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Characteristics and Contribution of Citrus Orchards to Carbon Storage in Southern Senegal

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Abstract

The mitigation of climate change and its adverse consequences is highly urgent. This study assesses the carbon sequestration potential of citrus orchards in southern Senegal. The authors measured dendrometric parameters for 120 trees across five citrus species, three sites, and three age classes, using allometric equations to estimate above-ground biomass and carbon stocks. The key finding is that carbon storage varies significantly by site, species, and age, with one site (Kabadio) and two species (orange, mandarin) showing the highest potential. Diameter was found to be the strongest predictor of above-ground biomass and carbon stock, while tree height was a weaker indicator, likely due to management practices like pruning. The results suggest that citrus plantations can contribute to carbon sequestration in addition to their economic and food functions.

Keywords

Citrus Orchards, Above-Ground Biomass, Carbon Stock, CO_2 Sequestration, Climate Change

1. Introduction

In West Africa, fruit growing is a major agricultural sector with strong potential for supplying local markets with a wide range of products [1]. In Senegal, it occupies an important place in agricultural production systems: according to the Directorate of Agricultural Analysis, Forecasting and Statistics (DAPSA), approximately 12% of households are involved in fruit growing, reflecting its significant socio-economic role [2]. However, this national average masks significant regional disparities. Tree farming is particularly developed in the southern regions, notably in Casamance, where 52% of households in Sédhiou, 40% in Ziguinchor, and 26% in Kolda are involved in fruit production. Citrus fruits are among the main crops grown, with average production per household ranging from 212 kg to 232 kg for the 2022-2023 agricultural season.

Thanks to its favorable soil and climate conditions and its strong agricultural potential, Casamance has established itself in recent years as the main horticultural center in southern Senegal. Most of the country's fruit production, particularly citrus fruits and mangoes, comes from this region [3]. Fruit growing is also an essential source of income, on which nearly 80% of the rural population is partially dependent [4]. Beyond their socio-economic importance, fruit tree plantations such as citrus orchards are of major environmental interest. These plant formations contribute to climate change mitigation by sequestering atmospheric carbon through photosynthesis and storing it in biomass [5]. This sequestration process involves capturing, transforming, and storing carbon that would otherwise contribute to global warming through a cumulative effect [6]. In addition, carbon sequestration and the reduction of emissions from avoided deforestation are now receiving increasing attention as greenhouse gas (GHG) mitigation strategies [7]. However, analyses of biomass production and carbon storage reported in the literature indicate strong variations depending on climatic conditions, soil characteristics, and orchard management practices, highlighting the decisive role of management in determining carbon sequestration potential [8]-[10].

However, anthropogenic activities such as fossil fuel combustion, deforestation, and land use change contribute significantly to the accumulation of carbon dioxide (CO_2) in the atmosphere [11]. Deforestation alone generates approximately 1.1 GtC/year, or nearly 25% of global GHG emissions [12].

In this context of climate emergency and the search for sustainable solutions to reduce GHG emissions, tree plantations, particularly citrus orchards, appear to be relevant mitigation levers. Nevertheless, in Senegal, and more particularly in Casamance, the real contribution of these plantations to the fight against climate change remains poorly studied and documented. Indeed, studies on the sequestration capacity of woody resources have already been conducted in Casamance. However, these studies mainly focused on natural woody vegetation, such as forest resources and woody components within agroforestry parklands [13]-[16]. This study is part of this effort and aims to assess the carbon sequestration potential of citrus orchards to estimate their contribution to climate change mitigation in the Lower Casamance region.

2. Materials and Methods

2.1. Study Area

This study was conducted in the Bignona department, located in southwestern Senegal (12˚45′N, 16˚30′W) (**Figure 1**), with a focus on the villages of Teuby, Mangagoulack, and Kabadio. It covers an area of 5,295 km. The area, which is subject to a southern coastal Sudanian climate [17], experiences average annual temperatures around 27.10˚C [18] and annual rainfall of approximately 1,322.66 mm [19]. The Republic of the Gambia borders it to the north, the Ziguinchor department to the south, the Sédhiou region to the east, and the Atlantic Ocean to the west [20].

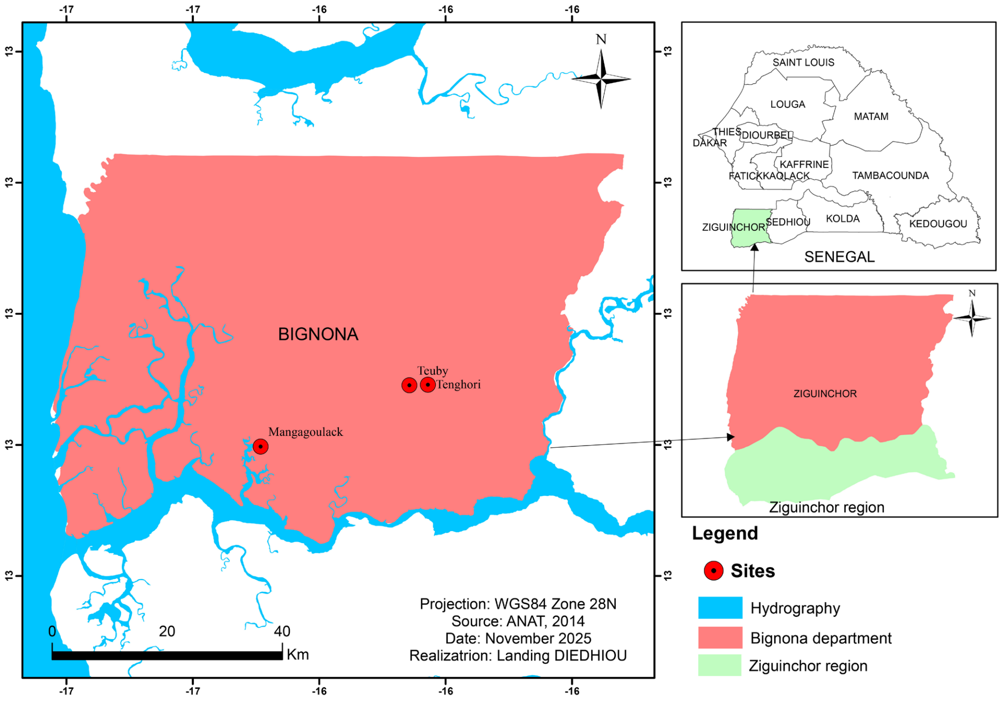

Figure 1. Geographic location of the study area.

