Trees, Forests and People 16 (2024) 100569

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Quantifying the impact of Great Green Wall and Corporate plantations on tree density and biomass in Sahelian Senegal

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A R T I C L E I N F O

Keywords:
Great green wall
Remote sensing
Plantation
Tree density
Above-ground biomass
Sahel

A B S T R A C T

The Great Green Wall (GGW) is an international initiative to combat land degradation and restore native plant life in the Sahel, but due to a lack of monitoring tools, it remains unknown to be considered as success or failure. Here, we quantify the impact of GGW plantations and Corporate plantations (privately owned) in Sahelian Senegal based on remote sensing data and deep learning by mapping individual trees and their biomass across the Sahel region. Tree features (cover, density and above-ground biomass) have been computed in every hectare of 42 plantations (of both, corporate and GGW) and their surrounding non-planted areas, subsequently used for a comparative analysis of tree features. Results showed that gains in tree features varied substantially between plantations. At plot scale, among Corporate plantations, the average gain in tree density was 61.16±42.12 trees/ha while it was 5.7 ± 5.8 trees/ha for GGW plantations. In regards to tree cover, the average gain was 618.5 ± 588.5 m^2/ha for Corporate plantations and 71.72±108.89 m^2/ha for GGW plantations. For the above-ground biomass, the average gain was 3.36±3.29 tons/ha in the Corporate plantations and 0.46±0.67 tons/ha in the GGW plantations. The average gain in foliar biomass in the Corporate plantations was 0.15±0.13 tons/ha and in the GGW plantations, it was 0.02±0.03 tons/ha. The average gain in wood biomass was 3.21±3.12 tons/ha among the Corporate plantations and was 0.43±0.64 tons/ha among the GGW plantations. Notably, regarding the relative benefit in terms of ecosystem services per unit of density, each tree in GGW plantations contribute more to ecosystem services per unit of density compared to Corporate plantations. In GGW, each gained tree contributes 18 m^2 of cover, 116.1 kg of above-ground biomass, 5.6 kg of foliar biomass, and 114.2 kg of woody biomass, while in corporate plantations, on the other hand, each gained tree adds 9 m^2 of cover, 48.4 kg of above-ground biomass, 2.3 kg of foliar biomass, and 46.3 kg of woody biomass. These findings are opposed to conventional paradigms, suggesting that the Great Green Wall, while perhaps missing its tree density targets, has succeeded in its mission to produce ecosystem services per tree. This raises important questions about the redefinition of objectives in reforestation projects, focusing on quality rather than quantity, a perspective that could transform our understanding of the successes and failures of these essential ecological restoration initiatives. However, the assessment primarily relies on indicators such as cover and biomass, potentially overlooking other crucial ecosystem services. Therefore, while our conclusions underscore the effectiveness of reforestation initiatives, future research should aim to establish a more comprehensive understanding of ecosystem services by incorporating additional indicators beyond cover and biomass, such as species diversity, soil health, water retention, and habitat quality.

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https://doi.org/10.1016/j.tfp.2024.100569

Available online 10 May 2024

1. Introduction

The Sahel is an ecological transition zone between the Sahara desert and the sub-humid savanna zone, which stretches from Senegal in the west to Sudan in the east. Since the 1960s, the Sahel has suffered by several extreme droughts that have been related to climate change (Giannini et al., 2003; Zeng, 2003; Zeng and Yoon, 2009). These droughts caused a strong degradation of natural resources (Ndong et al., 2015), a decline in agro-silvopastoral production (SNPA/GMV 2012), large losses of livestock and famine to millions of people. Indeed, the aridification of the southern regions of the Sahara is thought to have accelerated over the past 6000 years (Kröpelin et al., 2008). The southern edge of the Sahara has experienced recent fluctuations spanning 1000 km, and expansion is expected to accelerate during the 21st century due to global warming (Zeng and Yoon, 2009).

Many efforts have been made to protect and restore these fragile ecosystems, and particular national reforestation projects throughout the African continent have been numerous in recent years, with varying degrees of success (Woodfine and Jauffret, 2009). In 2007, an original policy initiative was adopted termed the Great Green Wall (GGW) for the Sahara and Sahel initiative (Dia and Niang, 2010). For the first time, 11 Sahelian African countries (Senegal, Mauritania, Mali, Burkina Faso, Nigeria, Niger, Chad, Sudan, Ethiopia, Eritrea, and Djibouti) have joined forces in a pan-African reforestation project with the ambition of creating a continuous series of rehabilitated ecosystems along the length of the African continent, from east to west, covering more than 7000 km (Dia and Niang, 2010). The original vision of the GGW project is to set up planting walls of high tree density to block the expansion of the desert.

In Senegal, this ecological restoration project is now being carried out by the *Agence Sénégalaise de la Reforestation et de la Grande Muraille Verte* (ASERGMV). The success of the project is not only linked to the improvement of technical competencies (such as skills related to environmental science, forestry, ecology and land management) but also to a large extent based on the human factor (how the local communities nurture and tend to these planting activities). Here, the model of governance, the economic interests of populations, and the necessity of sustainable development have been among the parameters to be considered (Boëtsch and Späni, 2013; Turner et al., 2023). An important question to be addressed is to what extent the immediate impact of these plantation initiatives can be observed? Several studies have addressed the vegetation characterization along the GGW during recent years (Abakar Guihini et al., 2021b, 2021a; Mahamat Saleh et al., 2015; Niang et al., 2015, 2014) and the challenges in its establishment and management (Chotte and Thibon, 2021; Ducourneau et al., 2016). As to this date, no study has yet addressed this at the level of single trees and by comparing vegetation features between GGW plantations and those of the surrounding non-planted areas to produce a comprehensive assessment of the planting activities, considering the effect of local biotic and abiotic conditions. How do tree features (cover, density and above-ground biomass) in GGW plantations differ from those in surrounding areas?

Remote sensing is one of the most reliable measurement tools for accurate monitoring of land cover over large areas. The acquisition of a series of multispectral satellite images associated with the appropriate analysis method provides a mapping of vegetation types (Gougeon and Leckie, 2003; Srestasathiern and Rakwatin, 2014). Nowadays, with the evolution of remote sensing technologies, new approaches based on deep learning and satellite images have been developed to identify wood vegetation at the level of individual trees, particularly in the Sahel region. For instance, remote sensing from moderate-resolution satellite images over a large area in the Sahel has allowed the creation of geographic databases on tree densities and cover rates (Brandt et al., 2016) to study woody communities on a larger scale. Segmentation techniques were applied to very high-resolution images to map the crown of each tree (Brandt et al., 2020). A combination of crown area-based allometric equations with satellite imagery was also used to estimate foliage dry mass, wood biomass, and root biomass for individual trees (Tucker et al., 2023). These studies have pave the road towards quantifying the impact of GGW plantations on woody vegetation across the Sahel. Here, we make use of the detailed mapping of woody vegetation in Brandt et al. (2020) to analyze the GGW's impact on tree characteristics in semi-arid Senegal at the level of individual trees. Our study aims to provide new insights into whether trees in GGW plantations in Sahelian Senegal have different characteristics or services as compared to trees in privately initiated plantations. We hypothesize that GGW plantations exhibit higher values in tree features analyzed, as compared to surrounding areas. The analyses include a comparison of tree density, tree cover, and dry mass (above-ground, wood and foliage) in plantations and surrounding non-planted areas for 42 designated sites.

2. Method and materials

2.1. Description of the study area

The study sites are located in the silvopastoral region of Ferlo, northern Senegal (Fig. 1A). The mean of the annual relative humidity is 42.8 ± 3 % over the period 1981–2020, with a monthly maximum mean of 85.1 % in September and a monthly minimum mean of 12.6 % in February ("POWER | Data Access Viewer," v2.0.0). The rainfall is concentrated to a period of 3 to 5 months (late June to early October). The average annual rainfall is 424±142.7 mm during 1981–2020, with a monthly average maximum of 159.8 mm in August and a monthly average minimum of 21.1 mm in June. The average annual temperature is 27.8 ± 0.4 °C, the average annual maximum temperature is 44.8 °C and the average annual minimum temperature is 11.9 °C during 1981–2020 ("POWER | Data Access Viewer," v2.0.0). In the region, the Harmattan wind plays an important role in soil particle transport between late November and mid-March. This very dry northeasterly wind is usually laden with fine particles (0.5 to 10 mcm) (Lyngsie et al., 2013). The vegetation is mixed wood and grassland, where trees are often sparse and vegetation cover is low. Therefore, two strata typically coexist; an herbaceous stratum with annual or perennial species and a woody stratum with trees and shrubs (Akpo et al., 2003; Hiernaux and Le Houérou, 2006).

