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Values of the stored carbon stock according to the type of reforestation in Bouaflé Classified Forest (Côte d'Ivoire)

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Abstract

Forest management concerns drive managers to develop economic, environmental, and social innovations. This study, which is part of a policy, emphasizes the importance of reforestation in the economic value of the carbon stock sequestered in the Bouaflé Classified Forest. To achieve these objectives, botanical and dendrometric inventories were carried out. The floristic diversity and the structural parameters of the different plots made it possible to determine the quantity of carbon and carbon dioxide (CO_2) stocks and the economic value of the carbon stock of the reforested areas. The results revealed four species of reforestation. The species have an average diameter between 20 to 30 cm and a height between 8 and 16 m. The monospecific plantation which stored the highest carbon rate is the Fraké 1987 plot, with a value of 5264.73 tonnes. Its monetary value is estimated at 57964.674 Euros for the CDM carbon price, 90811.3226 Euros for the Voluntary Market carbon price and 270501.812 Euros for the REDD+ Carbon price. In the multi-species plantations, the largest quantity of carbon was stored by the Fraké-Framiré 1981 plot with a value of 657.99 tonnes. Therefore, the type of reforestation plays an important role in atmospheric carbon sequestration and the resulting carbon value.

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Introduction

Climate-related issues are a significant concern with the Framework Convention on Climate Change (UNFCCC, 1992). Government agreements have been made to curb climate change and the resulting risks (Tellenne, 2023). However, non-compliance with numerous international commitments by the contracting parties leads to a recurring increase in CO_2 emissions (Tellenne, 2023). Thus, to encourage compliance with international conventions, the notion of "carbon value" has been established (Antoniuk, 2023). This concept's advantage is associating a quantified value with the precautionary principle in climate matters. It also aims to make investment choices effective in reducing greenhouse gas emissions (Antoniuk, 2023).

Carbon market mechanisms have been put in place (MacLeod and Adamczyk, 2022; Sachs and Sachs, 2022), and the emission quotas exchange allows countries to transact on CO_2 quotas (Ernst, 2022). Carbon credits thus enable the financing of projects based on the reduction of CO_2. These projects relate to the conservation of forest cover and the reforestation of bare land as recommended by REDD+ (Sonwa *et al.*, 2022). This reforestation will have to be oriented towards the restoration of the forest cover, the production of timber, or even the production of wood energy (Sonwa *et al.*, 202).

Côte d'Ivoire is increasingly involved in climate-related issues through its engagement in the REDD+ mechanism, allowing it to benefit from multilateral funds for the sustainable conservation of severely degraded forest cover (SODEFOR, 2023). Regular monitoring and measurement of CO_2 emissions and forest carbon stock have become a priority for the country (REDD, 2023). The Société de Développement des Forêts (SODEFOR), a technical structure committed to implementing the commitments contained in the REDD+ mechanism, manages 236 classified forests, including the Bouaflé Classified Forest (SODEFOR, 2023). The Bouaflé Classified Forest is subdivided into a series of production and reconstitution reforestation. Monospecific and multispecific reforestation is practiced there (SODEFOR, 2023). However, the contribution of these types of reforestation to atmospheric carbon sequestration remains poorly understood. Therefore, this study's objective is to improve knowledge of the carbon value of the Bouaflé classified forest.

Material and methods

Study site

The Bouaflé Classified Forest is located in the Haut-Sassandra region (Fig. 1) in the center-west of Côte d'Ivoire. Covering an area of 20,350 hectares, it is located near the town of Daloa between 6°46′ and 6°55′ North latitude and 6°04′ and 6°15′ West longitude (SODEFOR, 2023). The ombrothermic diagram reveals a dry season between November and February and a rainy season between March and October. Temperatures vary between 26 and 28°C, with an average of 27.2°C. The vegetation consists mainly of silvicultural plots based on Terminalia ivorensis A. Chev, Terminalia superba EngI. & Diels, Cedrela odorata L., Gmelina aborea Roxb, Tectona grandis L, crops and fallow land (SODEFOR, 2023).