2.2. Data Collection

In each village, an inventory was carried out on a one-hectare citrus plantation. The choice of plantations was based on several criteria: the age of the orchards, the varieties grown, the type of plant spacing, the accessibility, and the level of technical expertise of the owners in plantation management. These criteria were selected to ensure that the plantations inventoried were sufficiently representative and to provide reliable data on well-managed orchards. Within each selected plantation, all species present were inventoried, taking into account their age, classified into three groups: 0 - 5 years, 5 - 10 years, and >10 years. Dendrometric parameters, including diameter, height, and crown size, were measured.

Floristic diversity was estimated using species richness and several diversity indices, including Shannon and Pielou.

2.2.1. Species Richness

Total species richness (S) is the total number of species in the population of a given ecosystem [21].

2.2.2. Shannon-Weaver Diversity Index (H')

This index accounts for species richness and the abundance of individuals within each species. The Shannon-Weaver Index ranges from 0 to ln(S), approximately 4.5 for a relatively rich community [22]. It expresses the relative importance of the number of abundant species in a given environment. The index is minimal when all individuals belong to the same species, and is maximal when each individual represents a distinct species [23]. It is calculated as follows:

$$H' = -\sum_{i=1}^{n} p_i \ln p_i$$

where p is the relative abundance of species i, and ln is the natural logarithm.

2.2.3. Pielou's Evenness Index (E)

Regularity corresponds to the ratio between the diversity obtained and the maximum possible diversity (lnS) of the number of species. It varies between zero (0) and one (1). Pielou's index (E) tends towards zero (0) when there is dominance. It tends towards one (1) when the distribution of individuals between species is regular [24]. This measures the evenness of species distribution, calculated as:

$$E = \frac{H'}{H \max}$$

where $H \max = \ln (S)$ is the maximum diversity.

2.2.4. Estimation of Biomass and Carbon Stock

1. Determining the above-ground biomass (ABG)

The Above-ground biomass (ABG) was determined using allometric equations applicable to plant species in tropical forests. The choice of these equations depends on the number of parameters they incorporate (diameter, height, and specific wood density) and their simplicity [25]. The pantropical equations developed by [26] have been widely used in tropical Africa. Indeed, [27] revised the pantropical allometric equations by integrating biomass data for 4004 trees, including 1006 trees from tropical Africa. A pantropical allometric equation with three predictors (diameter, total height, and wood density), valid for all tropical forest types. Thus, we chose the equation of [27] applicable to our study area, which is located in West Africa. And wood density was taken from the ICRAF Wood density database and that of [28], which is 0.55. It is expressed in kg. Although wood density varies among species and environments, in the absence of species-specific values for all five Citrus species sampled in Senegal, a representative mean value of 0.55 g/cm^3 was adopted based on major wood density compilations such as the African Wood Density Database. Thus, above-ground biomass was estimated using the following allometric equation:

$$ABG = 0.0637 \times \left(\rho D^2 H\right)^{0.976}$$

where: ρ = Specific gravity of wood (g/cm^3); H = Height (m); D = Diameter (cm).

2. Estimation of total carbon stock and total CO_2 sequestration

Typically, 45% - 50% of the biomass of any plant species is regarded as carbon [29]. The total carbon stock was estimated by multiplying the above-ground biomass by a factor of 0.5, according to [29]-[31]. It is expressed in tons per hectare (t/ha). The carbon stock was calculated using the following formula:

$$Carbon\,stock = AGB \times 0.5$$

The total carbon stock was then converted into tons of CO_2 equivalent (CO_2 sequestration) by multiplying the carbon stock by a conversion factor of 3.67. This conversion factor corresponds to the molecular weight ratio between carbon dioxide (CO_2) and elemental carbon (C), expressed as:

$$\text{Ratio} = \frac{Mm\left(\text{CO}_2\right)}{Ma\left(C\right)} = \frac{44}{12} = 3.67$$

This ratio indicates that one unit of carbon combines with oxygen to form 3.67 units of carbon dioxide. It is commonly used to estimate the total amount of CO_2 sequestered or released from a given carbon pool. It is expressed in tons per hectare (t/ha).

$$\text{Total CO}_2 \text{ sequestered} = Carbon\ stock \times 3.67$$

2.3. Data Analysis

The collected data were analyzed using R software (version 4.3.1) via the RStudio interface. A three-factor analysis of variance (ANOVA) was performed to assess the effects of the factors studied. When the ANOVA was significant, the means were compared using Tukey's HSD test at a significance level of 5%. For variables that did not meet the validity conditions for ANOVA, a nonparametric Kruskal-Wallis test was applied, followed by a Dunn multiple comparison test. In addition, a mixed data factorial analysis (FAMD) was performed to visualize the factorial relationships between the variables.

