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Importance, diversity and economic value of trees associated with cocoa trees in different agroforestry systems

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Abstract

The expansion of cocoa cultivation in Côte d'Ivoire, although crucial to the national economy, has been at the expense of forest cover, leading to massive deforestation, loss of biodiversity and degradation of essential ecosystem services. Cocoa-based agroforestry systems (SAFc), incorporating shade trees, are increasingly being promoted as a sustainable solution for reconciling agricultural productivity and environmental conservation. This study aimed to (1) characterise the floristic diversity of shade trees associated with cocoa trees in different SAFc in the Nawa region; (2) assess the structural characteristics of these trees; (3) estimate biomass and carbon sequestration of SAFc; and (4) compare the economic value of trees associated with SAFc. Sixteen (16) cocoa plantations representing four types of SAFc (full sun systems, shaded systems and two intermediate systems) were selected and floristic surveys were carried out. A total of 83 tree species in 62 genera and 32 botanical families were recorded, with higher species richness in shaded systems (52 species) and intermediate 2 (40 species). Structural analysis revealed a predominance of young trees (diameter class [10-20] cm), suggesting active regeneration. Overall, the results indicate that intermediate SAFc systems offer an optimal balance between cocoa productivity, biodiversity conservation and the provision of ecosystem services, particularly in terms of biomass accumulation and carbon sequestration. Promoting intermediate SAFc could therefore strengthen the sustainability of cocoa production in Côte d'Ivoire.

Keywords: Cocoa-based agroforestry systems; Biodiversity; Carbon sequestration; Economic value of trees; Côte d'Ivoire

1. Introduction

Growing cocoa *Theobroma cacao* L. (Malvaceae) is a vital part of life in many tropical regions of the world. The sector supports the livelihoods of between 40 and 50 million people worldwide, mainly small-scale producers [1]. In Côte d'Ivoire, which is the world's leading producer of cocoa beans with almost 2 million tons per year, cocoa accounts for 40% of export earnings and contributes more than 15% of the country's gross domestic product (GDP) [2]. This sector directly employs around one million producers and generates income for nearly 5 million people, representing about one-fifth of the Ivorian population [3, 4]. Cocoa farming is a fundamental pillar of Côte d'Ivoire's rural economy, providing a stable source of income for thousands of small-scale farmers [4]. However, the rapid expansion of cocoa farming in Côte d'Ivoire over the years has occurred at the expense of forest cover, contributing to massive deforestation and degradation of forest ecosystems [5]. Several studies, such as Barima *et al.* (2016) [6] , Kouadio *et al.* (2021) [7], Kouassi *et al.* (2021) [8] and Kalischek *et al.* (2023) [9] indicate that cocoa cultivation is responsible for more than 37% of forest cover loss in protected areas in Côte d'Ivoire. This phenomenon has led to a significant decline in biodiversity, a reduction in essential ecosystem services, and the weakening of soils, with adverse effects on long-term quality and

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fertility [10, 11]. Added to this are the consequences of climate change, which directly impact agricultural production in general and cocoa farming in particular, with fluctuating yields due to increasingly unpredictable climatic variations [12].

Faced with these challenges, the implementation of alternative solutions for more sustainable and environmentally-friendly cocoa farming is increasingly being encouraged. Among the proposed approaches, cocoa agroforestry, which integrates shade trees and woody species within cocoa plantations, appears to be an efficient solution. Agroforestry systems (SAFc) offer multiple benefits, not only in terms of environmental protection, but also in terms of economic and social benefits for farmers. Trees associated with cocoa trees help regulate the microclimate by moderating extreme temperatures, improve soil fertility by fixing nitrogen and restoring organic matter, and promote carbon sequestration [13, 14]. In addition, these trees can provide households with non-wood products such as fruits, leaves and seeds, as well as fuel wood and medical products, offering an additional source of income and/or subsistence [15, 16].