Data collection

The floristic inventory sites were determined from the type of reforestation, the reforested species, the age of the reforestation plot, the regeneration period and the type of exploitation. The inventory sites were located using a GPS. Transect sampling was used (Rabiou *et al.*, 2015; Ouattara *et al.*, 2016). Linear transects represented by 100 m strips were installed in the blocks of the different types of reforestations.

The individuals present 5 meters on either side of the transect line were inventoried. A total of five readings were taken per block, with a total of 45 readings in the multi-species blocks and 40 readings in the monospecific blocks.

Within each sample plot, reforested species were identified and counted. For each individual of reforested species, the circumference and the total height were measured and recorded.

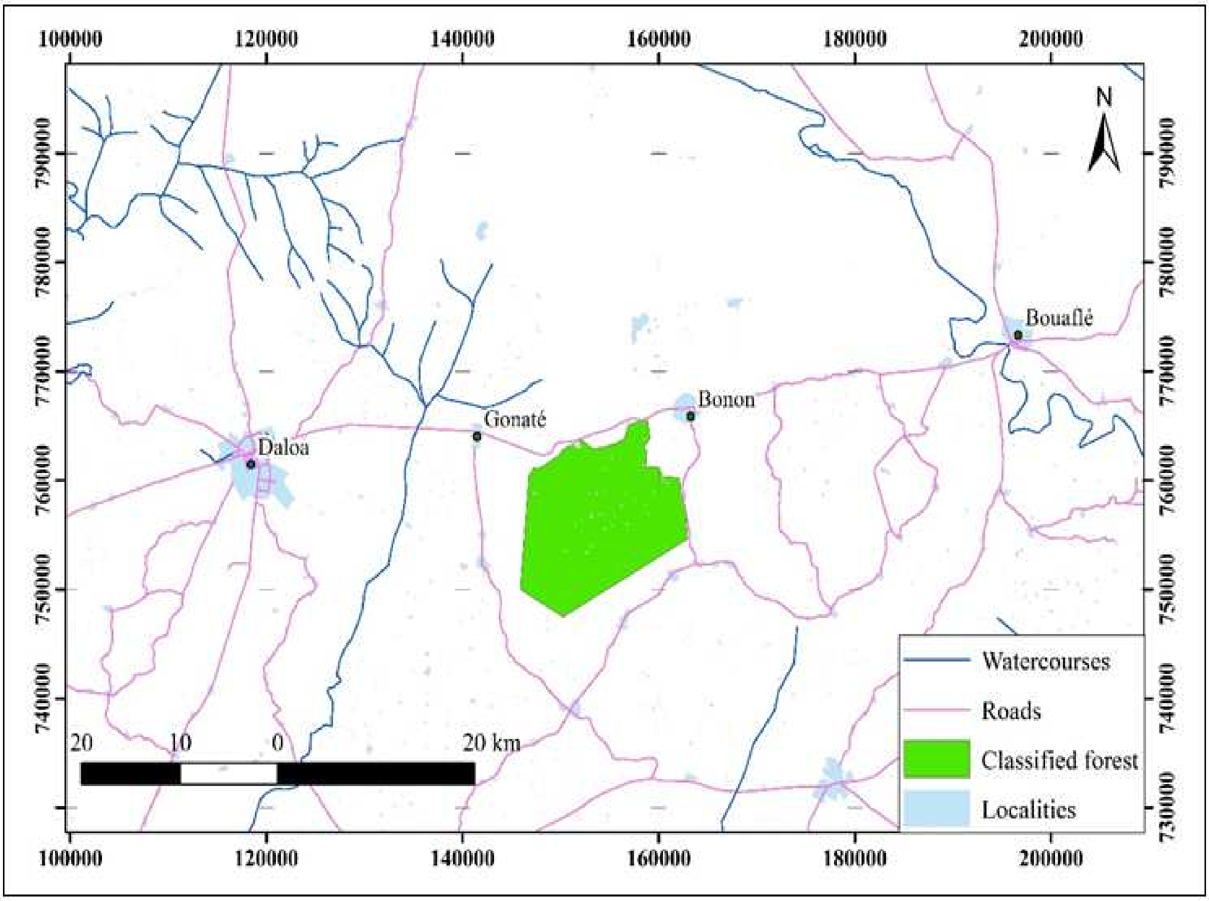

Fig. 1. Location of Bouaflé classified forest.