3. Results

3.1. Floristic Composition of Citrus Plantations

Table 1 shows the floristic composition of citrus plantations at the three sites covered by the study (Kabadio, Mangagoulack, and Teuby). A total of 19 varieties belonging to five species and the same family (Rutaceae) and genus (Citrus) were recorded, including 12 in Kabadio, nine in Mangagoulack, and seven in Teuby. However, certain varieties are found in all plantations, such as Tangelo, Ponka, and Fanta orange. Thus, the varieties present in the plantations are symbolized by (1) and those absent by (0).

Table 1. Floristic composition of citrus plantations.

Species	Varieties (local names)	Sites Kabadio	 Mangagoulack	 Teubi
Mandarin tree (*Citrus reticulata* L.)	Tangelo	1	1	1
	Tangor	0	1	1
	Ponka	1	1	1
	Blidah	0	1	0
	Celiciana	1	0	0
	Dombondie	1	0	0
Orange tree (*Citrus sinensis* L.)	Orange ordinaire	0	1	0
	Japonais	0	1	0
	Fanta orange	1	1	1
	Thomson	1	0	0
	Marcéline	1	0	0
Citronnier (*Citrus limon* L.)	Citron vert	1	1	0
	Citron vol	1	0	0
	Lime tahiti	0	0	1
Grapefruit tree (*Citrus maxima* L.)	Pomélo	0	0	1
	Pamplemousse blanc	1	0	0
	Pamplemousse rouge	1	1	0
Clementine tree (*Citrus clementina* L.)	Clémentine ordinaire	0	0	1
	Clémentine espagnol	1	0	0

3.2. Woody Vegetation Diversity of Citrus Orchards

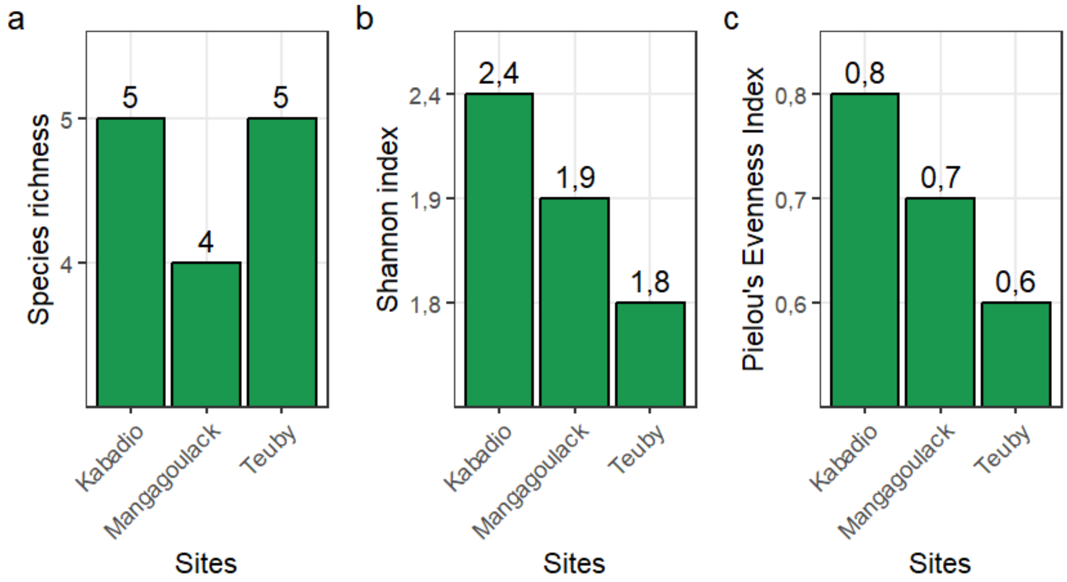

Figure 2. Floristic composition and diversity: species richness (a), Shannon index (b), and Pielou index (c).

A comparison of the floristic diversity indices between the three sites studied (Kabadio, Mangagoulack, and Teuby) (**Figure 2**) highlights remarkable variations in the structure of plant communities. Species richness is highest in Kabadio and Teuby, with five species recorded in each, while Mangagoulack has four. This trend is also reflected in the Shannon index, which reaches a maximum value in Kabadio (H = 2.4), indicating a more balanced species diversity and less dominance of particular species. Conversely, the lower values observed in Mangagoulack (H = 1.9) and Teuby (H = 1.8) indicate a more unbalanced structure of the stands. Pielou's evenness index confirms this hierarchy, with a better distribution of individuals among species in Kabadio (E = 0.8) compared to Mangagoulack (E = 0.7) and Teuby (E = 0.6).

