and are mutually exclusive and collectively exhaustive, such that their areas sum approximately to the total biome area for each year (closed composition). Annual areas (ha) for each category were exported as .csv files, cleaned, standardised and consolidated in the Google Colab environment. A summary of LULC classes and their temporal evolution (Table 1).

LULC transition data:

Land-use and land-cover transition data were obtained from the annual pixel-level transition matrices of MapBiomas Brazil Collection 10 at 30×30 m resolution. For each pair of consecutive years (t, t+1), was classified pixel transitions into five mutually exclusive categories. For each year, the area (ha) associated with each category was summed over the Atlantic Forest biome, resulting in annual transition areas for the five classes used in subsequent analyses (Table 3).

Categories:

The 'open' class group encompasses MapBiomas Brazil Collection 10 legend classes mapped as Pasture, Agriculture and Non-vegetated area (including subclasses such as beaches/dunes, urban infrastructure and mining). The 'vegetation' group includes all Forest formations and Herbaceous and Shrubby Vegetation/Non-forest natural formations. Accordingly, category 1_2 represents pixel-wise transitions from open classes (Pasture, Agriculture, Non-vegetated area) to forest or non-forest natural vegetation between year t and t+1, while 2_1 represents the reverse transitions from forest and other natural vegetation to open classes. Category 3 aggregates gross gains in Forest Plantation from any non-plantation class, and therefore reflects all transitions into planted forests regardless of simultaneous losses elsewhere. Categories 4 and 5 summarise hydrological changes: 4 comprises transitions from Water and Marine Environment to non-water land-cover classes (reductions in water surface), whereas 5 comprises transitions from non-water classes to Water and Marine Environment (increases in water surface).

Data processing and statistical analysis

All analyses were performed in the Google Colab environment using Python 3, with integration to Google Drive for data storage and management. Input datasets were structured as dataframes using the pandas library. Prior to statistical analysis, all variables were standardised using the z-score method, resulting in a mean of zero and a standard deviation of one, which is essential for comparing variables expressed in different units and magnitudes.

Because SOC, LULC areas and transition areas are annual biome-aggregated time series, was first examined their temporal structure. Time-series plots and Kendall correlations between year and each variable were inspected, revealing monotonic trends for several LULC classes and for SOC. These checks indicate the presence of temporal autocorrelation and shared trends, which motivated a cautious, exploratory interpretation of the multivariate analyses rather than formal time-series modelling.

LULC class areas form a closed composition that approximately sums to the total biome area in each year. To reduce singularity and compositional dependence, PCA was applied to the proportional area of each LULC category relative to total biome area, and Hydrography was retained only for descriptive summaries, not as an active variable in the PCA.

Principal component analysis (PCA):

Principal Component Analysis (PCA) was conducted using the scikit-learn library as an exploratory multivariate technique for dimensionality reduction. PCA was applied to investigate the relationship between total SOC stocks and: (i) the area occupied by each LULC class and (ii) annual land-use transition areas. Independent PCAs were performed for each dataset to identify distinct multivariate patterns associated with land-use composition and transition dynamics.

To evaluate variable structure, grouping patterns and relative contributions to the principal components, heatmaps of PCA loadings were generated using the seaborn and matplotlib libraries (Fig. 1 and Fig. 2). PCA biplots were also produced to illustrate the distribution of years and variable vectors within the component space, for land-use classes (Figs 3, A; 4, A; 5, A) and transitions (Figs 3, B; 4, B; 5, B), enabling the simultaneous interpretation of variable contributions and temporal patterns.

PCA was employed as an exploratory tool to identify the variables that most strongly co-vary with soil organic carbon stocks rather than to establish causal relationships. In addition, was calculated Kendall's rank correlation coefficients between SOC, LULC classes and land-use transitions as non-parametric measures of association that do not rely on normality assumptions (Tables 3 and 4).