The inventoried reforested species are grouped into eight diameter classes with a regular amplitude of 10 cm. The different established height strata are, the lower tree stratum (2 to 4 m), the middle tree stratum (4 to 8 m), the upper tree stratum (8 to 16 m), the emergent stratum (16 to 32 m) and the upper emergent stratum (beyond 32 m).

Data analysis

Density shows the number of individuals of wood species per unit area. According to the expression of the density according to Rollet (1979), D = n/s, D is the density in stems/ha; n is the number of stems (individuals) of the considered environment and s is the total area of the environment in hectares. The amount of carbon sequestered by reforested species of reforestation types is calculated from the equation of Brown and Lugo (1992) whose expression is C (t/ha) = Biom (t) x CF where Biom (t) is the total biomass and CF = 0.5 is the conversion factor. As for the total biomass, it is obtained by summing the aerial and root biomasses according to the formula Biom (t) = AGB + BGB where Biom (t) is the total biomass (t); BGB is belowground biomass (t) and AGB is aboveground biomass (kg). Aboveground biomass is calculated using the allometric model of Chave *et al.* (2014) from the equation AGB = 0.0673 × (ρD2H)0.976 where AGB (kg) is the aboveground biomass or aerial biomass; ρ (in g/cm^3) is the specific density of wood of a species; H (m) is the total height of the tree and D (cm) is the diameter of the tree. The specific density (ρ) of reforested species is determined by referring to the reference list of Reyes *et al.* (1992). The average value was adopted for species with several values of specific gravity. Belowground biomass was calculated using the equation (IPCC, 2006) BGB = AGB x R where BGB (t) is belowground biomass; AGB is the aboveground biomass (kg) and R = 0.24 is the stem/root ratio. The stock of carbon dioxide (CO_2) sequestered by reforested species of the types is obtained from the equation (IPCC, 2006) m (CO_2) = C (t/ha) x M(CO_2)/M(C) where m (CO_2) is the mass of atmospheric CO_2 sequestered; C (t/ha) is the amount of total carbon sequestered; M (CO_2) = 44 is the molar mass of CO_2; and M(C) is the molar mass of carbon.

The economic value of the carbon stock of reforested species is calculated from the carbon markets set up since the 2000s. In this study, the choice was made on the Clean Development Mechanism (CDM) market prices, voluntary markets and Reduced Emissions from Deforestation and Degradation (REDD+). The average sale price of forest credit is 3 euro/tonne of CO2 equivalent (teq CO2) for the CDM, 4.7 euro/teq CO2 for voluntary markets (Chenost *et al.*, 2010) and 14 euro/tonne of carbon (low value) or 100 euro/tonne of carbon (high value) for REDD+ (Boulier and Simon, 2010).

Results

The floristic inventory made it possible to identify 3185 individuals from 4 reforestation species. These are *Cedrela odorata* L. (Meliaceae) or Cedrela, *Gmelina arborea* Roxb. (Verbenaceae) or Gmelina, *Tectona grandis* L.f. (Verbenaceae) or Teak and *Terminalia superba* Engl. & Diels (Combretaceae) or Fraké. The reforestation blocks comprise one species in a monospecific plantation or two species in a multispecific association.

Table 1. Densities of reforestation in the Bouaflé classified forest.

Type of planting	Type of reforestation	Average density (stems/ha)
Monospecific	Cedrela 1981	3.4±4.25
	Cedrela 1986	48.74±63.63
	Cedrela 1987	3.92 ± 20
	Frake 1986	8.6±7.01
	Frake 1987	2.78 ± 2.88
	Gmelina 1986	3.45 ± 2.50
	Teak 1984	6.69±8.78
	Teak 2015	17.88±18.49
Multi-species	Cedrela-Teck 1986	3.29 ± 4.50
	Cedrela-Teck 1987	1.21 ± 1.02
	Fraké- Framiré 1981	1.2 ± 1.19
	Fraké- Framiré 1983	2.1 ± 2.49
	Fraké- Framiré 1984	1.94 ± 1.65
	Frake-Teck 1985	2.85 ± 4.60
	Frake-Teck 1987	1.66 ± 2.02