3.3. Effects of Site and Biological Factors on Dendrometric Growth

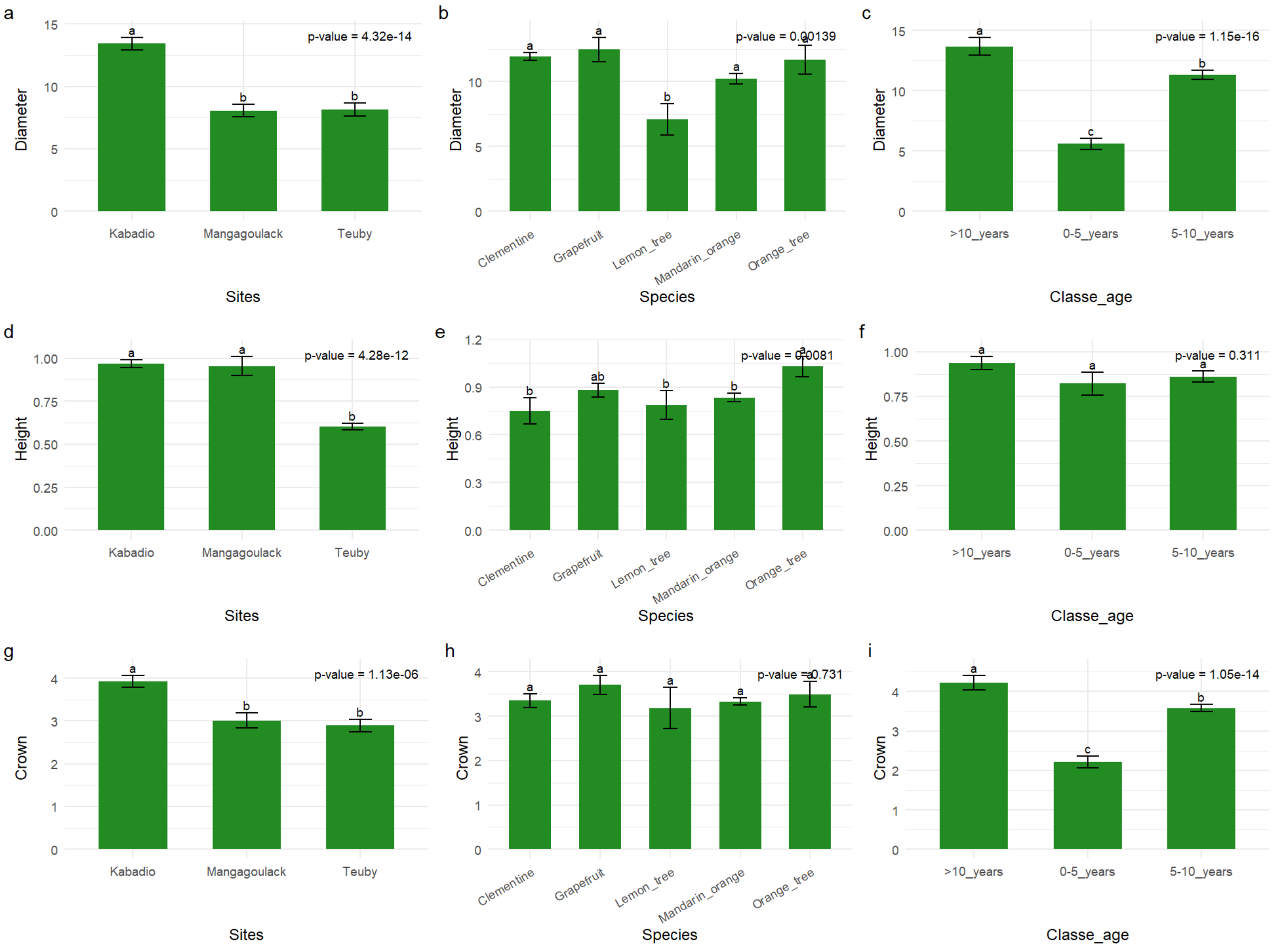

Figure 3. Variations in diameter (a), height (b), and crown size (c) depending on sites, species, and age class.

Figure 3 shows variations in diameter, height, and crown size according to site, species, and age class. For diameter, highly significant differences are observed between sites (**Figure 3(a)**; $p = 4.32e^{-14}$) and between age classes (**Figure 3(c)**; p =

$1.15e^{-16}$), reflecting a marked influence of site conditions and tree development stage on diameter growth. Indeed, individuals at the Kabadio site have significantly higher diameters compared to the other two sites (Mangagoulack and Teuby). In addition, individuals over 10 years old have a larger diameter, followed by the 5 - 10-year age class. Similarly, the effect of species on diameter appears to be very significant (Figure 3(b); $p = 0.001$), with statistically lower diameters in Citrus limon (lemon tree) compared to other species.

Regarding height, the site effect is also very significant (Figure 3(d); $p = 4.28e^{-12}$), indicating clear contrasts in vertical growth between sites, with higher values obtained in the Kabadio and Mangagoulack sites. The species has a highly significant effect on height (Figure 3(e); $p = 0.008$). Indeed, the orange tree and the Grapefruit species have significantly higher heights compared to other species. On the other hand, age has no statistical influence on height (Figure 3(f); $p = 0.31$).

Finally, significant differences were found between sites (Figure 3(g); $p = 1.13e^{-6}$) and between age classes (Figure 3(i); $p = 1.05e^{-14}$) for the crown size. Individuals over 10 years old located at the Kabadio site have significantly larger crown dimensions. Conversely, the effect of species on crown development is not significant (Figure 3(h); $p > 0.05$).

3.4. Distribution of Species' Above-Ground Biomass According to Age Classes and Sites

Figure 4 shows a comparative analysis of above-ground biomass by species, according to two levels of structuring: age class (Figure 4(a)) and site (Figure 4(b)). Analysis of variance (ANOVA) applied to the dataset revealed significant interactions between the species factor and the age class factor ($p = 4.18e^{-0.6}$), as well as between the species factor and the site factor. These results highlight the need to interpret the effect of species by taking into account variations related to sites and age classes for the above-ground biomass variable.

In the age class structure (Figure 4(a)), differences in above-ground biomass between species become more pronounced as individuals age. In fact, the >10-year and 5 - 10-year age classes have the highest biomass levels, with a particularly significant contribution from the orange tree and Mandarin orange species, while Lemon tree and Clementine have significantly lower values. Conversely, in the 0 - 5-year class, above-ground biomass remains low overall, with no significant difference between species.

According to the structure by site (Figure 4(b)), there were clear contrasts in the expression of the species' above-ground biomass. The Kabadio site is distinguished by higher overall biomass for all species, particularly the orange tree and Grapefruit, suggesting that environmental conditions are more favorable to above-ground growth. Conversely, the Mangagoulack and Teuby sites have lower biomass levels and a less marked and insignificant interspecific hierarchy.