The study was conducted in 13 communes where GGW plantations and Corporate plantations (for Arabic Gum production) have been installed. GGW plantations are located in the communes of Syer, Mbane, Labgar, Louguéré Thioly, Mboula, Houdalaye and Tessékéré. The Corporate plantations are areas designated for tree plantation managed by a private entity for the production and trading of Arabic gum. Corporate plantations are different from GGW plantations that are managed by the *Agence Sénégalaise de la Reforestation et de la Grande Muraille Verte* (ASERGMV). Corporate plantations are implemented in the communes of Boulal, Dahra, Deali, Kamb, Ouarkhokh, and Sagatta (or Sagatta Djolof). The shapefile delineating the planting plots comes from a local agency and it includes also privately-owned plots like Corporate plantations. A total of 42 planting plots are located in the study area, including 12 Corporate plots and 30 GGW plots (Fig. 1A).

2.2. Data collection and analyses

2.2.1. Data collection

The tree density and coverage database of Brandt et al. (2020) provides geo-referenced polygonal vectors of individual tree canopy geometry for arid and semi-arid areas of the Sahel in Africa. We have used the most recent version of this database (Fig. 1B). From this data source, Tucker et al. (2023) estimated the foliage dry mass, the wood and root biomass of each tree using allometric equations based on the crown area of trees. The term biomass in this study refers to dry biomass. The woody features that were used in this study are tree density, tree cover, above-ground biomass, woody biomass and foliar biomass. Then, sorting by geographical coordinates was carried out to find and download all individual instances of trees encompassed by the shape-files of the study area.

Three buffer zone configurations, a 5 km buffer zone, a 10 km buffer zone and a 10 km buffer zone with an additional 2 km exclusion zone perimeter around the plantation (Fig. 2), were applied to each plantation and a comparative density analysis was computed between the different buffer zones to test the importance of this choice on the analysis output.

The ANOVA test was performed on 100 random samples taken from each buffer zone. This process was iterated 100 times. In each iteration, 100 random samples were extracted from each buffer zone. The choice of 100 samples was based on statistical considerations to ensure the robustness and reliability of the results. Specifically, using 100 samples allowed for a comprehensive assessment of the variability in tree density within each buffer zone configuration. This process was iterated 100 times to account for potential variability in the random sampling process (Moore and McCabe, 1989). The consistent outcome across all 100 repetitions revealed p-values very close to zero (statistically significant difference in tree density among the three buffer zones) (Fig. 3). It is an indication that the observed differences between the groups are unlikely

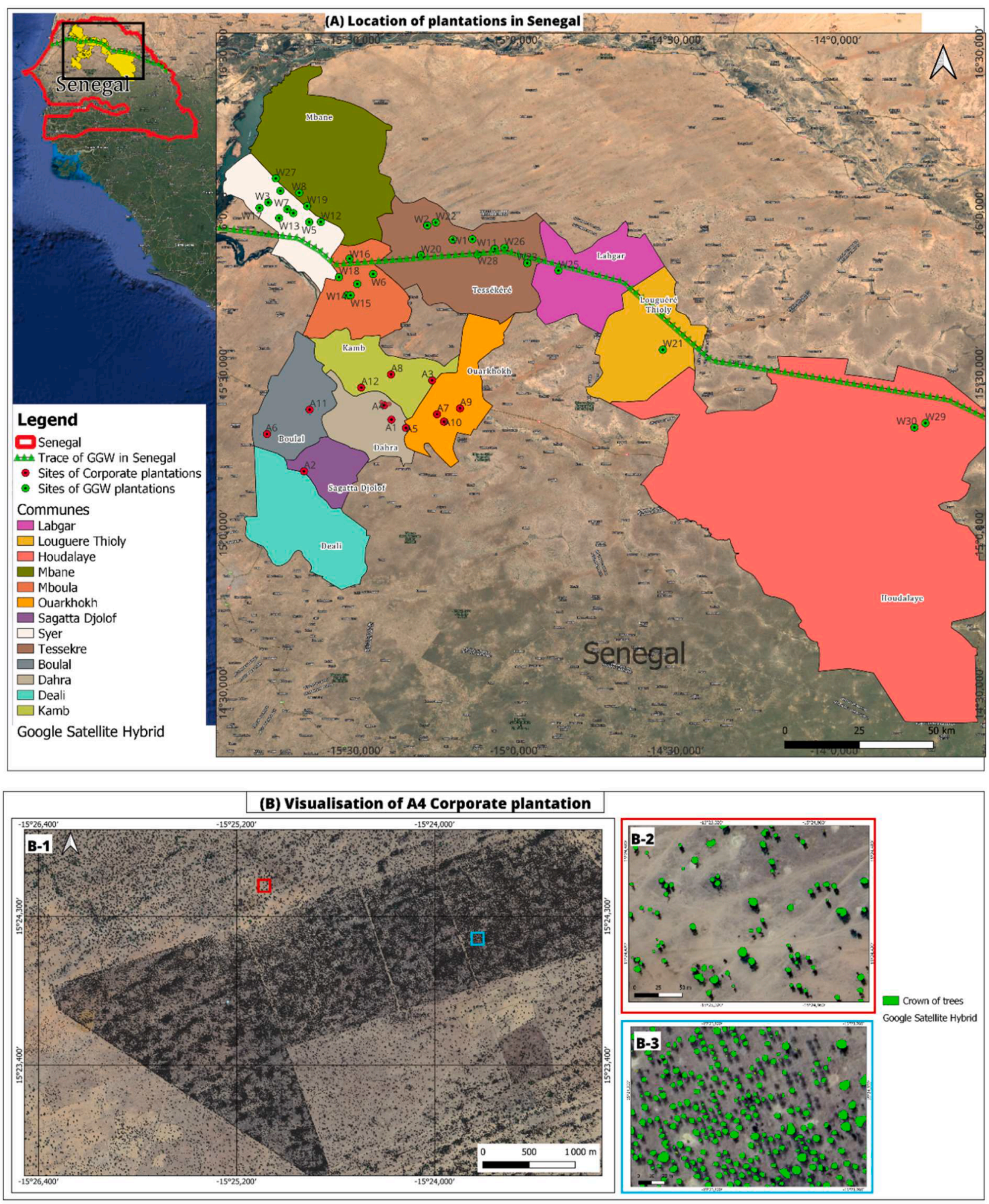

Fig. 1. (A) Location of sites of GGW and Corporate plantations and the trace of the GGW in Senegal. (B) Visualization of geo-referenced polygons of individual tree canopies from the Brandt et al. (2020) database. Tree Individual canopy in a plantation B-3 (−15.39384560, 15.40281971). Tree individual canopy in a non-planted area B-2 (−15.41696360, 15.40780851).

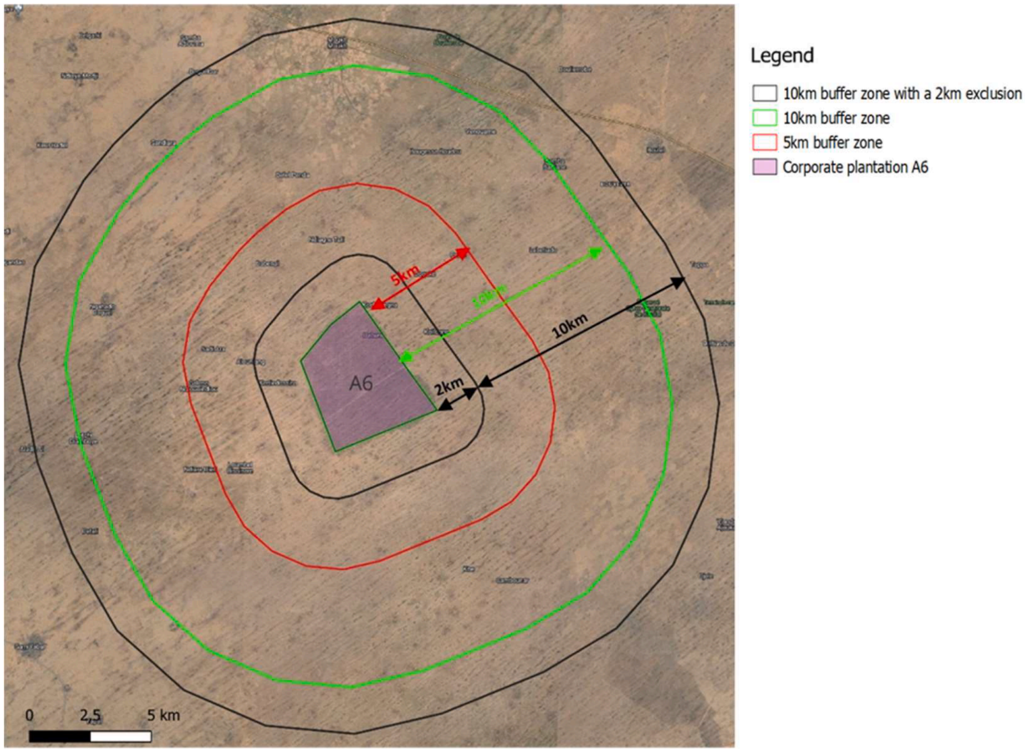

Fig. 2. Illustration of the three buffer zone configurations around the plantation A6.

to have occurred by chance alone. Specifically, in most replications, the 10 km buffer with a 2 km exclusion zone exhibited the highest average tree density per hectare, followed by the 10 km buffer without an exclusion zone, while the 5 km buffer displayed the lowest average tree density per hectare (Table 1, Fig. 3).