The various reforestations have an average density of 375 stems/ha (Table 1). The type of reforestation that harbors the highest density of reforested species is Cedrela-1986 with an average density of 48.74 stems/ha. An irregular distribution of the stems of reforested species in the different diameter classes is observed. This has an 'inverted J' shape (Fig. 2). The distribution of species in height classes is unevenly distributed. The highest density of species was observed in the height class [8;16] and the lowest density was observed in the class [2;4] (Fig. 3). In monospecific plantations, the amount of aerial biomass in the Fraké-1987 plot is 8491.5 t/ha. The Teck-2015 plot has the lowest amount of aboveground biomass with a value of 53.84 t/ha (Fig. 4). The highest underground biomass is observed in the plot of Fraké-1987 with a value of 2037.97 t/ha. On the other hand, the plot of Teck 2015 harbors the lowest quantity of underground biomass, i.e., 12.92 t/ha (Fig. 5). In the multi-species plantations, the highest aerial biomass was observed in the Fraké-Framiré-1981 plot with a value of 1061.27 t/ha. The lowest value was observed in the Fraké-Teck-1985 plot, i.e., 232.89 t/ha. The parcel that harbors the largest quantity of underground biomass is that of Fraké-Framiré-1981, with a value of 254.7 t/ha, while that of Fraké-Teck-1985 contains the lowest quantity, i.e., 55, 89 t/ha.

Table 2. Quantities of carbon in reforestation.

Type of planting	Type of reforestation	Biomass (t)	C (t/ha)	CO2 (t/ha)
Monospecific	Cedrela 1981	217.29	54.32	199,367
	Cedrela 1986	450.70	225.35	827.03
	Cedrela 1987	613	306.50	1124.84
	Frake 1986	919.88	459.94	167.99
	Frake 1987	10529.46	5264.73	19321.55
	Gmelina 1986	82.91	41.46	152.15
	Teak 1984	212.01	106	389.04
	Teak 2015	66.76	33.38	122.50
Multispecies	Cedrela-Teck 1986	566.61	283.30	1039.73
	Cedrela-Teck 1987	783.67	391.84	1438.04
	Fraké- Framiré 1981	1315.97	657.99	2414.81
	Fraké- Framiré 1983	1081.19	540.60	1983.99
	Fraké- Framiré 1984	760.51	380.25	1395.54
	Frake-Teck 1985	288.77	144.38	529.89
	Frake-Teck 1987	1053.01	526.51	1932.28
	Total	18941.76	9416.56	33038.77

On all the plots of reforestation inventoried, the estimated total biomass is 18941.74 tons. In monospecific plantations, the highest total biomass per block is observed in the Fraké-1987 plot with a value of 10529.46 tonnes; the lowest total biomass was observed in the Teck-2015 plot with 66.76 tons. In the multi-species plantations, the greatest quantity of total biomass is observed in the Fraké-Framiré-1981 plot (1315.97 t) and the lowest quantity in the Fraké-Teck 1985 plot (288.77 t) (Table 2).

Table 3. Financial cost in the carbon stock of the types of reforestation.

Type of reforestation	CDM Carbon Price (€)	Voluntary Market Carbon Price (€)	Carbon Price REDD+
Cedrela 1981	598.102584	937.027382	2791.145393
Cedrela 1986	2481.1017	3887.05933	11578.47459
Cedrela 1987	3374.53179	5286.76647	15747.81502
Frake 1986	503.96094	789.538806	2351.81772
Frake 1987	57964.674	90811.3226	270501.812
Gmelina 1986	456.443391	715.094646	2130.069158
Teak 1984	1167,13269	1828.50787	5446.619195
Teak 2015	367.508829	575.763832	1715.041202
Cedrela-Teck 1986	3119.18652	4886.72555	14556.20377
Cedrela-Teck 1987	4314,13353	6758.8092	20132,62314
Fraké- Framiré 1981	7244.4456	11349.6314	33807.41281
Fraké- Framiré 1983	5951.97403	9324.75931	27775.8788
Fraké- Framiré 1984	4186.61845	6559.03558	19537.55278
Frake-Teck 1985	1589.6612	2490.46921	7418.418913
Frake-Teck 1987	5796.83739	9081.71191	27051,90782
Total	99116.3126	155282.223	462542.7923