No formal time-series models (e.g. autoregressive or distributed-lag models) were fitted, so all PCA and correlation results should be interpreted as descriptive patterns of co-variation over time rather than as estimates of mechanistic effects. The interpretation of PCA loadings followed the framework proposed by Johnson & Wichern (2007), with the arbitrary sign of components used only to describe contrasts between groups of variables rather than absolute directions of effect, and the combined use of PCA and Kendall correlation is treated here as an exploratory strategy following Santi et al. (2012), Batista et al. (2021) and Crivelari-Costa et al. (2023).

From a process perspective, SOC stocks in the 0–30 cm layer typically respond to land-use changes over time scales of years to decades rather than instantaneously. In this study, were related annual SOC totals to contemporaneous LULC and transition metrics without explicit lag structures, which likely smooths short-term responses and limits causal interpretation at biome scale.

RESULTS AND DISCUSSION

The results are presented in two complementary parts. First, temporal trends in SOC stocks, LULC areas, and transition magnitudes for the Atlantic Forest biome are described. Second, PCA and Kendall correlations are used as exploratory tools to characterise multivariate patterns of co-variation between SOC and land-use variables over time, rather than to infer causal effects or to build predictive time-series models.

Soil organic carbon

Over the analyzed historical series, the total soil organic carbon (SOC) stock in the Atlantic Forest biome exhibited relative stability, with a slight decreasing trend between 1985 and 2023 (Table 1). Estimates indicate a reduction from approximately 5,660 Gt in 1985 to about 5,617 Gt in 2023, with a peak observed in 1995 (5,675 Gt) and gradual decreases after 2005.

Table 1. Soil organic carbon dynamics in the Atlantic Forest biome

Year	SOC stock (Gt C)
1985	5,660
1995	5,675
2005	5,643
2015	5,627
2023	5,617

Note: 1 Gt = 10^9 t of carbon.

This behavior suggests that, although the biome still functions as an important national-scale reservoir of soil carbon, land-use and land-cover changes observed over recent decades are consistent with limited SOC gains, resulting in an overall pattern of stagnation or slow loss over time. This pattern is consistent with studies reporting SOC loss or stabilization in landscapes subjected to agricultural intensification, urban expansion, and conversion of natural vegetation (Carvalho et al., 2010; Zhang et al., 2024).

In this context, the results are consistent with the relevance of conservation-oriented agricultural management strategies as key approaches for maintaining and increasing SOC stocks. Practices such as pasture restoration and improvement, adoption of integrated production systems, and increased permanent soil cover have been widely recognized for their potential to restore carbon stocks in degraded soils, as highlighted by Resende & Rosolen (2013) and Conant et al. (2017).

These temporal patterns should be interpreted considering that biome-scale SOC reflects the cumulative effects of past land-use histories and slow adjustment processes, so annual LULC transitions are unlikely to produce large detectable changes in total SOC without accounting for response lags.

Land-use and land-cover dynamics

Between 1985 and 2023, a significant reduction in native forest area was observed, decreasing from approximately 34.15 to 30.51×10^6 ha, while agricultural areas expanded markedly, increasing from 10.65 to about 20.81×10^6 ha (Table 2). Over the same period, forest plantations also expanded continuously, from 0.91 to 4.45×10^6 ha.

Table 2. Areas of land-use and land-cover classes in the Atlantic Forest biome for selected years

Classes	Year				
	1985	1995	2005	2015	2023
Forest (10^6 ha)	34.15	31.26	30.76	30.95	30.51
Herb./shrubby (10^6 ha)	4.26	4.13	4.13	3.84	3.47
Agriculture (10^6 ha)	10.65	15.25	16.48	20.35	20.81
Forest plantation (10^6 ha)	0.91	1.70	2.36	3.98	4.45
Mosaic of uses (10^6 ha)	21.49	16.29	17.13	16.61	18.47
Pasture (10^6 ha)	35.86	38.36	35.67	30.50	28.09
Non-vegetated (10^6 ha)	1.33	1.53	1.90	2.26	2.55
Hydrography (10^6 ha)	2.02	2.16	2.25	2.18	2.32

In contrast, pasture areas declined from 35.86 to 28.09×10⁶ ha, as did herbaceous and shrubby vegetation, indicating a gradual replacement of these land-cover types by more intensive uses. Although the mosaic of uses exhibited temporal fluctuations and an overall reduction in total area, it reflects a spatial reorganization of the landscape over time, associated with increasing fragmentation and anthropogenic heterogeneity.