However, despite the potential benefits of cocoa-based SAFc, their adoption remains limited and knowledge about their optimal functioning is still insufficient. Questions relating to the diversity, functions and economic value of tree species associated with cocoa trees, as well as their impact on cocoa productivity, soil fertility and ecosystem services, remain partially resolved [17, 18]. Previous studies have shown that, although SAFc can improve the overall sustainability of plantations, it can lead to a temporary reduction in cocoa yields compared with monocultures [18]. Other studies have also shown that the impact of shade trees on cocoa yields can vary according to species and local conditions [17]. Furthermore, authors such as Niether *et al*. (2020) [18] have reported a reduction in yields under shade compared with monocultures, while other authors such as Isaac *et al*. (2007) [19] and Sauvadet *et al*. (2020) [20] emphasise that the presence of shade trees can extend the productive life of cocoa trees, particularly in environments where soils are poor or degraded. Knowledge of the diversity, structure and economic value of shade trees in cocoa-based SAFc is therefore essential for better management of ecosystem services and maintaining an adequate level of productivity for producers. In particular, it provides a compass for guiding farmers' adaptation strategies in response to new environmental conditions.

The aim of this study is to analyse the diversity, structure and economic value of trees associated with cocoa trees in different agroforestry systems in the Nawa region, one of the main cocoa-producing areas in Côte d'Ivoire. More specifically, this study aims to:

- Characterise the floristic diversity of shade trees associated with cocoa trees in different agroforestry systems in the region;
- Evaluate the structural characteristics of the trees in these different systems;
- Estimate the biomass and carbon sequestration of agroforestry systems;
- Compare the economic value of trees, considering their direct contribution (wood, fruit, other non-wood products) and indirect contribution (carbon sequestration).

2. Materials and methods

2.1. Study area

This study took place in the Nawa region (5°-6° N and 7°-8° W), specifically in the localities of Takoragui (05°45'18‘ N - 06°47'30’ W), Petit Bouaké (05°56'47‘ N - 06°19'46’ W), Bobouho 1 (05°35'33‘ N - 06°01'53’ W) and Gnaboya (06°04'31‘ N - 6°54'35’ W) (Figure 1). Located in the south-west of Côte d'Ivoire, the Nawa region is headed by the town of Soubré, 370 km from Abidjan, the economic capital, and 130 km from San-Pédro, the country's second largest port. This region is one of the main cocoa-producing areas in Côte d'Ivoire. According to data from the Conseil Café-Cacao (2013) [21], the Nawa region supplies approximately 20% of national production.

Phytogeographically, the Nawa region is located in the Guinean forest zone. This zone is characterised by a typical equatorial climate with bimodal rainfall of two rainy seasons and two dry seasons. The rainy seasons are generally from April to June and September to October, while the dry seasons are from November to March and July to August. Average annual rainfall ranges from 1300 and 1600 mm, with 115 rainy days per year. Average temperatures fluctuate between 24°C and 27°C and can reach up to 30°C during the dry season. The vegetation of the Nawa region, initially characterised by dense, humid forest or intermediate evergreen forest, has gradually been reduced in favour of huge plantations of perennial crops. The vegetation cover, similar to that of the Taï National Park, is now subject to abusive clearing by the local population, as well as abusive logging for timber and industrial purposes.

Generally speaking, most soils in the study area belong to the ferralitic soil class. These soils are highly desaturated, with the exception of part of the region, which has moderately and/or slightly desaturated ferralitic soils, particularly in the central and northern zones. Morphologically, these soils are characterised by the consistency of their horizons and the development of the entire profile. In terms of the development of soil profiles, the region's soils are characterised by a great thickness (from 10 to 40 cm) and by a texture varying between clayey silt and silty sand [22]. Deep and permeable, these soils are generally well suited to all types of food and industrial crops.