The carbon content (C) resulting from this total biomass is 9416.56 t/ha. The carbon dioxide equivalent is 33038.76 t/ha. In monospecific plantations, the largest amount of carbon was stored by the Fraké-1987 plot with a value of 5264.73 tons and the equivalent carbon dioxide is 19321.55 t/ha. The lowest carbon rate was recorded in the Teck-2015 plot with a value of 33.38 t/ha and the equivalent carbon dioxide of 122.50 t/ha. In the multi-species plantations, the largest quantity of carbon was stored by the Fraké-Framiré-1981 plot, with a value of 657.99 tonnes, or 2414.81 t/ha of carbon dioxide.

The smallest amount of carbon stored by the Fraké-Teck-1985 plot is 144.38 tons, and the carbon dioxide equivalent is 529.89 t/ha (Table 2).

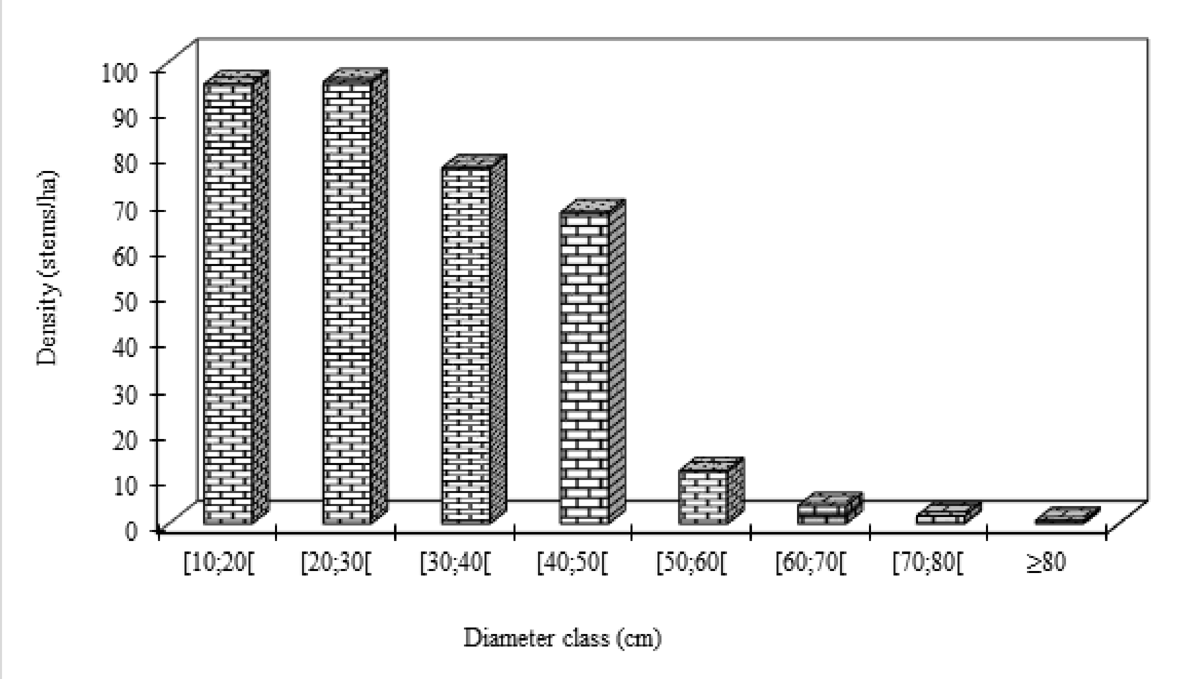

Fig. 2. Diameter classes of reforestation in Bouaflé classified forest.