These patterns are consistent with recent assessments identifying agricultural expansion, silviculture, and urbanization as major drivers of transformation in the Atlantic Forest biome, promoting the progressive replacement of natural formations by productive land uses and anthropogenic mosaics (IBGE, 2020; Guerrini et al., 2024). The combined reduction of forested and herbaceous areas and the increase in agriculture, forest plantations, and non-vegetated areas are consistent with the negative correlations observed between SOC and these more intensive land-use classes, as well as the land-use intensification gradient captured by the first principal component (PC1).

Land-use and land-cover transitions

Analysis of land-use and land-cover transitions indicates that, across all evaluated periods, areas converted from vegetation to open land uses exceeded, in magnitude, the reverse conversions from open areas to vegetation (Table 3). Between 1989–1990 and 1994–1995, for example, transitions from vegetation to open areas ranged from approximately 561 to 483×10³ ha, whereas conversions from open areas to vegetation remained around 350–376×10³ ha.

Table 3. Land-use transition areas in the Atlantic Forest biome (10³ ha)

Period (from–to)	Open to vegetation[1]	Vegetation to open[2]	Gain in forestry[3]	Reduce water[4]	Add water[5]
1989-1990	350	561	89	38	60
1994-1995	376	483	72	60	44
2004-2005	363	322	163	34	44
2014-2015	285	315	135	36	32
2022-2023	256	302	12	37	81

[1]Transitions from classes of pasture, agriculture or non vegetated areas to forest cover or natural non forest areas; [2]Transitions from forest cover or natural non forest areas to pasture, agriculture or non vegetated areas; [3]Transitions with gain in forestry areas; [4]Transitions that reduce water surface; [5]Transitions that add water surface.

During the periods 2004–2005 and 2014–2015, this pattern persisted, with a notable increase in areas associated with gains in forest plantations, reaching up to 163×10³ ha in 2004–2005, reflecting the expansion of silviculture in the biome. In the most recent period (2022–2023), a reduction in forest plantation gains was observed, accompanied by a relatively higher increase in areas with added water surface, possibly associated with changes in reservoirs and other water bodies.

Overall, these patterns are consistent with the positive correlations observed between SOC and transitions from open areas to vegetation, as well as with weaker negative correlations associated with the expansion of forest plantations. The results suggest that natural vegetation recovery processes are associated with the maintenance of soil carbon stocks, whereas the expansion of agricultural and homogeneous forest uses, when accompanied by reductions in native vegetation and hydrological alterations, contributes to SOC stagnation or loss.

Principal component analysis (PCA)

Principal Component Analysis (PCA) was applied to investigate the relationships between soil organic carbon stock (SOC) and (i) land-use and land-cover class areas and (ii) annual land-use transitions in the Atlantic Forest biome from 1985 to 2023. This approach reduced data dimensionality while preserving most of the original variability, allowing identification of multivariate patterns associated with land-use dynamics and soil carbon stocks.