Based on the results, the 5 km buffer zone was selected for subsequent analysis. The rationale for this choice was that, among the tested buffer zones, it showed the smallest differences in tree density, indicating a relatively more uniform distribution.

Then a grid of 1 ha was established on the extent of each plantation (planting plot) and its 5 km buffer and the woody biomass, the foliar biomass, the tree cover, and the number of trees were extracted in each hectare using the software QGIS. A subplot equals a 1 ha grid cell. As the shapes of the planting are irregular, the subplots with areas of less than 0:9 ha have been removed. An advanced cleaning has been done on the database, and each planting plot with its buffer zone configuration has been separated as an individual dataset.

The total number of datasets was 42, based on the number of 42 plantations or planting plots (12 Corporate plots and 30 GGW plots). A description of the data is presented in Table 3. The median size of the GGW plantations is 252.19 ha. The biggest GGW plantation covered 2107.05 ha as surface area and counted 2032 subplots after the

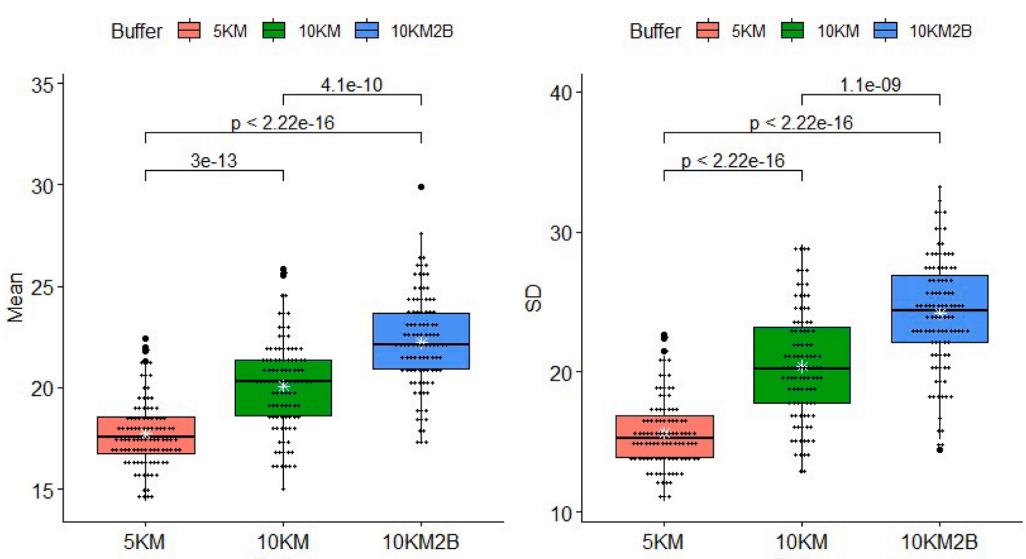

Fig. 3. Comparison of tree density in the three buffer zone configurations. Small black dots (100 per box) indicate the mean density value of each ANOVA simulation. White asterisks represent the average of all 100 replicates per box. 5 KM, 10 KM, 10KM2B represent respectively 5 KM buffer, 10 KM buffer and 10 KM buffer zones with 2 km exclusion.

Table 1
Ratio between gains of tree features to tree density reflecting gains in AGB, foliar and woody biomass, and the tree cover per unit of density in each plantation.

Code of plantation	commune	Management	Cover/density in m^2/tree	Woody/density in Kg/tree	Foliar/density in Kg/tree	AGB/density in Kg/tree
A1	Dahra	Corporate	7.83	41.85	2.04	43.15
A2	Deali, Sagatta Djolof	Corporate	0	0	0	0
A3	Kamb	Corporate	4.25	19.67	1.33	21.00
A4	Dahra	Corporate	7.90	40.16	2.03	41.88
A5	Dahra. Ouarkhokh	Corporate	11.59	60.11	2.83	63.37
A6	Boulal	Corporate	13.51	71.69	3.13	75.63
A7	Ouarkhokh	Corporate	10.37	52.24	2.47	54.94
A8	Kamb	Corporate	8.09	41.48	1.98	42.10
A9	Ouarkhokh	Corporate	4.88	18.89	1.67	18.33
A10	Ouarkhokh	Corporate	10.97	57.09	2.73	61.09
A11	Boulal	Corporate	9.69	51.58	2.63	53.68
A12	Kamb	Corporate	10.36	54.29	2.57	57.14
W1	Tessékéré	GGW	14.25	76.11	3.33	82.22
W2	Tessékéré	GGW	0	0	0	0
W3	Syer	GGW	0	0	0	0
W4	Syer	GGW	7.52	46.25	2.50	48.75
W5	Syer	GGW	0	0	0	0
W6	Mboula	GGW	29.86	188.57	7.14	195.00
W7	Syer	GGW	19.88	114.44	4.44	117.78
W8	Mbane	GGW	1.53	15.00	0	12.50
W9	Syer	GGW	20.58	130	6.67	156.67
W10	Mboula	GGW	32.67	194.44	7.78	206.67
W11	Tessékéré	GGW	19.75	130	6.67	133.33
W12	Syer	GGW	0	0	0	10
W13	Syer	GGW	0	0	0	0
W14	Mboula	GGW	29.28	220	10	200
W15	Mboula	GGW	0	0	0	0
W16	Mboula	GGW	0	0	0	0
W17	Syer	GGW	0	0	0	0
W18	Mboula	GGW	0.61	10	3.33	23.33
W19	Mbane, Syer	GGW	11.13	61.25	2.50	62.50
W20	Tessékéré	GGW	0	0	0	0
W21	Louguéré Thioly	GGW	0	0	0	0
W22	Tessékéré	GGW	0	0	0	0
W23	Tessékéré	GGW	0	0	0	0
W24	Tessékéré	GGW	10.98	55.71	2.86	58.57
W25	Labgar	GGW	4.69	30	1.43	35.71
W26	Tessékéré	GGW	62.24	440	20	510
W27	Mbane, Syer	GGW	7.58	43.00	2.00	44.00
W28	Tessékéré	GGW	13.52	72.38	3.33	76.19
W29	Houdalaye	GGW	0	0	0	0
W30	Houdalaye	GGW	0	0	0	0

advanced cleaning. The smallest GGW plantation was 53.66 ha in size and had 47 subplots after the advanced cleaning. As for the Corporate plantation, the median size is 850.23 ha. The biggest Corporate plantation covered 2375.81 ha size and counted 2266 subplots after the advanced cleaning. The smallest Corporate plantation was 146.66 ha in size and had 128 subplots after the advanced cleaning. The non-planted areas, within the 5 km buffer, included on average 11900 subplots, after the advanced cleaning (Table 3).

- *Tree cover.* The data from Brandt et al. 2020 also include the shape file of all individual tree crowns represented as a polygon. For each polygon, we computed the surface area in QGIS. The tree cover per hectare in percentage was computed using the following equation:
  $T_c = \frac{C}{S} * 100$
  C=sum of the surface area (in ha) of the individual tree in the subplot and S=subplot area in ha.
- *Tree density.* For each shape of the different individual tree crown polygons, the centroid was created. The tree density was calculated at the subplot level using the equation below:

$$D = \frac{N}{S}$$

With D= density, N = total number of centroids of the tree canopy geometry in the plot, and S=subplot area in ha.

- *Dry mass (Above-ground biomass, woody dry mass and foliar dry mass).* For each tree polygon of Brandt et al. (2020) data, Tucker et al. (2023) computed the wood dry mass (WBs) and foliar dry mass (FBs) using the allometric equations of (Hiernaux et al., 2023), which are based on the individual's tree crown area. In a subplot, the sum of these different masses was computed to obtain biomasses per hectare. The above-ground biomass of a tree refers to the sum of woody dry mass and foliar dry mass.

$$\text{DM} = \sum_{i=0}^{n} m$$

With DM= total dry mass in a plot and m= above-ground biomass or foliar dry mass or woody dry mass of individual trees.

2.2.2. Data analysis

To analyze the impact of plantations, tree density, tree cover, above-ground biomass, woody dry mass and foliar dry mass were computed in every subplot of planting plots and their respective buffer zone that represented the non-planted areas. Then, checking of empty plots was performed and data were separated per plantation. Afterward, a comparison analysis of woody features between plantations and the non-planted area for each dataset was conducted. Due to the high variability of woody features (tree density, tree cover, woody dry mass and foliar dry mass) in the non-planted areas, a random sample of 100 plots has been done 100 times if a plantation was higher than 200 ha. If not, the total plots available were used in the comparison analysis. Finally, the comparison analyses have been computed 100 times in each dataset. The comparison analysis used in this study is the Student T.test and its non-parametric test, using a threshold of 5 %. Several indicators were computed for each plantation.