In monospecific plantations, the highest economic value in carbon stock is that of the Fraké-1987 plot with 57,964.674 Euros for the CDM carbon price; 90811.3226 Euros for the Voluntary Market carbon price and 270501.812 Euros for the REDD+ Carbon price. The lowest economic value is observed in the Teck-2015 plot with a value of 367.508829 Euros for the CDM carbon price; 575.7638321 Euros for the Voluntary Market carbon price and 1715.041202 Euros for the REDD+ Carbon price. In the multi-species plots, the plot with the highest economic value in terms of carbon stock is that of Fraké-Framiré-1981 with 7244.445603 Euros for the CDM carbon price; 11349.63144 Euros for the Voluntary Market carbon price and 33807.41281 Euros for the REDD+ Carbon price.

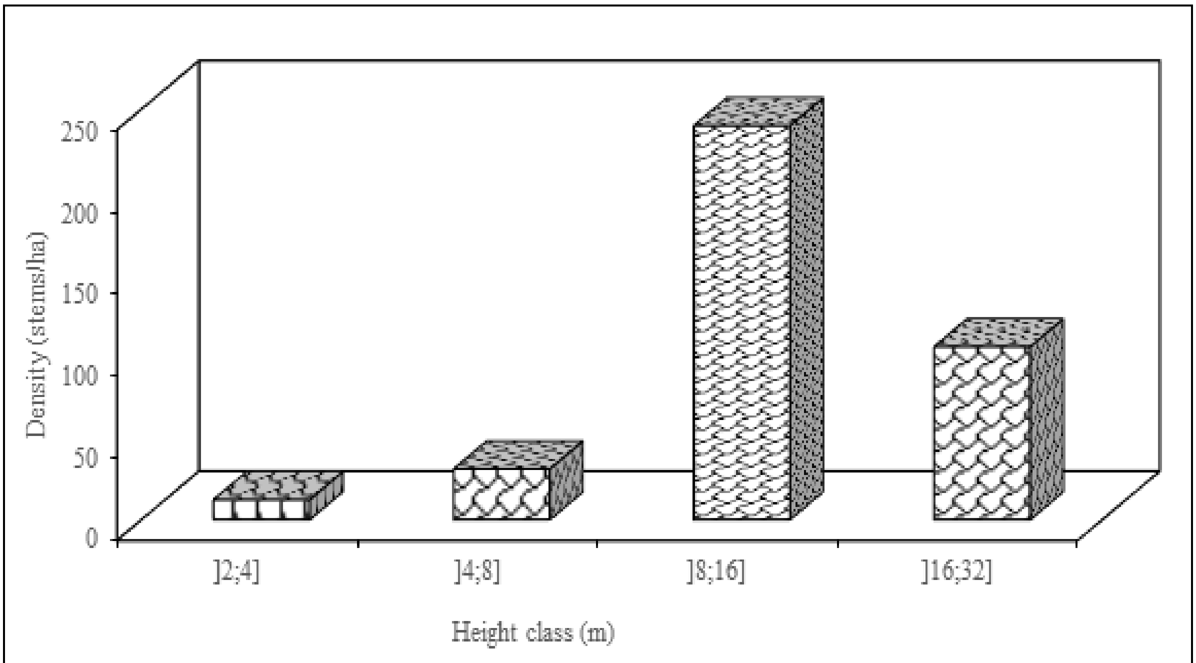

Fig. 3. Classes of heights of reforestation in Bouaflé classified forest.

The lowest economic value was observed in the Fraké-Teck-1985 plot with 1589.661196 Euros for the CDM carbon price; 2490.469206 Euros for the Voluntary Market carbon price and 7418.418913 Euros for the REDD+ Carbon price. The financial costs of the carbon dioxide sequestered by all types of reforestations, estimated from the carbon markets considered (CDM, voluntary market, REDD+), correspond respectively to 99,116.28 Euros, 155,282.172 Euros and 462,542.64 Euros (Table 3).