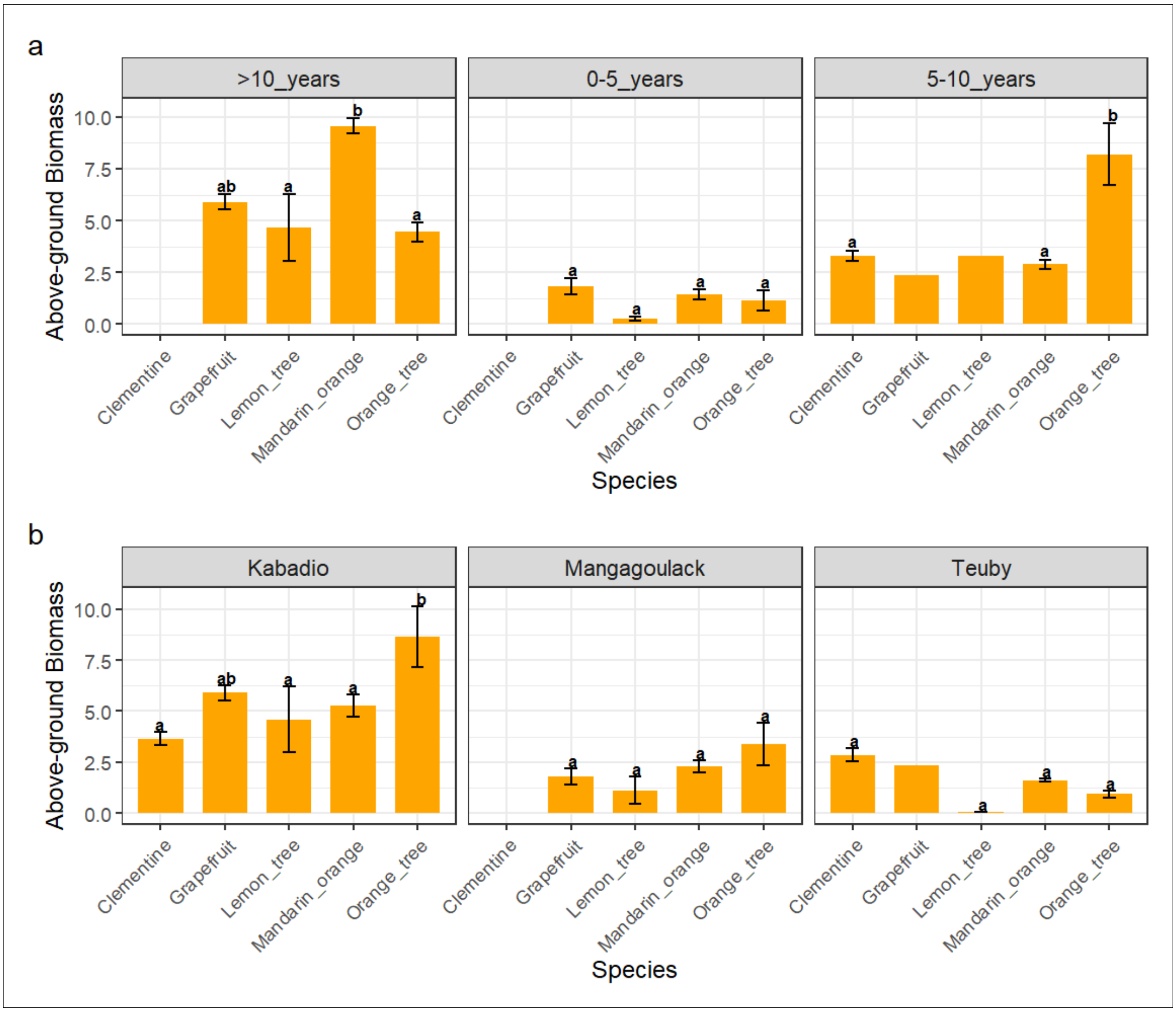

Figure 4. Variation in above-ground biomass by species according to age class (a) and site (b).

3.5. Carbon Stock and Equivalent CO_2

Figure 5 shows the variation in the amounts of carbon stored and CO_2 equivalent sequestered according to site, species, and age class of the plantation.

Overall, across the three sites, 221.62 tons of carbon were stored, with a total CO_2 equivalent sequestered of 813.35 tons. The Kruskal-Wallis test applied to the dataset reveals highly significant differences ($p < 0.01$) in total carbon stock (C_stock) and its CO_2 equivalent (Eq CO_2) across site, species, and age class. On a spatial scale (**Figure 5(a)**, and **Figure 5(d)**), the Kabadio site has significantly higher stocks per hectare, with 157.66 tons of C (t C/ha) and 578.60 tons of CO_2 equivalent, far exceeding those of Mangagoulack and Teuby, indicating a significantly higher sequestration capacity at this site. A species effect was also noted (**Figure 5(b)**, and **Figure 5(e)**). Indeed, stands and plantations with a predominance of Mandarin orange and orange tree have the highest carbon stocks, reaching 89.97 tons and 70.33 tons of C, respectively, corresponding to approximately 330.22 and

258.11 tons of CO_2 equivalent. Conversely, Clementine, Grapefruit, and Lemon trees have more modest stocks, reflecting interspecific differences in growth, structure, or density. Finally, the effect of age class is very clear (**Figure 5(c)**, and **Figure 5(f)**): trees aged 5 - 10 years have the highest stocks (138.84 t of C and 509.53 t of CO_2 equivalent) across the three sites, followed by trees aged > 10 years, while trees aged 0 - 5 years contribute little to the total stock. Although the 5 - 10-year age class exhibits the highest total carbon stock, this result mainly reflects the higher number of individuals sampled in this class, whereas trees older than 10 years store more carbon on average at the individual level.