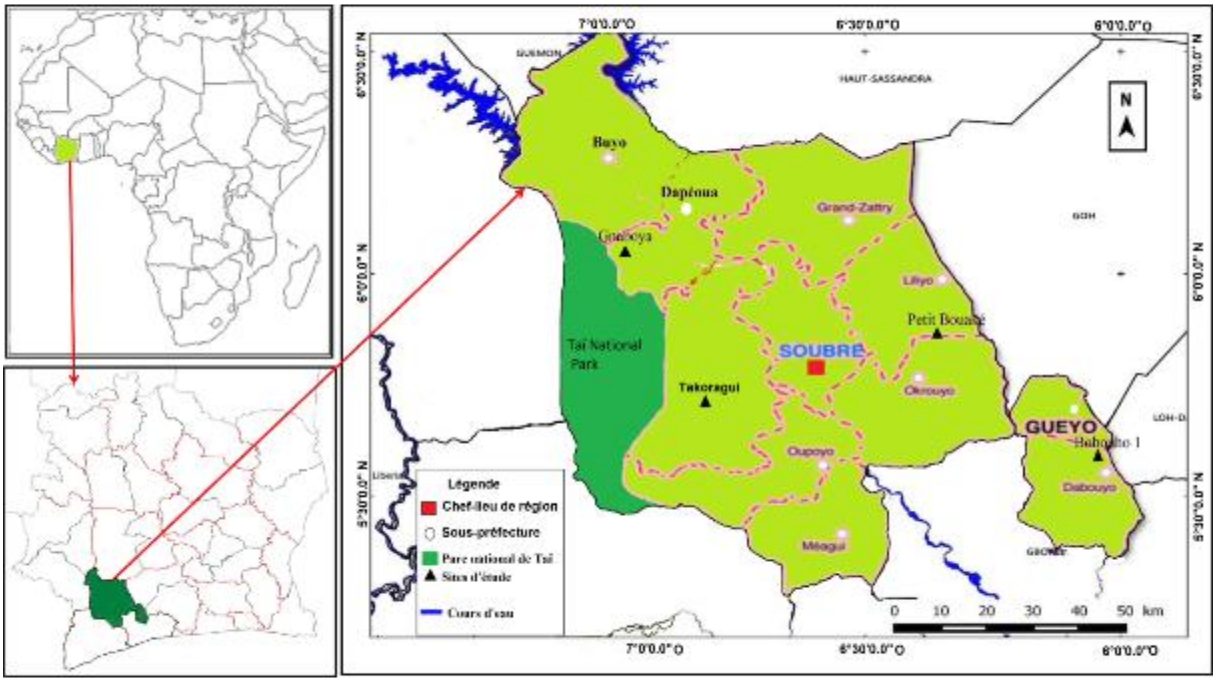

Figure 1 Location of the study area and sites

2.2. Study sites

In each of the four study locations (Takoragui, Petit Bouaké, Bobouho 1, and Gnaboya), four cocoa plantations were randomly selected, for a total of 16 study sites. The choice of plantations was guided by specific criteria, in particular the type of agroforestry system, which varied from an full sun system to shaded system, with two intermediate systems. The age of the selected plantations ranged from 4 to 40 years. All the plots studied were family farms, varying in size from site to site.

The full sun system was identified in Takoragui. The number of trees in the plantations was less than five per 30 m x 30 m quadrat, corresponding to a density of less than 56 trees/ha. These sites were characterised by an almost total absence of shade trees, leaving the cocoa trees exposed to direct sunlight.

The shaded system was observed in the Gnaboya plantations. These plantations, belonging to the group of heavily shaded systems, contained more than 10 trees per quadrat, equivalent to a density of over 112 trees/ha. This type of system is characterised by dense vegetation cover, providing significant shade for the cocoa trees.

The intermediate systems were divided into two categories. Intermediate system 1, located at Petit Bouaké, represented a configuration between the two extremes of full sun and shaded systems. The number of trees in these plantations ranged from 5 to 6 per quadrat, resulting in a density between 56 and 67 trees/ha. This intermediate system is characterised by low shade coverage, closer to the no-shade system than to the heavily shaded system.

Intermediate system 2 was observed at Bobouho 1. This system, although similar to the first intermediate system, was closer to the shaded system. The plots contained between 7 and 9 trees per quadrat, giving a density of between 78 and 100 trees/ha. This system thus provides moderate shade coverage, falling between the two extremes of full sun and heavy shade.

2.3. Floristic inventory

An inventory of the woody species present on each study site was carried out. The surface survey method was used for this purpose. This method involves recording all the taxa encountered within square, rectangular or circular surfaces, with the aim of identifying as many species as possible [23].

Four square plots of 30 m per side were set up in each cocoa plantation. All the trees and shrubs in the plots with a diameter of at least 10 cm at breast height were marked, numbered and measured individually. For each tree or shrub, the scientific and/or vernacular name, diameter, height and canopy diameter were determined. These woody plants, which provide shade within the various agroforestry systems, were categorised according to whether they are forest species or fruit trees/shrubs.