- *Number of tests with p.value under 0.05 ($N(t < 0.05)$).* It represents the count of tests conducted in each dataset where the p-value was found to be significant (< 0.05).

$$\mathbf{N}_{(t<0.05)} = \sum_{i=1}^{n} \mathbf{I}(\boldsymbol{pi} < 0.05)$$

n is the total number of test repetition; ***pi*** is the p-value obtained from the *i* th test; $\mathbf{I}(\boldsymbol{pi} < 0.05)$ is an indicator function that equals 1 if *pi* < 0.05 (the test is statistically significant) and 0 otherwise (the test is not statistically significant).

- *Average of tree features in plantations ($\overline{Xp}$).* It represents the average number of trees per hectare, the average amount of dry mass (above-ground, foliar and woody) per hectare and the average tree cover per hectare in the specific plantations.

$$\overline{\mathbf{Xp}} = \frac{\sum_{i=1}^{n} \textbf{\textit{tree features in plantation i}}}{\boldsymbol{N}}$$

N is the total number of hectares in plantations being considered; ***tree features in plantation i*** represents the count of trees per hectare, the amount of dry mass (above-ground biomass, foliar and woody) and the sum of tree cover per hectare in the i th plantation.

- *Average of tree features in non-planted area ($\overline{Xw}$).* It gives the average number of trees per hectare, the average amount of dry mass (above-ground, foliar and woody) per hectare and the average tree cover per hectare in the 5 km buffer

$$\overline{\mathbf{Xw}} = \frac{\sum_{i=1}^{n} \textbf{\textit{tree features in non planting area i}}}{\boldsymbol{N}}$$

N is the total number of hectares in non-planted area being considered; ***tree features in non-planted area i*** represents the count of trees per hectare, the amount of dry mass (above-ground, foliar and woody) and the sum of tree cover per hectare in the i th non-planted area.

- *Gain in tree feature (Gain).* It refers to the number of trees, the amount of foliar dry mass and the quantity of above-ground biomass and woody dry mass due to planting or plantation.

$$\mathbf{Gain} = (\overline{\mathbf{Xp}} - \overline{\mathbf{Xw}})$$

$\overline{\mathbf{Xp}}$= mean of tree features in the plantations and $\overline{\mathbf{Xw}}$= mean of tree features in the non-planted areas being considered.

The following scheme (Fig. 4) illustrates the workflow of the data collection and analysis.

3. Results

3.1. Impact of plantations on the tree density

Indicators of the impact of plantations in regard to tree density are presented in Table 4. In terms of the number of tests with significant differences between the tree density in plantations and the tree density in non-planted areas, there are 13 GGW plantations (W1, W6, W10, W13, W17, W19, W21, W22, W24, W25, W27, W28, W29) out of 30 for which the comparison test between planting and non-planted areas produced a p-value below 0.05 for 100 repetitions performed, while there are 11 Corporate plantations (A1, A3, A5, A6, A7, A8, A9, A10, A11, A12, A4) out of 12 for which the comparison test between planting and non-planted areas has given a p-value below 0.05 for 100 repetitions performed. The number of plantations for which 80 to 100 comparison tests out of 100 repetitions have given a p-value below 0.05, are 21 for GGW cases and all plantations for Corporate cases. These findings indicate a substantial impact of both GGW and Corporate plantations on tree density when compared to non-planted areas.

GGW plantations have a lower range of tree density, ranging from 6 ± 7 to 63±19 trees/ha, compared to Corporate plantations that have a wide range of tree density, from 18±14 to 175±48 trees/ha and among the 10 plantations with the highest average density of trees per hectare 9 are from this last category (A6, A5, A7, A8, A12, A4, A10, A1, A3) and one is from GGW (W29) (Fig. 5). Then in plantations (both GGW and Corporate), the average tree density per hectare ranges between 6 ± 7 and 175±48 trees/ha, while it ranges between 10±8 and 53±23 trees/ha on average in non-planted areas. Within the non-planted areas around the GGW plantations, the average tree density ranges from 10±8 to 53±23 trees/ha. Within the non-planted areas around the Corporate plantations, the average tree density ranges from 12±9 to 23±16 trees/ha.

Regarding gains in tree density due to plantations, 83 % of plantations (GGW and Corporate plantations together) have positive gains in tree density, but especially Corporate plantations consistently provided higher numbers than GGW plantations (Fig. 6). The gains of Corporate plantations ranged from 6 to 160 trees/ha, while the gains of GGW plantations ranged from 0 to 21 trees/ha. Among the 10 plantations with the largest gains in tree density, 9 are Corporate plantations (A5, A6, A7, A8, A12, A4, A10, A1, A3) and 1 (W28) is a GGW plantation. The plantations for which the gains in tree density are equal to zero are 7 (W3, W5, W13, W15, W16, W21, W23) out of the 42 plantations and all seven are GGW plantations. These findings emphasize the significant contribution of Corporate plantations in enhancing tree density as compared to GGW plantations.

3.2. Impact of plantations on the tree cover

Indicators of the impact of plantations in regard to tree cover are presented in Table 4, which details comparison tests conducted.

Concerning the number of tests with significant differences between tree cover in plantations and tree cover in non-planted areas, 6 (W1, W10, W13, W21, W28, W6) out of 30 GGW plantations and 10 (A1, A10, A11, A12, A4, A3, A5, A6, A7, A8) out of 12 Corporate plantations showed significant differences in tree cover compared to non-planted areas for all 100 replicate tests. The number of plantations for which 80 to 100 replicate tests out of 100 repetitions have given a p-value below 0.05, are 14 for GGW cases and 11 for Corporate cases.

In regards to average tree cover per hectare, the Corporate plantations on average have a higher range of tree cover (from 2 % to 25 % tree cover per hectare) than the GGW plantations (from 0.75 % to 13.91 % tree cover per hectare) (Fig. 5). The 10 plantations with the highest cover rates included 7 Corporate plantations (A6, A5, A7, A12, A8, A10, A4) and 3 GGW plantations (W6, W10, W29) highlighting the generally higher tree densities in Corporate plantations. Across both types of plantations, the average tree cover per hectare ranges from 0.75 % to 25

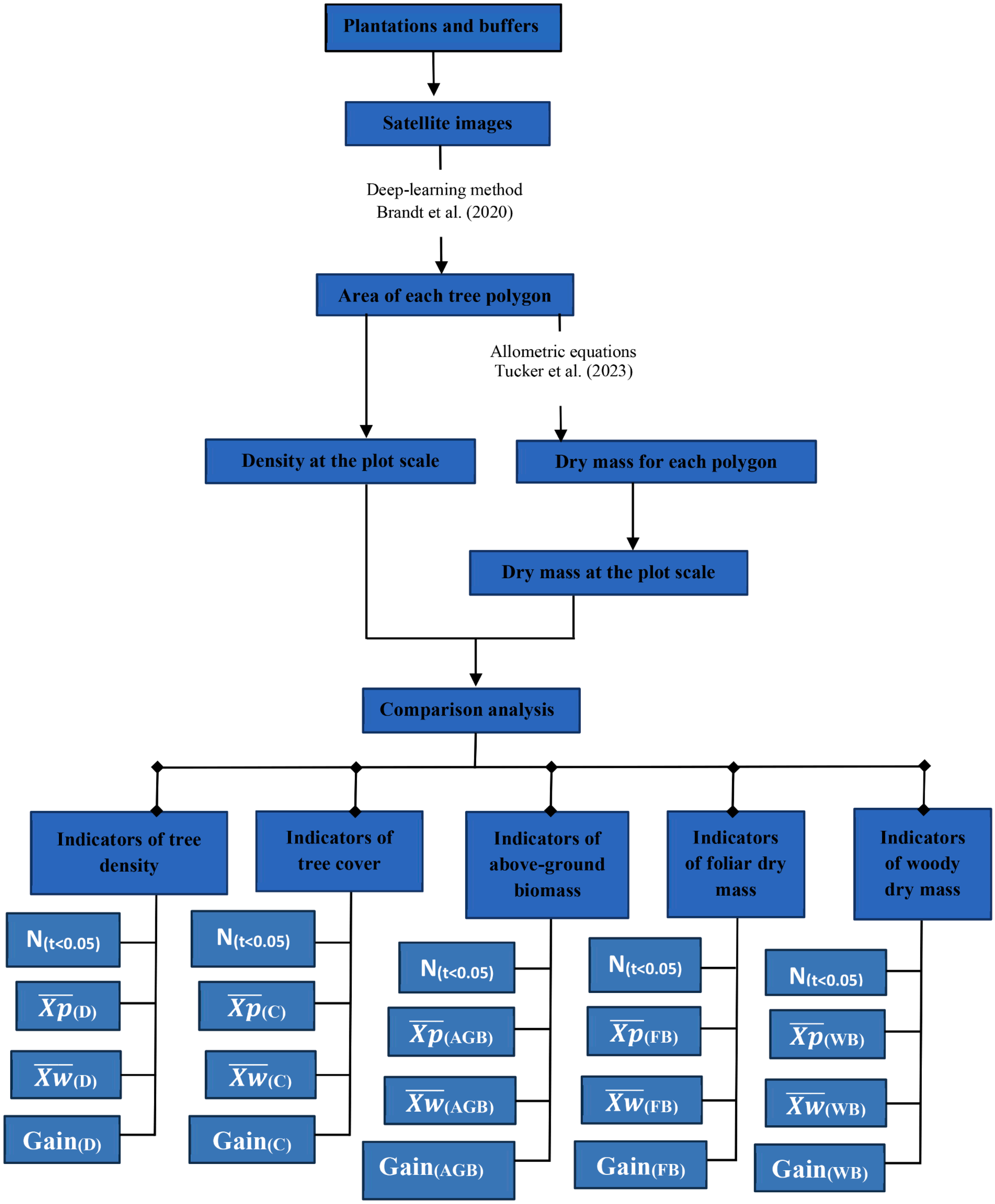

Fig. 4. Workflow of the data collection and analysis.