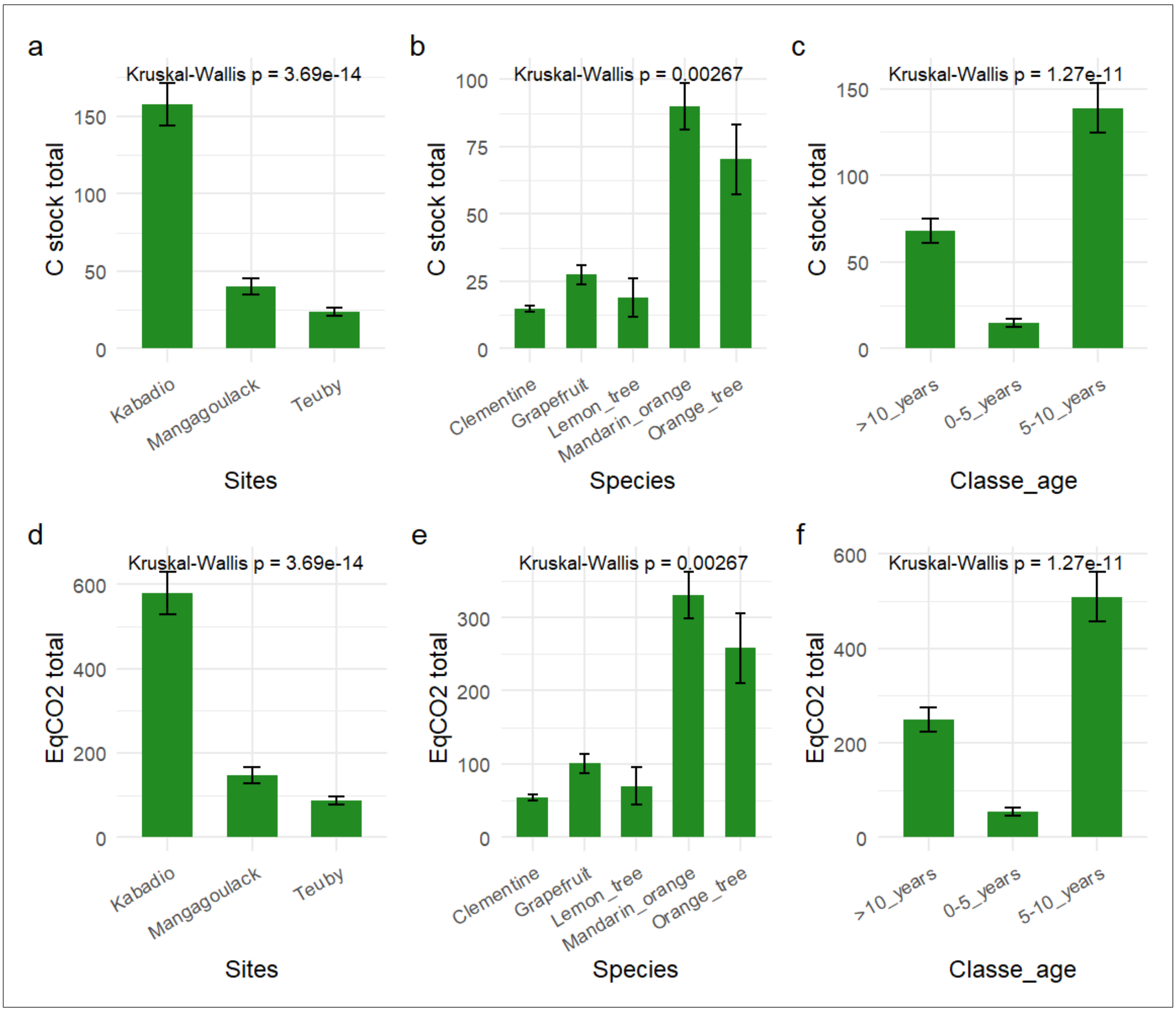

Figure 5. variation in the amounts of carbon stored and CO_2 equivalent sequestered according to site, species, and age class.

3.6. Relationships between Structural Parameters and Biomass/Carbon Stock

Figure 6 shows Pearson's correlation matrix between the quantitative variables used in this study. It reveals strong, structuring relationships between dendrometric variables and biomass, carbon stock, and the amount of CO2 equivalent sequestered. Diameter appears to be the central variable in the system, showing very strong positive correlations with above-ground biomass (ABG), carbon stock (C_stock), and CO_2 equivalent (Eq CO_2), with high coefficients (r = 0.91). Crown also shows substantial correlations with these same variables (r ≈ 0.73 - 0.77). Conversely, height shows moderate correlations with the other variables (r ≈ 0.33 - 0.50), suggesting a more independent contribution to the overall functioning of the system and variability that is partially uncorrelated with dimensions directly related to carbon storage.

The near-perfect relationships observed between ABG, C_stock, and Eq CO_2 (r = 1.00) reflect an expected functional redundancy, as these variables are mathematically and conceptually linked.

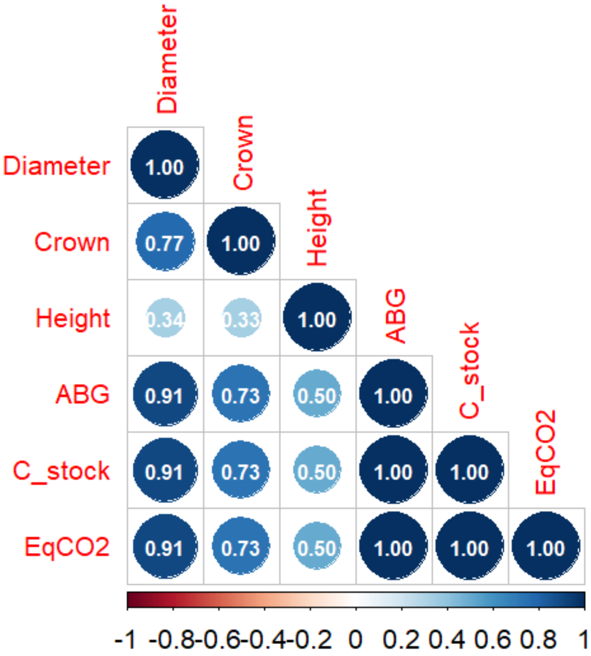

Figure 6. Pearson correlation matrix between variables.