2.4. Characterization of the structure of different agroforestry systems

Analysis of the structural diversity of agroforestry systems provides an understanding of how plant species occupy space, how they are arranged and their ecological role. This diversity can be assessed both horizontally and vertically, by examining a number of parameters including species composition, species density, and the distribution of individuals according to their size and height in each agroforestry system.

2.4.1. Analysis of horizontal structure

Determination of species richness

Species richness refers to the total number of species present in a given plant community. It was used to compare woody floristic diversity among the different cocoa agroforestry systems (SAFc) studied, without considering the abundance or relative frequency of the recorded species. This parameter gives an initial indication of the biodiversity in each system, making it possible to identify the biotopes that support the greatest diversity of plant species [24].

Determining the average density of species

The density (d) of species represents the number of individuals present per unit area, generally expressed as the number of stems per hectare. It has been used to quantify land cover by woody species, and to measure the abundance of woody vegetation in each SAFc [25]. The average density is calculated according to the following formula (1):

$$\boldsymbol{d} = \frac{\boldsymbol{n}}{\boldsymbol{S}} \qquad (1)$$

where n is the total number of individuals inventoried in the area and S is the total area sampled (in hectares). This index gives a clear indication of the distribution of trees in the plots studied, reflecting the potential impact of competition for resources (light, water, and nutrients) between trees and cocoa trees.

Assessment of diametric structure

Analysis of the diametric structure makes it possible to illustrate the distribution of individuals according to their size, and to identify the dynamics of regeneration or ageing of trees within biotopes. It can also be used to assess the degree of disturbance or conservation of a biotope [24, 26]. In each SAFc studied, tree diameters were measured at breast height (DBH), which corresponds to a standard height of 1.30 m above the ground level, following forest measurement protocols [25]. A measuring tape was first used to measure the circumference of the stem at this height, then the measured circumference was converted into diameter using the following formula (2):

$$\boldsymbol{DHP} = \frac{\boldsymbol{C}}{\boldsymbol{\pi}} \qquad (2)$$

where C is the measured circumference, and π is a constant equal to 3.1416. For trees with buttresses or irregularities at 1.30 m, the diameter measurement was taken slightly above the base of the buttresses to obtain a more representative value of the trunk. The trees were then classified into 10 cm diameter bands, which were used to produce the histogram of diametric structures [24, 26].

Determination of basal area

The basal area or basal cover is the sum of the cross-sectional areas of the trunks of all the trees in a survey, measured at 1.30 m above the ground [25]. The basal area of a stand makes it possible to assess the density and stability of the stand, and is higher the denser the stand. The basal area of the various SAFc studied was determined using the following formula (3):

$$\boldsymbol{S = \frac{DHP^2 \times \pi}{4}} \qquad (3)$$

2.4.2. Analysis of vertical structure

The vertical structure makes it possible to describe the distribution of trees according to their height, which is essential for understanding species stratification in agroforests. This stratification directly influences light distribution, a key factor in photosynthesis, and therefore affects the productivity of the agroforestry system [24].

To compare the strata of the different SAFc studied, the height of the trees was estimated within these agroforests. Three strata were established, based on the work of Kouamé (1998) [24] and Bakayoko (1999) [27]:

- The medium tree stratum, comprising trees between 4 and 8 meters' high;
- The upper tree stratum, comprising trees from 8 to 16 meters' high;
- The emergent stratum, including trees taller than 16 meters'.

Tree heights were determined using a clinometer, which measured the angle of the line of sight between the observer, located at a known distance from the tree, and the top of the tree. The height of the tree (H) was then calculated using the following formula (4), based on the tangent theorem:

$$\boldsymbol{H = D \times \tan \alpha + h} \qquad (4)$$

where *D* is the horizontal distance between the observer and the tree, α is the angle measured with the clinometer, and *h* is the height of the observer from the ground (at eye level).

2.5. Determination of woody plant biomass

Estimating the biomass of woody plants (trees and shrubs) in the different cocoa production systems makes it possible to assess their carbon sequestration capacity, which is a key indicator for measuring their contribution to combating climate change. The total woody biomass was calculated from the sum of the above-ground and below-ground fractions of the inventoried individuals. This estimate was made using the allometric method [28]. The biomass calculation is then used to determine the sequestered carbon rate.