%. Non-planted areas show average tree covers ranging from 2% to 15 %. The data suggest that tree cover is generally higher in plantations compared to non-planted areas, which demonstrates the positive impact of tree plantations in increasing tree cover per hectare.

Concerning gains per hectare of tree cover due to plantations, 69 % of plantations (GGW and Corporate plantations taken together) have positive gains in tree cover. Corporate plantations have generally larger gains in tree cover compared to GGW plantations (Fig. 6). The gains in tree cover of Corporate plantations ranged from 0 to 2161.81 m^2/ha, while the gains of GGW plantations ranged from 0 to 418.03 m^2/ha. Among the 10 plantations with the largest gains of tree cover per hectare, 8 are Corporate plantations (A6, A5, A7, A12, A8, A10, A4, A1) and 2 GGW plantations (W6, W10). Plantations for which the gains in tree cover are equal to zero are 13 including 12 GGW plantations (W2, W3, W5, W12, W13, W16, W17, W20, W21, W22, W29, W30) and one Corporate (A2) out of the 42 plantations.

In assessing the impact of tree plantation, the ratio of gain of tree cover to gain of density (Table 1) emerges as a critical metric to highlight the relative benefit of each plantation in terms of ecosystem services. Comparing the two plantation projects, GGW plots exhibit a more

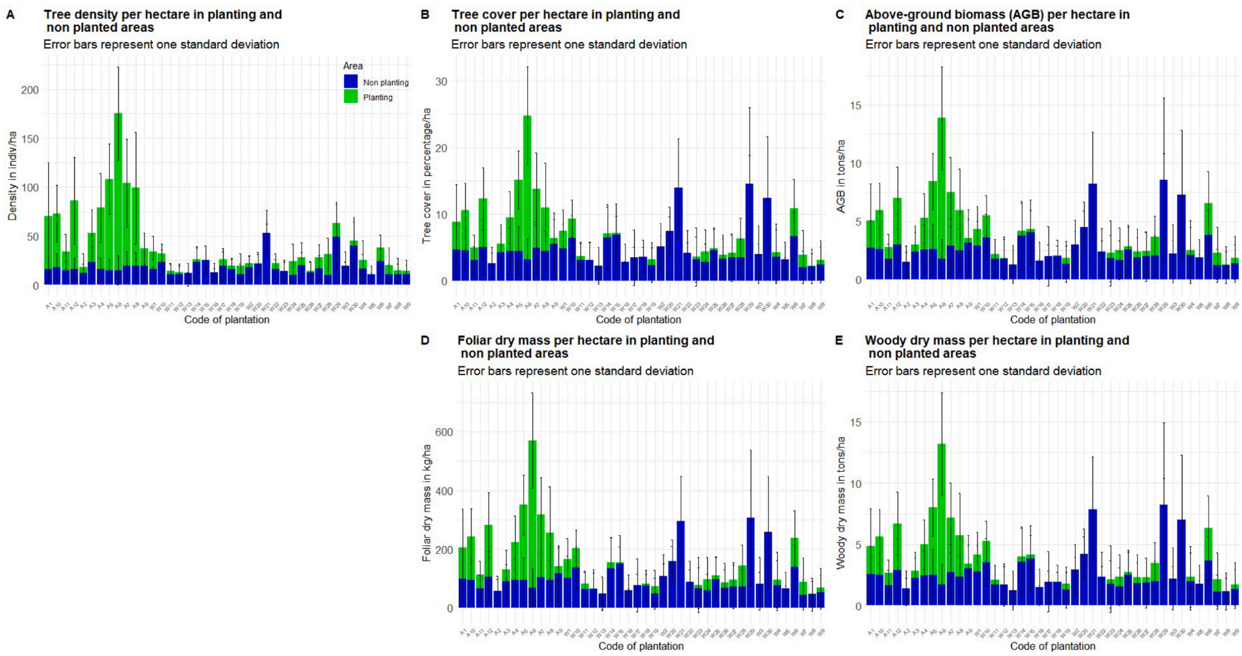

Fig. 5. Average of tree features per hectare in planting and non-planted area.

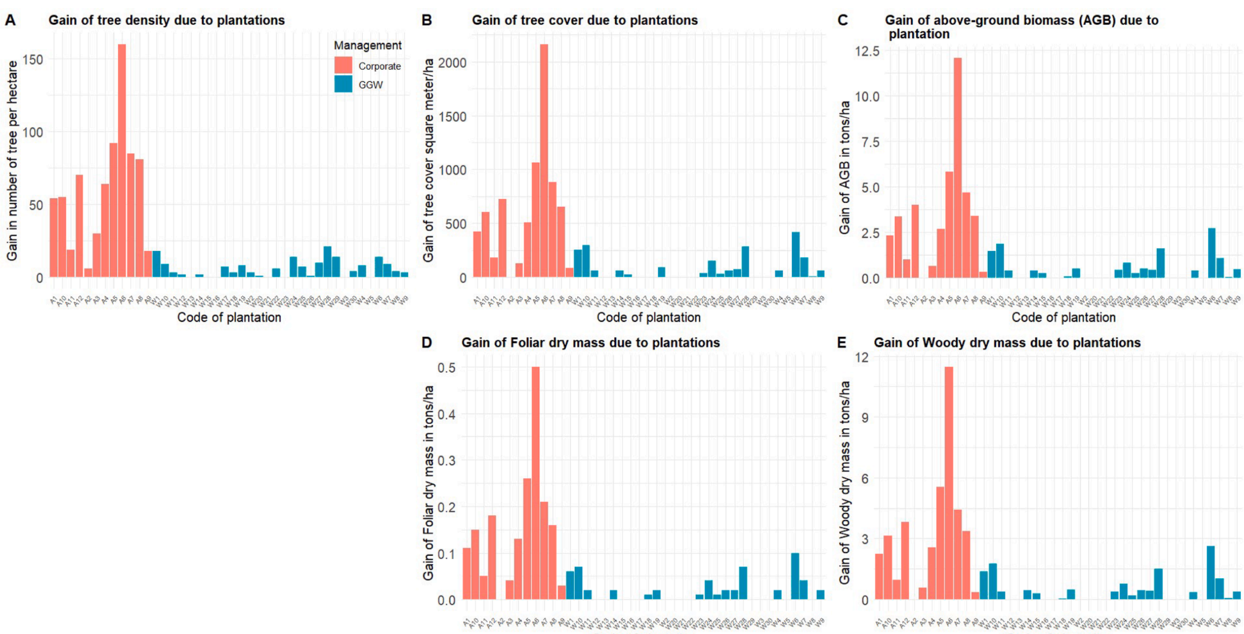

Fig. 6. Gain in tree features at plot scale due to plantations.

diverse set of ratios, indicating a potentially broader range of afforestation outcomes. The examination of Corporate plots reveals a varied spectrum, where ratios range from 4.25 m^2/tree to 13.51 m^2/tree. Notably, plots A6, A5, A10, and A7 exhibit higher ratios, indicating a substantial increase in tree cover relative to density. On the GGW side, the ratios display a wider range, spanning from 0.61 m^2/tree to an exceptionally high 62.24 m^2/tree. Specific plots, such as W26, W10, W6, and W14, stand out with remarkably high ratios, implying a significant gain in tree cover despite a relatively lower increase in tree density. GGW plots overall showcase greater variability in the relationship between tree cover and density compared to Corporate. Of particular note are GGW plots W26, W10, W6, W14, W9, W7, W11, W1 and W28 and the corporate plot A6 which stand out with the 10 highest ratios in the entire dataset, signifying a substantial increase in tree cover relative to density.

3.3. Impact of plantations on biomass (Above-ground, foliar and woody dry mass)

Indicators of the impact of plantations in regard to above-ground biomass are presented in Table 5. After comparing the AGB in plantations and the AGB in non-planted areas 100 times, the number of tests with a p-value below 0.05 varies from plantation to plantation. Indeed, there are 6 GGW plantations (W1, W6, W10, W13, W21, W28) out of 30 for which the comparison test between planting and non-planted areas has produced a p-value below 0.05 for all 100 repetitions performed, while there are 9 Corporate plantations (A1, A5, A6, A7, A8, A10, A11, A12, A4) out of 12 for which the comparison test between planting and non-planted areas has produced a p-value below 0.05 for all 100 repetitions performed. The number of plantations for which 80 to 100 comparison tests out of 100 repetitions have produced a p-value below 0.05, are 13 for GGW cases and 11 for the case of Corporate.