Discussion

Tropical forests contain large amounts of carbon, mainly stored by trees (Laporte *et al.*, 2010). Thus, faced with the degradation of forest cover, policies have advocated the strengthening of protected areas and the reforestation of classified forests (Tiébré *et al.*, 2016). The Bouaflé classified forest is part of this framework with a plant cover of monospecific and multispecific reforestation (SODEFOR, 2023). This study showed the presence of 4 species belonging, unlike the work of Kouamé (1998), who counted 72 main reforested and marketed species. This indicates to what extent the reforested species of the Bouaflé classified forest have diminished following human activities. According to Sangne *et al.* (2008), the destruction of the forest following human activities does not promote the survival of these species. Their exploitation explains the low density of reforested species with large diameters.

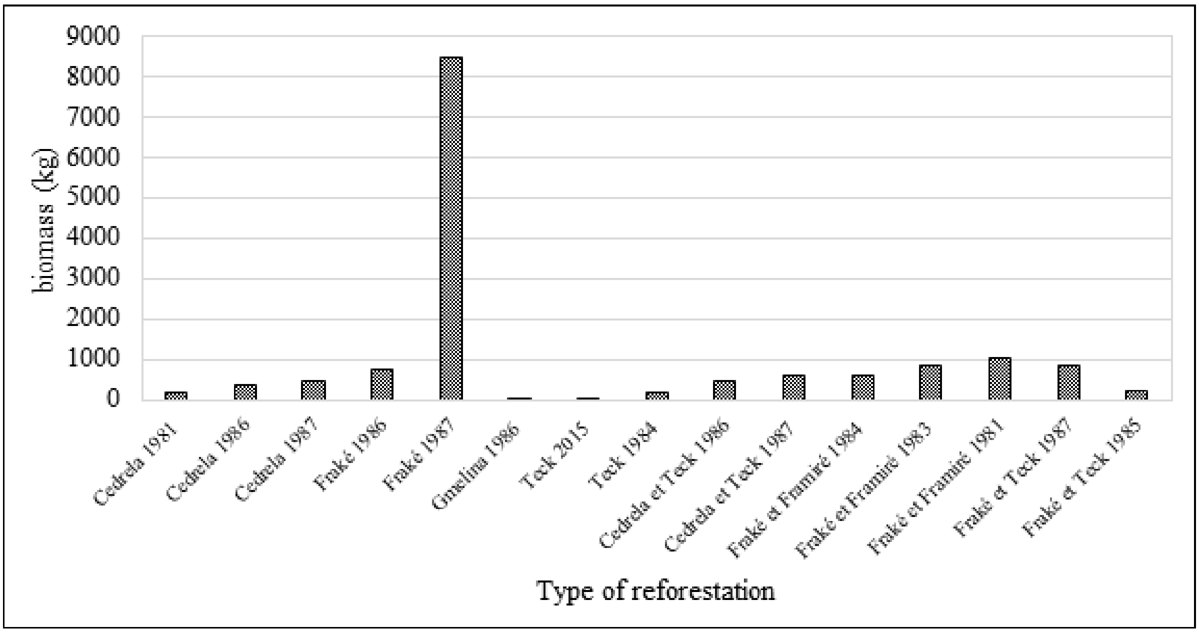

Fig. 4. Aerial biomass of reforestation in Bouaflé classified forest.

The dominance of stems in the 8 to 16-meter class could be due to the logging in the FCB. Only the reforested species found in the blocks whose exploitation has not been completed and those not exploited reach a height greater than or equal to 40 meters. The large amount of biomass and carbon in the Fraké-1987 and Fraké-Framiré-1981 plots could be explained by the rapid growth of the Fraké. Ouattara *et al.* (2013) state that fast-growing species can reach very large diameters at maturity. For Thompson *et al.* (2004), the DBH influences the quantity of biomass (aerial, underground) and, therefore, the rate of carbon sequestered by a tree. The more the tree grows, the more carbon it sequesters and it is considered a carbon sink. The low values observed in the Teck-2015 and Fraké-Teck-1985 plots could be linked to the predominance of woody plants with small diameters. The frequency of logging of reforested species will determine the diameter of the trees on the plot, thus affecting the amount of total biomass and carbon stock. Mbow (2009) indicates that logging most often targets large trees, thus drastically reducing biomass stocks over the years. According to the observations of Monssou *et al.* (2016), the quantities of biomass and carbon recorded in agroforestry systems are low due to crops that are less rich in woody species. Farmers cut down certain trees for better productivity of their crops. This directly impacts wood potential and, at the same time, reduces biomass and carbon stocks. Several plots are infiltrated by farmers with activities that limit carbon sequestration.