2.5.1. Estimation of above-ground biomass

Above-ground biomass (AGB) was estimated using the equation of Chave *et al*. (2014) [28]. This equation uses measurements of DBH, tree height (H) and wood specific gravity. The mathematical expression of this allometric equation is as follows:

$$\boldsymbol{AGB_{est} = 0,0673 \times (\rho \, DHP^2 H)^{0,976}} \qquad (5)$$

Where AGB_{est} the estimated above-ground biomass (in kilograms);

- DBH is the diameter at breast height (measured at 1.30 m from the ground) in centimeters.
- H is the total height of the tree in meters';
- ρ is the specific density of the wood in g/cm^3.

When the specific density of the wood was not available for a given species, a default reference value of 0.58 g/cm^3 was used, in accordance with the recommendations of Reyes et al. (1992) [29] for African tropical forests.

Estimation of root biomass

The underground (or root) biomass of the trees was estimated from the above-ground biomass, using a conversion coefficient based on the root-to-shoot biomass ratio. According to the Intergovernmental Panel on Climate Change (GIEC, 2006) [30], this coefficient is 0.24 for tropical forests. The formula used to estimate root biomass is as follows:

$$\boldsymbol{BGB_{est} = AGB_{est} \times R} \qquad (6)$$

where BGB_{est} denotes the estimated underground biomass, expressed in kg, and *R is* the root-to-shoot biomass ratio.

Estimation of total biomass

The total biomass (BT) is obtained by summing the above-ground biomass (ABG) and the root biomass (BGB).

$$BT = AGB + BGB \qquad (7)$$

2.6. Estimation of carbon stocks and carbon dioxide sequestered

The rate of carbon sequestered by woody plants in each SAFc was estimated by converting the total biomass into carbon. According to the recommendations of the GIEC (2006) [30], approximately 50% of the dry biomass of trees consists of carbon. The following formula (8) is therefore used to calculate the amount of sequestered carbon:

$$C = BT \times 0,5 \qquad (8)$$

where *C* represents the amount of sequestered carbon (in kg).

The total amount of sequestered carbon by each SAFc was converted into carbon dioxide equivalents (CO_2eq). These CO_2 equivalents were calculated using the following formula (9):

$$CO_2eq = C \times \frac{44}{12} \quad (9)$$

where *C* represents the amount of carbon sequestered (in tones), 44 is the molar mass of CO_2, and 12 is the molar mass of carbon.

2.7. Estimation of the economic value of trees associated with cocoa trees in the different agroforestry systems

The potential economic value of trees associated with cocoa trees in the different SAFc was estimated on the basis of sequestered CO_2 equivalents, which can be valued on different carbon markets in terms of carbon credits. In this study, three main carbon markets were taken into account to estimating the economic value of trees associated with cocoa trees: the Clean Development Mechanism (CDM) markets, voluntary markets, and Reducing Emissions from Deforestation and Forest Degradation (REDD+) markets.

The average sale price of forest credits is 3 euros/teq CO2 for the CDM, 4.7 euros/teq CO2 for voluntary markets [31] (Chenost *et al*., 2010) and 14 euros/tC (low value) or 100 euros/tC (high value) for REDD+ [32].

To calculate the economic value (EV) of SAFc according to each carbon market, the sequestered carbon dioxide equivalents (CO_2eq) were multiplied by the price of carbon credits on the market considered, according to the following formula (10):

$$VE = CO_2eq \times prix\ du\ crédit\ carbone \qquad (10)$$

2.8. Data analysis

The data collected in the different SAFc were processed using several statistical methods. The Mann-Whitney U test was used to compare species richness between the different SAFc. This test was used to verify the significance of the differences in species richness observed between the woody species present in these systems. A histogram of diameter classes and heights was produced for each SAFc, enabling the identification of characteristic structures of each stand. Data relating to basal area and woody density were compared between the different SAFc using an analysis of variance (ANOVA) to determine whether any differences in density and basal area were statistically significant. The Tukey's HSD post-hoc test was used for pairwise comparisons when the calculated probability was significant.