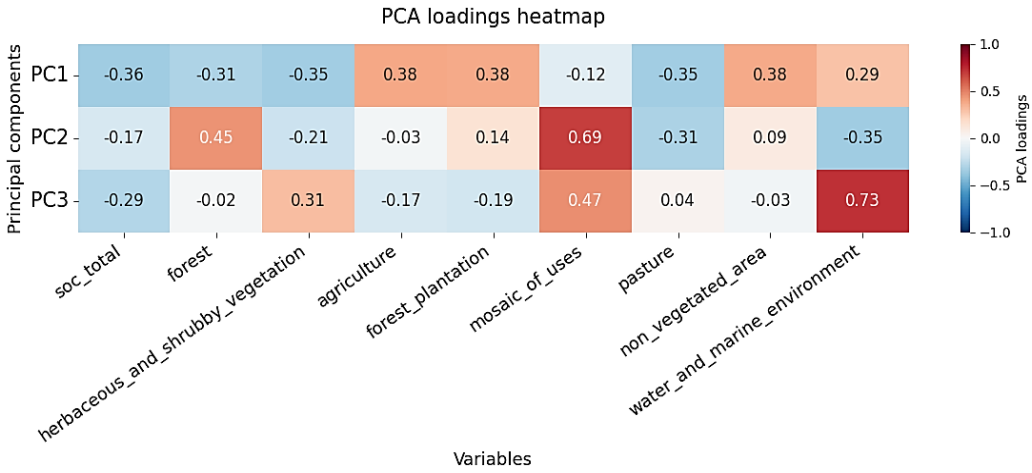


Figure 1. Heatmap of PCA loadings for land-use and land-cover variables and total SOC in the Atlantic Forest biome.

For the PCA including SOC_total and land-use and land-cover classes, the first three principal components explained 97.24% of the total variance, with 74.21% attributed to PC1, 19.11% to PC2, and 3.93% to PC3.

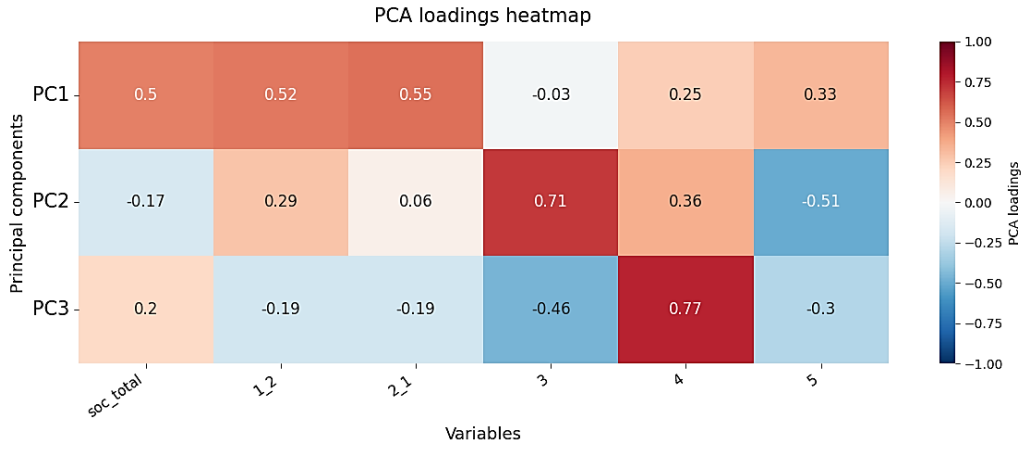


Figure 2. Heatmap of PCA loadings for land-use and land-cover transition variables and total SOC in the Atlantic Forest biome.

For land-use transitions, PC1 showed positive loadings for SOC_total, transitions from open areas to vegetation (1_2), transitions from vegetation to open areas (2_1) and both reductions and increases in water surface (≈ 0.50–0.55), while gains in forest plantations contributed little to this axis (Fig. 2 and Fig. 3; B). This component represents a general gradient in the magnitude of land-use and hydrological change over time, indicating that years with more intense transition activity tend to display larger SOC fluctuations, although this association may partly reflect the common temporal structure of the series. The high proportion of variance explained by the first components supports their use for summarising dominant multivariate patterns in the data (Morrison, 2003; Johnson & Wichern 2007; Jolliffe & Cadima, 2016).

Loadings are shown in the heatmaps in Fig. 1 (land-use classes) and Fig. 2 (transitions), while the distribution of years and variables in component space is illustrated in the biplots in Figs 3A–5A (LULC) and Figs 3, B–5, B (transitions).