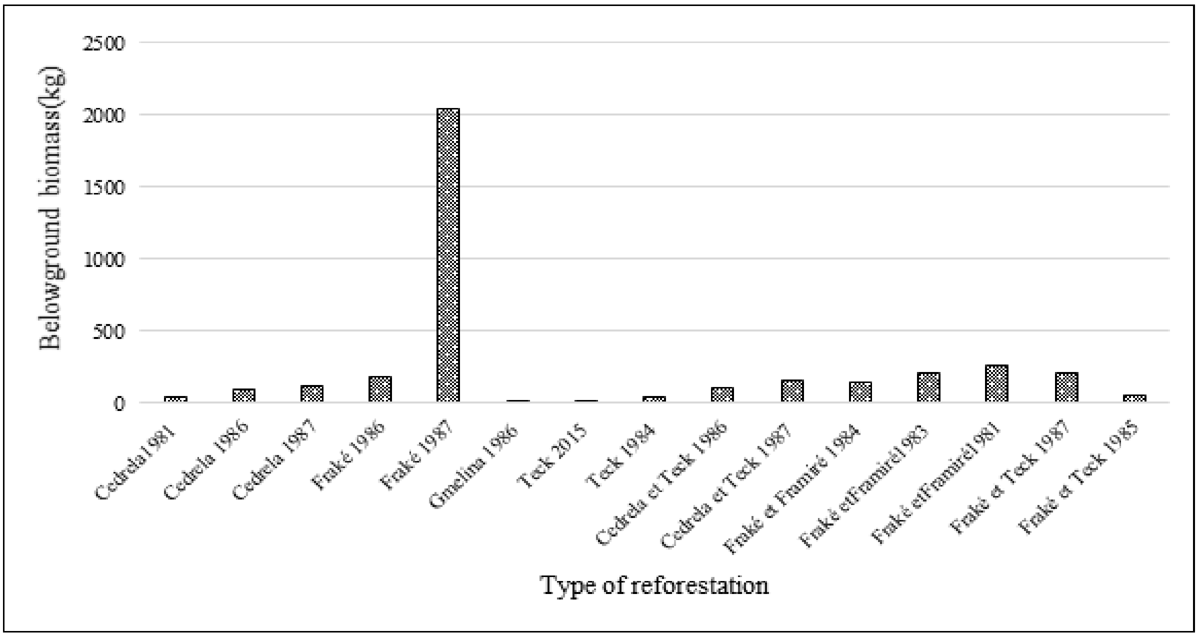

Fig. 5. Underground biomass from reforestation in Bouaflé classified forest.

The carbon storage potential of the trees of the different types of reforestation of the Bouaflé classified forest reflects the importance of the forest in reducing atmospheric carbon by regulating the temperature and the climate. Indeed, thanks to photosynthesis, forests participate in the fixation and storage of atmospheric carbon, i.e., trees capture atmospheric CO_2 (REDD+ Côte d'Ivoire, 2023). Among all the mechanisms for mitigating the adverse effects of climate change, forests remain the best mechanism since it is less expensive (REDD+ Côte d'Ivoire, 2023).

Conclusion

This work has made it possible to identify the place of the types of reforestation undertaken in the classified forest of Bouaflé in the monetary value of the carbon stock sequestered by the reforested species. There is a strong accumulation of carbon in sites that host single-species and multi-species reforestation systems in Fraké. This translates into a high monetary value of the carbon sequestered by this forest species. This study could constitute a database to guide managers in choosing species during reforestation activities. This study alone cannot comprehensively assess the carbon sequestration capacity in the Bouaflé classified forest. Further investigation may address the following points:

First, assess the impact of logging on the sequestration of atmospheric carbon in the classified forests of Côte d'Ivoire;
Second, assess the carbon sequestration capacity of non-reforested species in the classified forests of Côte d'Ivoire.

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