The Factorial Analysis of Mixed Data (FAMD) (**Figure 7**) reveals a clear structure of variables along the first two axes, which together explain 81.8% of the total inertia (Dim 1: 65%, Dim 2: 16.8%). Axis 1 is mainly associated with quantitative variables related to tree size, biomass, and carbon storage, including diameter, crown, carbon stock (C_stock), CO_2 equivalent (Eq CO_2), and above-ground biomass (ABG), all of which are positively projected and strongly correlated with each other. This structure suggests a dominant gradient of structural development and carbon storage capacity, indicating that individuals to the right of axis 1 have high values for these quantitative variables. Axis 2 is mainly driven by the Height variable, reflecting a height gradient that is partially independent of other structural dimensions, suggesting that height growth is not strictly synchronized with biomass and carbon accumulation.

The projection of the sites reveals sharp contrasts between spatial units. Indeed, the Kabadio site stands out for its positive position on axis 1, indicating trees characterized by high diameters, biomass, and carbon stocks. Conversely, Mangagoulack and Teuby are located in the negative part of axis 1, reflecting stands that are generally less developed in terms of structure and carbon storage, with some differentiation along axis 2, suggesting distinct growth strategies (particularly in terms of height). The ellipse of individual concentration indicates moderate intra-site variability, while the inter-site separation highlights the marked influence of local conditions on the structure and carbon sequestration function of stands.

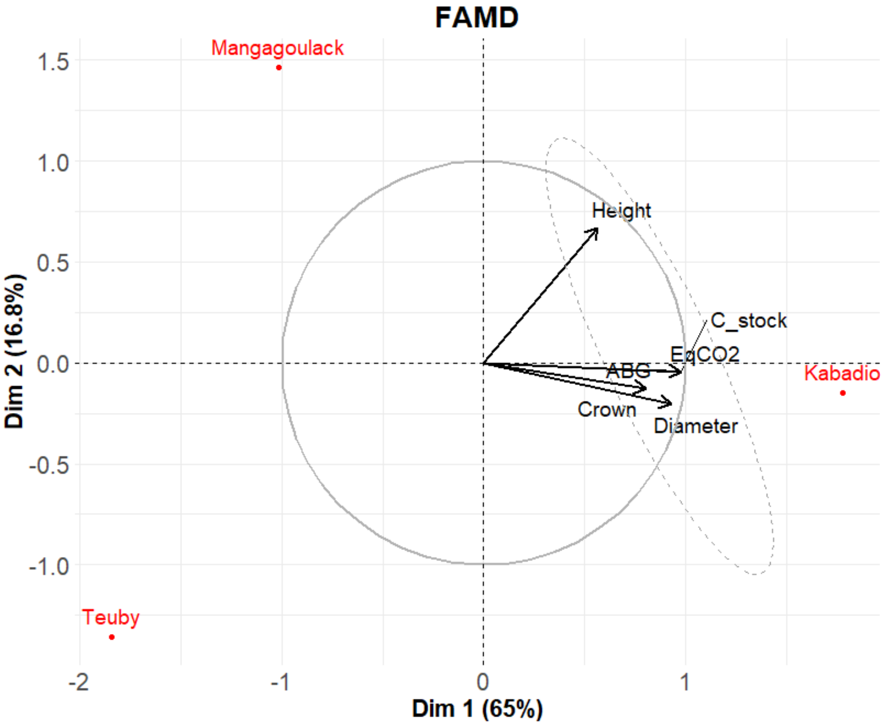

Figure 7. Factorial Analysis of Mixed Data (FAMD) for dendrometric and carbon storage variables

4. Discussion

This study highlights some very interesting findings concerning the characteristics of the systems studied and their contribution to carbon storage, as presented below. It should be noted, however, that this study provides only an overview of the effects of environmental conditions and climatic factors on the carbon sequestration potential of citrus orchards in southern Senegal. Another limitation of this study is that it only takes into account above-ground biomass, without considering the amount of carbon stored in the soil of the plantations studied.

4.1. Floristic Diversity and Structuring of Citrus Orchards

The results show that citrus plantations in the study area have relatively low floristic diversity, with a limited number of species, all belonging to the Rutaceae family. This is often linked to the economic choices made by producers without any real perspective on the impact of these choices on the sustainability of production systems. Several studies have shown that specialized orchards tend to have limited taxonomic diversity [32] [33], but high intraspecific variability, particularly in terms of local or introduced varieties. However, clear differences were noted between sites, particularly with higher species diversity and evenness in Kabadio, reflected in higher Shannon and Pielou indices. This structure suggests greater diversity and a better distribution of individuals between species in Kabadio, with no marked dominance of any one species, unlike in Mangagoulack and Teuby, where certain species are more dominant.

4.2. Effects of Site, Species, and Age on Dendrometric Growth

Analysis of dendrometric parameters highlights a marked influence of site and age class on diameter and crown, while height appears to be more dependent on species and site than on the age of individuals. The significantly higher diameters observed in Kabadio reflect edaphic, climatic, and management conditions that are more favorable to radial growth. The strong influence of age on diameter and crown size is consistent with fruit tree growth models, where citrus growth is gradual and closely linked to the age of the plantation in question. This is consistent with the observations of [34], who showed that biomass and dendrometric dimensions increase with age.