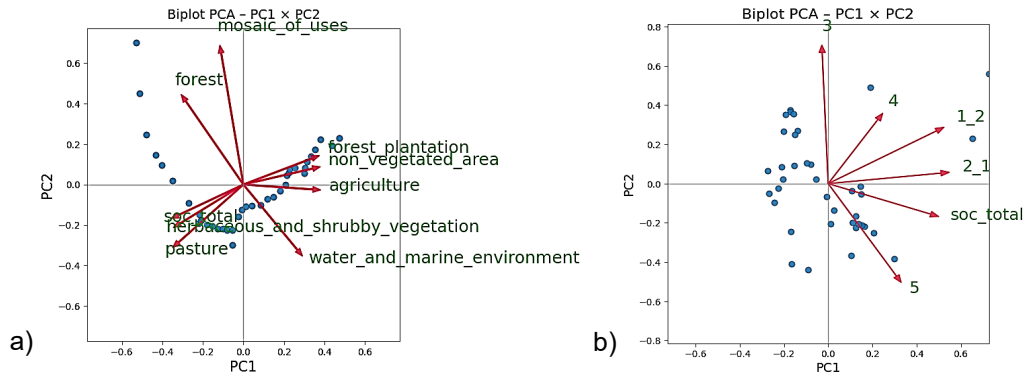


Figure 3. PCA biplots (PC1 × PC2) for (A) land-use and land-cover variables and SOC, and (B) land-use and land-cover transition variables and SOC in the Atlantic Forest biome.

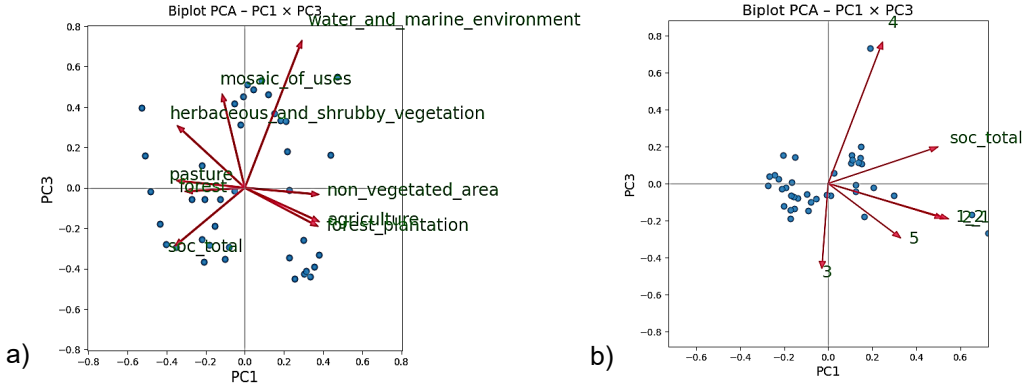


Figure 4. PCA biplots (PC1 × PC3) for (A) land-use and land-cover variables and SOC, and (B) land-use and land-cover transition variables and SOC in the Atlantic Forest biome.

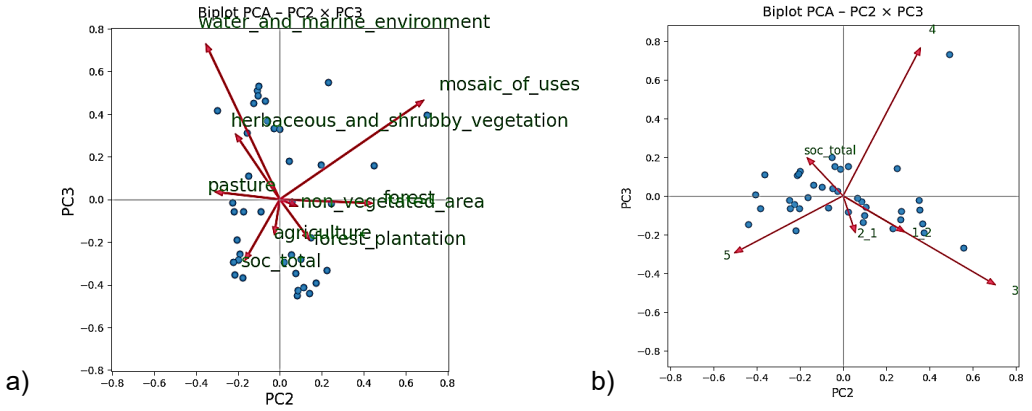


Figure 5. PCA biplots (PC2 × PC3) for (A) land-use and land-cover variables and SOC, and (B) land-use and land-cover transition variables and SOC in the Atlantic Forest biome.