Differences in biomass and carbon sequestration between systems were also compared using an ANOVA followed by post-hoc tests to identify significant differences. The relationship between tree density and the amount of carbon sequestered was also studied to assess the effectiveness of the systems in capturing carbon.

Estimates of the economic value of carbon sequestration were compared between the SAFc studied in order to assess the differences in potential profitability in relation to the ecological characteristics of these SAFc.

The various statistical analyses and graphs were produced using R software version 4.0.2 (R core team, 2020) and Microsoft Excel. The significance of the tests was assessed at the $\alpha = 0.05$ threshold.

3. Results

3.1. Richness, diversity and composition of trees associated with cocoa trees

Eighty-three (83) tree species divided into 62 genera and 32 botanical families were identified in the study cocoa plots (Table I). The predominant families, in terms of the number of species, are the Moraceae with 10 species (12.05%) and the Meliaceae with 8 species (9.64%). Euphorbiaceae, Fabaceae, Sterculiaceae and Rubiaceae are represented by 5 species each, i.e. 6.02%. All the other families together represent 54.23% of species and each family has a frequency of less than 5% (Figure 2).

Overall, species richness was greater in the shaded system with 52 species and in the intermediate system 2 (40 species). Analysis of species abundance shows significant variation between the different SAFc ($F = 5.675$; $p = 0.0008$) (Figure 3). A significant difference was also observed between the average species richness of forest species and that of fruit species in the different cocoa systems ($p = 0.0003$, Mann-whitney U test). The most common forest species were *Albizia adianthifolia* (Schumach.) W.Wight (Fabaceae), *Ceiba pentandra* (L.) Gaertn. (Malvaceae), *Ficus exasperata* Vahl (Moraceae), *Funtumia elastica* (Preuss) Stapf (Apocynaceae), *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg. (Euphorbiaceae), *Spathodea campanulata* P.Beauv. (Bignoniaceae), *Spondias mombin* L. (Anacardiaceae) and *Terminalia superba* Engl. & Diels (Combretaceae). These species were represented by more than 12 individuals across all SAFc. The fruit tree species commonly found in the plantations are as follows: *Persea americana* Mill. (Lauraceae), *Mangifera indica* L. (Anacardiaceae), *Cola nitida* (Vent.) Schott & Endl. (Malvaceae), *Psidium guajava* L. (Myrtaceae). Non-woody species such as *Cocos nucifera* L. (Arecaceae) and *Elaeis guineensis* Jacq. (Arecaceae) have also been identified.

Table 1 List of woody species collected in the different agroforestry systems

Especies	Famillies	SSO	SI1	SI2	SO	Number of individuals
Albizia adianthifolia	Fabaceae	0	0	0	14	14
Albizia ferruginea	Fabaceae	0	0	6	0	6
Albizia sp	Fabaceae	0	0	0	1	1
Albizia zygia	Fabaceae	0	0	0	2	2
Alstonia boonei	Apocynaceae	0	0	1	1	2
Aningueria altissima	Sapotaceae	0	0	2	1	3
antiaris africana	Moraceae	0	0	0	1	1
antiaris toxicaria	Moraceae	0	0	1	0	1
Baphia nitida	Fabaceae	0	0	2	0	2
Blighia sapida	Sapindaceae	0	0	0	2	2
Blighia welwitschii	Sapindaceae	0	0	0	1	1
Carapa procera	Meliaceae	0	2	0	0	2
Carica papaya	Caricaceae	0	3	2	0	5
Ceiba pentandra	Malvaceae	2	3	6	5	16
Celtis sp	Ulmaceae	0	0	0	3	3
Celtis zenkeri	Ulmaeae	0	1	0	0	1
Citrus maxima	Rutaceae	0	0	2	1	3
Citrus reticulata	Rutaceae	0	3	0	0	3
Citrus sinensis	Rutaceae	3	1	0	2	6