In regards to average AGB per hectare, Corporate plantations have a wide variation ranging from 1.22 tons/ha to 13.86 tons/ha compared to GGW plantations that have a lower range of AGB, ranging from 423.24 kg/ha to 7.81 tons/ha and the 10 plantations with the highest average AGB per hectare included 7 Corporate (A6, A5, A7, A12, A10, A8 and A4) and 3 GGW (W6, W10 and W29). In plantations (both GGW and Corporate), the average AGB per hectare ranges between 423.24 kg/ha and 13.86 tons/ha, while on average it ranges between 1.17 tons/ha and 8.55 tons/ha in non-planted areas. This range suggests diverse natural vegetation biomass within non-planted areas, with very sparse vegetation or potentially degraded land and indicates potential variability in biomass density over a larger area. Within the non-planted areas around the GGW plantations, the average AGB ranges from 1.17 tons/ha to 8.56 tons/ha. Within the non-planted areas around the Corporate plantations, the average AGB ranges from 1.5 tons /ha to 3.17 tons /ha.

Regarding gains of AGB per hectare due to plantations, 71 % of the plantations showed positive gains and Corporate plantations have generally larger gains compared to GGW plantations. The gains of Corporate plantations ranged from 0 to 12.1 tons/ha, while the gains of GGW plantations ranged from 0 to 2.73 tons/ha. Among the 10 plantations with the largest gains of AGB per hectare, 8 (A6, A5, A7, A12, A8, A10, A4, A1) are Corporate plantations and 2 (W6 and W10) are GGW plantations. The plantations for which the gains of AGB per hectare are equal to zero are a total of 12 including 1 Corporate (A2) and 11 GGW plantations (W2, W3, W5, W13, W16, W17, W20, W21, W22, W29, W30) out of the 42 plantations.

Examining the ratio of gain in AGB to gain in density (Table 1) provides valuable insights into the success of tree plantation. For Corporate plots, the AGB/density gains ratios vary significantly, ranging from 18.33 kg/tree to 75.63 kg/tree. On the GGW side, the AGB/density gains ratios demonstrate even greater variability, spanning from 10 kg/tree to an extraordinary 510 kg/tree. Specific plots, such as W26, W10, W6, and W14, stand out with exceptionally high ratios, indicating a remarkable increase in above-ground biomass despite a relatively lower rise in tree density in GGW. These plots represent key areas where the plantation has resulted in substantial biomass accumulation. Comparing the two plantation projects, GGW plots exhibit a wider range of AGB/density ratios, reflecting diverse afforestation outcomes. GGW plots W26, W10, W14, W6, W9, W11, W7, W1 and W28, and the corporate plot A6 in particular, stand out with the 10 highest ratios in the entire dataset, suggesting an exceptional increase in above-ground biomass relative to tree density. This highlights the potential of GGW plantations to significantly contribute to carbon sequestration and ecosystem services despite a relatively lower rise in tree density.

The analysis of foliar and wood dry mass indicators yielded results similar to those observed for tree density, tree cover, and above-ground biomass (Table 6). Significant differences were found between plantations and non-planted areas, with both GGW and Corporate plantations demonstrating consistent impacts across the two indicators. Specifically, Corporate plantations exhibited a wider range of foliar and wood dry mass compared to GGW plantations in terms of both average quantity per hectare and gain per hectare, indicating substantial variability in biomass distribution. Examining the ratio of gain in foliar and wood biomass to gain in tree density provided further insights into the success of plantation projects, notably with GGW plantations consistently outperforming Corporate plantations in terms of these ratios. That suggests exceptional growth in foliar and woody biomass relative to tree density in GGW plantations. This highlights the potential of GGW plantations to significantly contribute to various ecosystem services, including habitat provision, nutrient cycling, and soil fertility enhancement.

4. Discussion

In the Sahel, the Great Green Wall (GGW) is one of the latest sub-regional initiatives to address land degradation and its impact on local livelihoods (Fall et al., 2010). The success or failure of this initiative is not agreed upon in the scientific and international community (Ducourneau, 2020; Mugelé, 2018). To better understand the impact of GGW projects, it is essential to assess the dynamics of ecosystem services in these target areas. This study, aims to highlight, in Sahelian Senegal, some services such as tree density, tree-cover and dry biomass in GGW plantations relative to corporate and surrounding plantations.

4.1. Impacts of plantations and the difference between GGW plantations and corporate plantations

The results of the analyses in this study provided consistent arguments outlining the positive impacts of the plantations on woody vegetation in the region. The consistently significant results across multiple repetitions suggest a robust pattern, indicating a strong influence of plantations on increasing tree features in the region. The higher number of Corporate plantations with significant differences might suggest a more widespread impact across Corporate sites, although the GGW plantations also show considerable effectiveness. It is worth noting that the average density of trees and biomass (AGB, foliar and woody dry mass) per hectare is above zero for each of the plantations, as well as in the non-planted areas, indicating the presence of trees in all cases. The findings indicate that trees are present and observable across diverse areas, extending beyond designated plantation areas. The study of Gore et al. (2023) on the dynamics of the vegetation cover in the region supports this view and shows an improvement of the surface areas of tree and shrub savanna of 11.40 % in Tessekere, 8.25 % in Syer and 2.70 % in Loughere Thioly. Dendoncker et al. (2020) rather claim that tree density in the region has stabilized since 2008 after a period (from 1965 to 1980) of decline. The wide distribution of trees thriving in various locations across the region supports an enhanced carbon sequestration potential, contributing substantially to climate change mitigation efforts (Gore et al., 2023).

However, it is mainly in the plantations that the highest quantities of tree features are found, especially in Corporate plantations. For example, the highest quantities of tree features in GGW initiative plantations are 38.43 tree/ha (tree cover of 11 %) whereas that of Corporate initiative are 175.48 tree/ha (tree cover of 25 %). Similarly, the highest values of biomass (aboveground, foliar and dry woody) were found in corporate plantations. This suggests that Corporate plantations can potentially accumulate higher values of key tree features per hectare. Besides, the variation of tree features within plantations may indicate a diverse range of tree species (mostly for GGW plantations) and ages, contributing to the overall biodiversity and resilience of the ecosystem (Diallo et al., 2011; Ndong et al., 2015).

The magnitude of gains in tree features differs depending on the specific plantation. The most noticeable gains at the hectare level were found for a Corporate plantation coded A6, located in the commune of Boulal. In Boulal, the gains in tree features at the commune level are 321,703 individual trees, 429.5 ha of tree cover, 23,382.4 tons of AGB, 22,396.9 tons of woody dry mass and 985tons of foliar dry mass. This is the most prominent gain in tree features among the communes (Fig. 7). Indeed, livestock frequentation is moderate in communes with corporate plantations such as Boulal, Darha, and Deali, which is positive for plantations (Diallo et al., 2011).

The increase in above-ground biomass is crucial ecologically, as it indicates healthier trees with more extensive foliage and wood, leading to enhanced photosynthesis, carbon capture, and ecosystem productivity (Giuliani et al., 2022; Gore et al., 2023). However, even though specific plantations have gained in tree density, they have not necessarily shown positive gains in tree cover, AGB, foliar, and woody dry mass. The reason for the situation in these plantations can be attributed to a variety of biotic and abiotic conditions, such as climate, soil type, management practices, and the planted tree species. Diallo et al. (2011) also mentioned that plantations are indeed distributed along an increasing rainfall gradient, with different topographical characteristics and protection status. Additionally, there are instances where tree density has not been gained, whereas there have been improvements in tree cover, AGB, foliar dry mass, and woody dry mass. Moreover, plantations exhibited positive gains in one or more tree features, aside from tree density. In our analysis, we assume that the conditions of the plantations are similar to the surrounding non-planted area. However, it is not necessarily always the case as indeed, planting in areas with a lot of topographic depressions, that can form temporal water ponds in the wet season, are generally avoided (Dendoncker et al., 2023). The temporal water ponds are used by the local community for livestock mainly and restriction of access is generally avoided. Topographic depressions are known to have higher tree density and diversity than the rest of the landscape (Dendoncker et al., 2023).

Moreover, it is GGW plantations (W3, W5, W13 (located in the commune of Syer) W16 (located in Mboula), and W21 (located in Louguéré Thioly)) in particular, that did not gain in any tree features. Indeed, Niang et al. (2014) highlighted the decline of several woody species in the region. Woody vegetation is progressively degraded by the simultaneous action of climatic deterioration and increasing human exploitation (Niang et al., 2014). This could partly explain the negative gain in terms of tree density for plantations. As existing woody vegetation is already in a state of degradation, new tree plantations could also be vulnerable to the same climatic and anthropogenic pressures that have contributed to degradation. This could make it more difficult for new trees to survive and grow, compromising the objectives of the planting initiatives.