PCA patterns for land-use and land-cover classes

In the PCA including SOC_total and land-use classes, PC1 showed positive loadings for Agriculture, Forest Plantation and Non-vegetated area (≈ 0.38) and negative loadings for Forest, Herbaceous and Shrubby Vegetation, Pasture and SOC_total (−0.35 to −0.29), while Mosaic of uses remained near zero (Fig. 1 and Fig. 3, A). This axis represents a clear land-use intensification contrast, opposing years and landscapes dominated by agriculture, planted forests and exposed surfaces to those with greater forest cover, herbaceous vegetation and pastures, with SOC aligned with the latter. These co-variation patterns are consistent with recent meta-analyses reporting substantial SOC losses following conversion of forests and grasslands to croplands (Beillouin et al., 2023.

Taken together, PC1 scores and SOC behaviour over time suggest that years with a higher relative dominance of intensive land uses tend to coincide with lower SOC stocks, whereas years with greater representation of native vegetation and pastures tend to coincide with higher SOC levels. However, part of this gradient may reflect shared long-term trends in land-use composition and SOC rather than direct causal responses, so PC1 should be interpreted as a descriptive axis of co-variation through time.

PC2 showed a strong positive association with Mosaic of uses (≈ 0.69) and a moderate association with Forest (≈ 0.45), along with a negative association with non-vegetated area (≈ −0.35) (Fig. 1 and Fig. 5, A). This component reflects a gradient between heterogeneous, partially forested landscapes and open, non-vegetated areas, suggesting that more diversified land-use configurations with greater tree cover co-vary with more favourable SOC conditions, in line with Conant et al. (2017).

PC3 exhibited a strong positive loading for Water and Marine Environment (≈ 0.73), with moderate positive contributions from Mosaic of uses and Herbaceous and Shrubby Vegetation, while Agriculture, Forest Plantation, and SOC total showed negative loadings (Fig. 1 and Fig. 4, A). This secondary component represents a gradient associated mainly with aquatic environments and non-forest vegetation, indicating localized co-variation between SOC and hydrological dynamics, with a smaller contribution to overall variance than the land-use intensification gradient of PC1.

Overall, Fig. 1 and Figs 3, A–5, A show that SOC is more strongly associated with forest, herbaceous and shrubby vegetation, and pasture, in contrast to agriculture, forest plantations, and non-vegetated areas. This pattern highlights the importance of conserving native vegetation and sustainably managed pastures for maintaining soil carbon stocks.

PCA patterns for land-use transitions

For land-use transitions, PCA was applied to SOC_total and the five transition categories (1_2, 2_1, 3, 4 and 5) derived from the MapBiomas transition matrices. Categories 1_2 and 2_1 represent bidirectional conversions between open classes (pasture, agriculture and non-vegetated areas) and vegetation (forest and natural non-forest formations), whereas category 3 captures gross gains in forest plantation area and categories 4 and 5 represent reductions and increases in water surface, respectively. The resulting components therefore summarise co-variation between SOC and the magnitude of these distinct types of transitions across years.

PC2 showed a strong positive association with gains in forest plantations (≈ 0.71) and a moderate positive association with water surface reduction, along with a negative association with water surface increase (Fig. 2 and Fig. 4B). This gradient highlights a distinct gradient associated with silvicultural expansion and hydrological change, with SOC co-varying with these processes but without implying direct causal effects.

PC3 was dominated by strong positive loadings for water surface reduction (≈ 0.77) and negative loadings for forest plantation expansion and water surface increase (Fig. 2 and Fig. 5, B), reflecting a specific hydrological gradient with secondary co-variation with SOC at biome scale.

Integration of PCA and Kendall correlations

The Kendall correlation coefficients are consistent with the multivariate patterns identified by PCA, showing that SOC co-varies positively with Forest, Herbaceous and Shrubby Vegetation and Pasture, and negatively with Agriculture, Forest Plantation and Non-vegetated area (Table 4 and 5).