The absence of a marked effect of age on height is consistent with observations made on citrus and other fruit trees, whose vertical growth is often limited by training methods, particularly pruning [35]. The interspecific differences observed, particularly the smaller diameters of lemon trees compared to other species, can be explained by intrinsic biological traits, such as tree architecture, wood density, or biomass allocation strategies [36].

4.3. Distribution of Above-Ground Biomass of Species by Age and Site

Above-ground biomass shows a clear structure according to age class and site, with significant interactions between species and these two factors. The marked increase in biomass in the 5 - 10-year and >10-year age classes is consistent with the growth dynamics of fruit trees, where the juvenile phase is characterized by limited biomass accumulation, followed by a phase of rapid growth and structural expansion. These findings corroborate those of [10] in tropical agroforestry systems, with more intense biomass accumulation as the stand in question ages.

The fact that interspecific differences become more pronounced with age highlights that biomass production potential depends not only on the species but also on its ability to exploit site conditions over time. The dominance of orange and mandarin trees in the older age classes confirms their structuring role in the orchards studied, a finding that is widely documented in tropical citrus farming systems, where these species are often favored for their vigor and productivity.

On a spatial scale, the superiority of the Kabadio site in terms of above-ground biomass suggests a favorable combination of environmental factors and cultural practices. Similar results were reported in the study conducted by [37] in Benin, highlighting the remarkable influence of environmental factors on biomass accumulation in *Acacia auriculiformis* A. Cunn. ex Benth. plantations.

4.4. Carbon Stocks and CO_2 Sequestration in Citrus Plantations

The results show that the citrus plantations studied are significant carbon reservoirs, with significant variations depending on the site, species, and age class. The Kabadio, Mangagoulack, and Teuby sites store 157.66, 40.32, and 23.83 t C/ha, respectively. The carbon storage capacity of an agroforestry system estimated by [37] varies between 12 and 228 t C/ha, with an average value of 95 t C/ha. The values obtained in this study fall within this range, with the Kabadio stock significantly exceeding the estimated average. This significant contribution by the Kabadio site to total carbon stocks and CO_2 sequestration confirms the central role played by plantation management practices and the area's soil, climate, and edaphic conditions in storage dynamics, consistent with dendrometric and biomass results.

The species effect observed, with higher stocks in mandarin and orange trees, is consistent with numerous studies indicating that species with high above-ground biomass and more developed architecture have greater sequestration potential. Conversely, the more modest stocks of lemon and clementine trees reflect their smaller size and growth strategy.

A particularly interesting result concerns the 5 - 10-year-old age class, which has the highest carbon stocks, even ahead of the >10-year-old class. This is explained by the fact that in the plantations under study, the majority of the trees measured are between 5 and 10 years old.

In terms of stored averages, individuals older than ten years (>10 years) store more carbon than other age classes. These results are similar to those of [37], who demonstrated that in *Acacia auriculiformis* plantations in the classified forests of Pahou and Ouèdo in southern Benin, carbon stocks varied according to age.

4.5. Relationships between Structural Parameters, Biomass, and Carbon Storage

The strong correlations observed between diameter, above-ground biomass, carbon stock, and CO_2 equivalent confirm the central role of diameter as an explanatory variable for carbon storage capacity. This result is consistent with the literature, which identifies diameter as the best predictor of biomass in most tropical allometric models. The crown also shows high correlations with biomass and carbon, reflecting the importance of leaf area and tree architecture in accumulation processes. This is related to the fact that biomass accumulation is gradual and closely linked to the increase in photosynthetic area induced by radial growth.

These results are consistent with those of [38], who reported a strong relationship between these parameters and biomass accumulation in citrus orchards in Pakistan.

Conversely, height shows weaker relationships, confirming that it contributes secondarily to carbon storage, particularly in fruit systems where vertical growth is limited by pruning and management practices. This confirms that height is not necessarily a good indicator of functional maturity and carbon storage capacity in citrus trees.

Factor analysis of the mixed data reinforces these interpretations by highlighting a structuring gradient of development and carbon storage driven by diameter, canopy, and biomass. The clear differentiation of sites on the main axis confirms that local conditions, and therefore the way orchards are managed, play a decisive role in the expression of the sequestration potential of citrus plantations.

5. Conclusion

This study highlights the significant role of citrus orchards in southern Senegal in biomass production and carbon sequestration, while emphasizing the strong influence of site conditions, species, and age structure on dendrometric growth and carbon storage. The results show that diameter and crown size are key determinants of above-ground biomass and carbon stocks, whereas height contributes only marginally, reflecting the effects of management practices such as pruning. The marked superiority of the Kabadio site in terms of biomass and carbon storage underscores the decisive role of local environmental conditions and orchard management. Species such as orange and mandarin trees, particularly in intermediate and older age classes, contribute most to carbon stocks, confirming their structuring role within the orchards. These findings provide useful guidance for orchard managers and policymakers, suggesting that promoting high-biomass species such as Orange and Mandarin, combined with site-specific management strategies, could enhance the climate change mitigation potential of citrus-based production systems. However, this study provides only a partial assessment of the sequestration potential of citrus systems, as it does not account for soil carbon or explicitly integrate climatic and edaphic variability. Future research should therefore incorporate below-ground carbon pools, detailed environmental parameters, and a broader range of orchard structures to achieve a more comprehensive evaluation of the carbon sequestration potential and sustainability of citrus-based production systems in southern Senegal.

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Conflicts of Interest

The authors declare no conflicts of interest.

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