Notably, Corporate plantations emerge as the most successful, representing 80 % of the top 10 ranked plantations concerning gains in tree features per hectare. For all tree features, at least 11 out of the 12 Corporate plantations (representing 92 % of Corporate plantations) have positive gains in tree features. At the same time, for the GGW initiative, it is around 53 % of the plantations. Both GGW and Corporate plantations had their highest success rate when considering the indicator of tree density gains, with 100 % of Corporate plantations showing positive gains and 77 % (or 23 out of 30) GGW plantations showing positive gains. Moreover, a comparison analysis between Corporate plantations and GGW plantations showed that average gains of tree features due to Corporate plantations are significantly higher than average gains of tree features due to GGW plantations (Fig. 8).

When looking at ratios between gains in different tree features and density, Comparing the two afforestation projects, GGW demonstrates a broader range of outcomes, emphasizing the diverse afforestation impact. Plot W26 stands out with the highest ratio, signifying exceptional growth in woody biomass relative to tree density and underscoring GGW's potential to contribute substantially to various ecosystem services.

When looking at the ratio between gain in cover and gain in density per hectare, we see that the average gain of cover per tree is higher in GGW plantations than in Corporate plantations (Table 1). In GGW plantations that have positive gain in tree cover, the ratio between gain in cover and gain in density per hectare was an average of 18 m^2 of crown cover per tree (with a maximum of 62 m^2 for W26). For Corporate, the average ratio was 9 m^2 of crown cover per tree. And similar trends were found for dry mass (AGB, woody dry mass and foliar dry mass) (Table 1). In GGW each tree gained add 116.1 kg of above-ground biomass wile in Corporate each tree gained add 48.4 kg of above-ground biomass, when considering only plantations with positive gains. This suggests that the planted trees in GGW plantations are bigger (and growing quicker than the trees in Corporate plantations), signifying

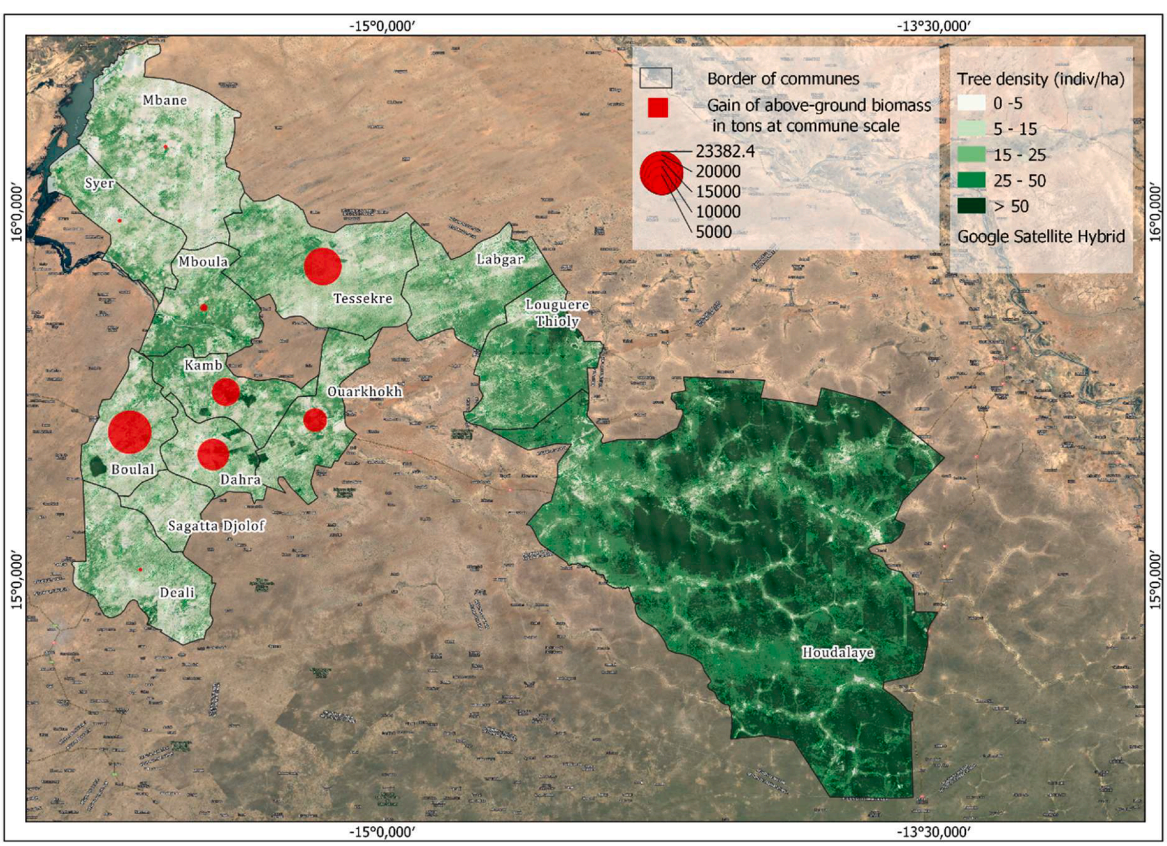

Fig. 7. Spatial distribution of tree density and gains of above-ground biomass (in tons) due to plantations at commune scale in Sahelian Senegal.

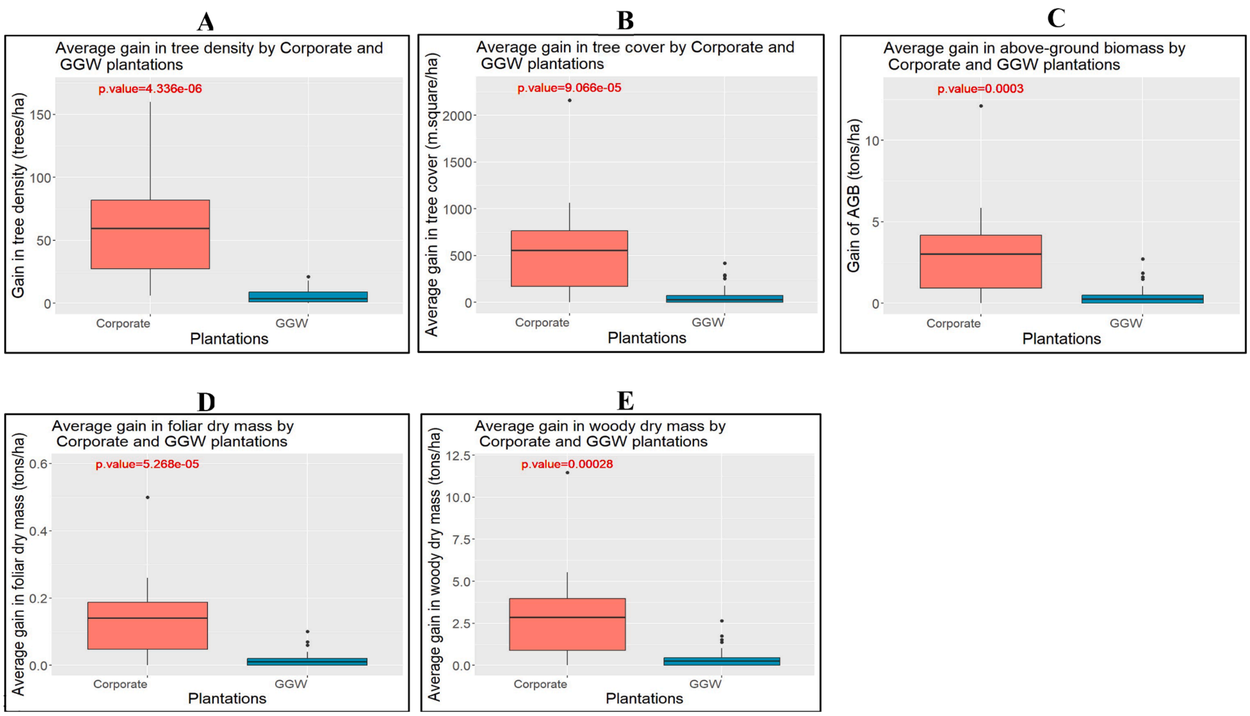

Fig. 8. Comparison of average gains of tree features due to GGW plantations with those due to Corporate plantations at plot scale.

exceptional growth in cover, foliar and woody biomass relative to tree density and underscoring GGW's potential to contribute substantially to various ecosystem services.