Table 4. Kendall correlation coefficients between SOC and land-use transitions

Variables	Total of SOC	1_2	2_1	3	4	5
Total of SOC	1.00000	0.50106	0.61494	-0.16512	0.20213	0.30462
1_2	0.50106	1.00000	0.38549	0.02133	0.23470	0.21763
2_1	0.61494	0.38549	1.00000	-0.32005	0.17780	0.40540
3	-0.16512	0.02133	-0.32005	1.00000	0.04125	-0.39687
4	0.20213	0.23470	0.17780	0.04125	1.00000	-0.10953
5	0.30462	0.21763	0.40540	-0.39687	-0.10953	1.00000

Strong negative correlations between Pasture and Agriculture ($\tau \approx -0.88$) and between Pasture and Forest Plantation ($\tau \approx -0.90$), as well as strong positive correlations between Agriculture and Non-vegetated area ($\tau \approx 0.96$) and between Forest Plantation and Non-vegetated area ($\tau \approx 0.98$), are consistent substitution pattern between land uses that tend to conserve SOC and those associated with SOC depletion.

For transitions, SOC_total showed moderate positive correlations with transitions from open areas to vegetation (1_2; $\tau \approx 0.50$) and from vegetation to open areas (2_1;

$\tau \approx 0.61$), and a positive correlation with water surface increase ($\tau \approx 0.30$). The weak negative correlation between SOC and forest plantation expansion ($\tau \approx -0.17$) suggests that plantation expansion at biome scale is not necessarily associated with SOC gains, possibly due to short rotations, intensive soil preparation, and replacement of more diverse vegetation by monocultures.

Table 5. Kendall correlation coefficients between SOC and land-use/land-cover classes

Variable	Correlation with total of SOC
Total of SOC	1.00000
Forest	0.45209
Herb./Shrubby	0.68691
Agriculture	-0.77058
Forest Plantation	-0.78137
Mosaic of Uses	-0.14979
Pasture	0.79757
Non-vegetated area	-0.79757
Hydrography	-0.44669

Taken together, PCA and correlation analyses are consistent with the view that conservation of native vegetation, restoration of degraded areas, and control of land-use transitions that intensify land exploitation are important pathways associated with the maintaining and increasing soil organic carbon stocks in the Atlantic Forest biome, in agreement with recent evidence from restored fragments and landscapes (Bieluczyk et al., 2023; Guerrini et al., 2024; Crivelari-Costa et al., 2023).

CONCLUSIONS

This study provides an exploratory, biome-scale assessment of how SOC stocks co-vary with land-use composition and annual land-use transitions in the Atlantic Forest, based on MapBiomas products and multivariate analyses. The results suggest that landscapes with greater proportions of native vegetation and pastures tend to be associated with higher SOC stocks, whereas more intensive agricultural and non-vegetated uses are associated with lower SOC levels.

Transitions from open areas to vegetation (i.e. pasture, agriculture, or non-vegetated areas converted to forests or natural non-forest formations) showed a positive association with SOC, while the inverse conversions, particularly from forests and natural formations to agriculture and non-vegetated areas, were associated with lower soil carbon stocks as part of broader land-use intensification patterns. These results suggest that both the direction and the intensity of land-use change are as relevant as the current land use for understanding SOC dynamics at the biome scale.

The PCA revealed that the main gradient of variation (PC1) contrasts landscapes with a higher proportion of native vegetation and pastures with those dominated by agriculture, forest plantations, and open areas, synthesizing an axis of land-use intensification that co-varies with most of the data variance. This pattern, corroborated by Kendall correlations, suggests that systems with greater permanent vegetation cover and lower soil disturbance tend to be associated with stronger carbon accumulation, whereas intensive agricultural systems and exposed surfaces tend to be associated with SOC loss at the biome scale.

Overall, the results indicate that integrated actions focused on the conservation of native vegetation, restoration of degraded areas, sustainable pasture management, and the reduction of conversions to intensive agriculture and non-vegetated areas are important pathways associated with mitigating carbon losses and promoting the recovery

of soil carbon stocks in the Atlantic Forest. These strategies gain additional relevance under climate change scenarios, as they simultaneously contribute to greenhouse gas mitigation and to the maintenance of essential ecosystem services within the biome.

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