Two factors could explain this fact. Firstly, the trees in Corporate company plantations are exploited for the Arabic Gum (Daniele et al., 2011). This exploitation could limit the growth of the tree (Dione and Vassal, 1998). Secondly, the density in the Corporate plantations is quite high and this could induce competition for resources between the different trees limiting their growth. In the case of plantations, the optimal density of individual tree is relative (Pisarenko et al., 1992). It is determined by the objectives, which may be to increase complex productivity (Pisarenko et al., 1992; Sharapov et al., 2024), like Arabic gum production for the case of corporate plantations, to obtain wood of the required quality and quantity, or to improve the stability and sustainability of ecosystems and their environmental and protective functions (Pisarenko et al., 1992; Sharapov et al., 2024), as being the case for the GGW plantations. For the success of the Great Green Wall, it is essential to identify the optimal density in the different areas. High density also reduces the positive impact of trees on the herbaceous layer (Gaafar et al., 2006). Thirdly, in Corporate plantations, it is uncertain whether the local populations have access to the plantations, and, on the other hand, the ecosystem services per tree are less appealing. Despite the need to consider sustainability thresholds, it is not truly worthwhile to aim for gains of over 61 trees per hectare (average gain of density in corporate plantations) when, in fact, one can achieve just as many ecosystem services with three times fewer trees (maximum gain of density in GGW plantations). Instead of adhering to goals of over-density, the emerging idea is to optimize the canopy per tree. Thus, achieving gains of over 61 trees per hectare might not be as beneficial as obtaining richer ecosystem services with reduced density. This approach contradicts conventional paradigms, suggesting that the Great Green Wall, even if it may have fallen short of its tree density goals, might have succeeded in its mission of producing ecosystem services per tree. Finally, the choice of indicators and the aim of the plantation is to be clearly identified. Using density as the main indicator of success could be misleading if the aim is to maximize carbon storage. Indicators of success should preferably be more based on the ecosystem services provided by trees than density per hectare.

4.2. Impact of trees on the ecosystem and livelihood of local populations

The increase in tree features is a positive indicator of the benefits of tree plantations for the environment and the local ecosystems. Gains in tree features due to planting are also a key indicator of the effectiveness of tree-planting initiatives. Monitoring vegetation using woody indicators is essential for understanding the state of forests and natural ecosystems, guiding conservation efforts, assessing the impacts of climate change (Hänke et al., 2016; Spiekermann et al., 2015; Williams-Linera et al., 2021) and promoting sustainable land management practices. It provides valuable data for policymakers, researchers, and environmental practitioners to make informed decisions toward ensuring the health and resilience of our ecosystems for the future.

The results of the current study are valuable, not only for governance policy but especially for the region of the study where the local population is highly dependent on woody vegetation in the dry season with no grass cover. At this period of the year, woody vegetation remains the main source of animal fodder and is, therefore, an important food supplement for livestock (Akpo, Grouzis, et Bâ 1995; Lo et al., preprint). up to 6.5 % of Senegal's Gross Domestic Product (GDP) and accounts for 55–70 % of rural income (PODES, 2004). In addition, *Acacia Senegal* is a species exploited, which is particularly important for commercial and industrial purposes (food, beverages, oenology, cosmetics, pharmaceuticals, etc.) (Daniele et al., 2011).

Trees play a crucial role in mitigating climate change by sequestering carbon dioxide from the atmosphere. Monitoring tree growth and carbon storage helps evaluate the contribution of forests to climate change mitigation and provides data for climate models (Robert and Saugier, 2004). Moreover, trees play a crucial role in the resilience of Sahelian ecosystems because of their resistance to climatic disturbances and the support services they provide. Turner et al., (2023) highlighted the evidence of GGW plantations to reduce wind erosion as planting of trees may contribute to fixation of dunes. Trees also contribute to the restoration of soil fertility by providing plant cover (Hiernaux, 1980), soil protection and raising the trophic level (Akpo and Grouzis, 1996).

4.3. Limitations regarding the use of remote sensing images

This approach based on satellite remote sensing to evaluate tree features is a novel one and allowed to study the impact of plantations on tree communities in Sahelian ecosystems in the northern Senegal region. The minimum tree densities found in the region (from 10±8 to 53±23 trees/ha on average in non-planted areas) are quite close to estimations of Dendoncker et al. (2020) in the same region. Dendoncker et al. (2020) assessed the woody vegetation changes in the region during the period 1965 to 2018 and found that average tree density was 11.9 ± 5.7 trees/ha in 2008. This finding aligns with the minimum tree densities estimated in the region in the present study. Niang et al., (2015) also assessed tree densities in the region and found 91 trees/ha for Tessékéré, 40 trees/ha for Labgar and 63 trees/ha for Louguéré Thioly. Although this work is not methodologically comparable to Dendoncker et al.'s estimations (2020), the values estimated for tree densities are for the majority within the ranges estimated for the region in our study. Dendoncker et al. (2020) focused on an area of around 3700 square kilometers, covering the area around the Tessékéré and Widou Thiengoly deep wells and the data collection involved manual counting of woody vegetation in specific plots (both 100×100 plots (100 random samples) and larger 1km^2 plots) using a variety of visual sources such as Corona images, aerial photos, the WorldView-1, and Bing images. Niang et al. (2015) used a lower size of the plots (50×50 m) and a lower size of the samples (60 plots for 4 communes) and the data collection was based on in-situ methods. The satellite remote sensing approach in the current study considered a larger plot size (100×100 m) and at least 100 plots per plantation site, which were replicated 100 times, across a 20,542 km^2 area. Furthermore, the data from Brandt et *al.* (2020) are based on satellite images of resolution of 0.5 m. This causes some limits in the detection of small trees and also in plantations of very high tree density, overlapping tree crowns can be difficult to separate correctly into individual crowns. This issue of overlapping of tree crowns can affect the counting of individual trees by the satellite sensor. Further investigations could be done to validate the data of Brandt et al. (2020) by field measurements or drone images to appreciate errors that could exist in this kind of data. Investigating these limitations, such as potential inaccuracies in satellite data or challenges in identifying specific tree species, would provide a more comprehensive view.

The data from Brandt et al. (2020) has other limitations: (i) Time difference in relation to date of planting: the satellite data represents a composite of images covering the period between 2003 and 2020, and although the Great Green Wall was launched in 2007, the plantations were not all implemented in the same year. The inception of Corporate plantations are a bit earlier starting at the beginning of the turn of the millennium. Recently, the same deep learning methodology was used on Planet image to produce a tree cover map representing a single year (Reiner et al., 2023). This new type of methodology could be used to eliminate this time difference, yet the resolutions of the images are a bit lower. (ii) One limit is that we based our evaluation on plot positions based on land proprieties. Indeed, the shape-file contains information on the place where the national agency or private company have land use right. However, for some plantations, only one part of the plot had a plantation. Different management techniques were also applied. With the new focus on GGW, it will be very important to collect and inform a Geographic information system of the different initiatives.

5. Conclusion

The study, based on comprehensive mapping of individual trees using a combination of very high-resolution satellite remote sensing data and deep learning, provides robust evidence of the positive impacts of Great Green Wall (GGW) and Corporate plantations in the Sahelian Senegal. This analysis underscores the significance of remote sensing methodologies in quantifying tree features and assessing reforestation initiatives. The observed gains in tree density, tree cover, above-ground biomass (AGB), foliar dry mass, and woody dry mass highlight the effectiveness of plantation projects in enhancing ecological health and productivity in the region. These findings hold substantial importance for future research, decision-making, and management of plantation initiatives. By leveraging remote sensing technologies, researchers and environmental practitioners can gain valuable quantitative insights into reforestation projects' effectiveness and their contribution to ecosystem restoration. Additionally, our study sheds light on the varying effectiveness levels between GGW and Corporate plantation efforts, providing valuable information for informed decision-making in future plantation projects.

However, it is essential to acknowledge the limitations of our study, particularly regarding data accuracy and the need for further research to understand the management systems applied to each GGW plantation in the region. Future studies should focus on addressing these limitations. Overall, our study serves as a valuable baseline for discussions with restoration practitioners on the one hand and to convince funding bodies on the other hand.

CRediT authorship contribution statement

Fréjuste Joseph Cofélas Fassinou: Writing – original draft, Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization. **Jean-Daniel Cesaro:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Maïalicah Nungi-Pambu:** Writing – review & editing, Data curation. **Rasmus Fensholt:** Writing – review & editing, Methodology. **Martin Brandt:** Writing – review & editing, Methodology. **Amah Akodewou:** Writing – review & editing, Visualization, Supervision. **Abdoul Aziz Diouf:** Writing – review & editing. **Tamsir Mbaye:** Writing – review & editing. **Simon Taugourdeau:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used are recent version of Brandt et al. (2020) https://doi.org/10.3334/ORNLDAAC/1832. Data supporting the conclusions of this study are available from the corresponding author, Cofélas FASSINOU, on reasonable request.

Acknowledgments

This study has been supported by the Carbon Sequestration and Greenhouse Gas Emissions in (Agro) Sylvopastoral Ecosystems in the Sahelian CILSS States (CaSSECS) project, under the Development Smart Innovation through Research in Agriculture (DeSIRA) Initiative. The authors would like to express their gratitude to the *Agence Sénégalaise de la Reforestation et de la Grande Muraille Verte* (ASERGMV) for their support during field visits. We extend our thanks to Ayi Segniagbeto for his careful proofreading of the manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2024.100569.

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