Cocos nucifera	Arecaceae	0	9	0	0	9
Cola nitida	Sterculiaceae	3	0	0	29	32
Cordia platythyrsa	Boraginaceae	0	0	0	1	1
Cordia sp	Boraginaceae	0	0	2	0	2
Detarium senegalense	Fabaceae	0	0	0	1	1
Diopyros sp	Ebenaceae	1	0	0	0	1
Diopyros sp 1	Ebenaceae	0	0	0	1	1
Distemonanthus benthamianus	Fabaceae	1	0	0	0	1
Durio zibethinus	Malvaceae	0	1	0	2	3
Elaeis guineensis	Arecaceae	2	3	0	16	21
Entandrophragma angolense	Meliaceae	0	0	0	3	3
Entandrophragma cylindricum	Meliaceae	1	0	0	1	2
Entandrophragma sp	Meliaceae	1	0	0	0	1
Entandrophragma sp 1	Meliaceae	0	2	0	0	2
Entandrophragma sp 2	Meliaceae	0	0	1	0	1
Entandrophragma utile	Meliaceae	1	0	1	1	3
Erythrophleum ivorense	Fabaceae	1	0	5	0	6
Ficus capensis	Moraceae	0	0	0	1	1
Ficus exasperata	Moraceae	3	0	7	4	14
ficus longifolia	Moraceae	0	0	1	0	1
ficus mucoso	Moraceae	0	0	2	0	2
Ficus sp	Moraceae	0	0	1	0	1
Funtumia elastica	Apocynaceae	1	0	14	1	16
Garcinia afzelii	Clusiaceae	0	0	4	4	8
Glyphaea brevis	Tiliaceae	0	0	0	4	4
Hevea brasiliensis	Euphorbiaceae	0	11	1	0	12
Khaya ivorensis	Meliaceae	0	0	0	1	1
Lannea acida	Anacardiaceae	0	0	0	1	1
Lophira alata	Ochnaceae	0	2	0	0	2
Macaranga barteri	Euphorbiaceae	0	0	0	1	1
Macaranga sp	Euphorbiaceae	0	0	1	0	1
Mangifera indica	Anacardiaceae	0	8	8	4	20
Mansonia altissima	Sterculiaceae	0	1	0	0	1
Mareya micrantha	Euphorbiaceae	0	0	0	1	1
Margaritaria sp	Phyllanthaceae	0	0	0	1	1
Milicia excelsa	Moraceae	0	0	2	3	5
Millettia zechiana	Fabaceae	0	0	0	4	4
Morinda lucida	Fabaceae	0	0	5	2	7

Musanga cecropioides	Moraceae	0	0	5	1	6
Nauclea diderichii	Rubiaceae	0	0	4	0	4
Nesogordonia papaverifera	Sterculiaceae	0	0	2	0	2
Persea americana	Lauraceae	3	7	11	6	27
Picralima nitida	Apocynaceae	0	1	0	0	1
Piptadeniastrum africanum	Fabaceae	0	0	0	3	3
pouteria aningeri	Sapotaceae	0	0	1	0	1
Psidium guajava	Myrtaceae	0	0	0	10	10
Pycnanthus angolensis	Myristicaceae	0	0	5	3	8
Rauwolfia vomitoria	Apocynaceae	0	0	1	3	4
Ricinodendron heudelotii	Euphorbiaceae	0	2	0	0	2
Rinorea sp	Violaceae	0	1	0	0	1
Spathodea campanulata	Bignoniaceae	0	8	6	0	14
spondias mombin	Anacardiaceae	0	23	2	0	25
Sterculia tragacantha	Sterculiaceae	0	0	3	3	6
Stereospermum sp	Bignoniaceae	0	0	0	1	1
Tamarindus indica	Fabaceae	0	0	0	2	2
Terminalia ivorensis	Combretaceae	0	0	2	0	2
Terminalia superba	Combretaceae	0	0	0	15	15
Thieghemella heckellii	Sapotaceae	0	0	0	3	3
Treculia africana	Moraceae	0	0	1	1	2
Trema orientalis	Ulmaceae	1	0	0	2	3
Triplochiton scleroxylon	Sterculiaceae	0	0	1	1	2
Vernonia colorata	Asteraceae	0	0	2	1	3
Xylopia aethiopica	Annonaceae	0	1	0	5	6
Zanthoxylum zanthoxyloides	Rutaceae	1	0	0	1	2
TOTAL 83	32	25	93	123	182	423

SSO : Full sun system ; SI1 : intermediary system 1 ; SI2 : intermediary system 2 ; SO : Shaded system

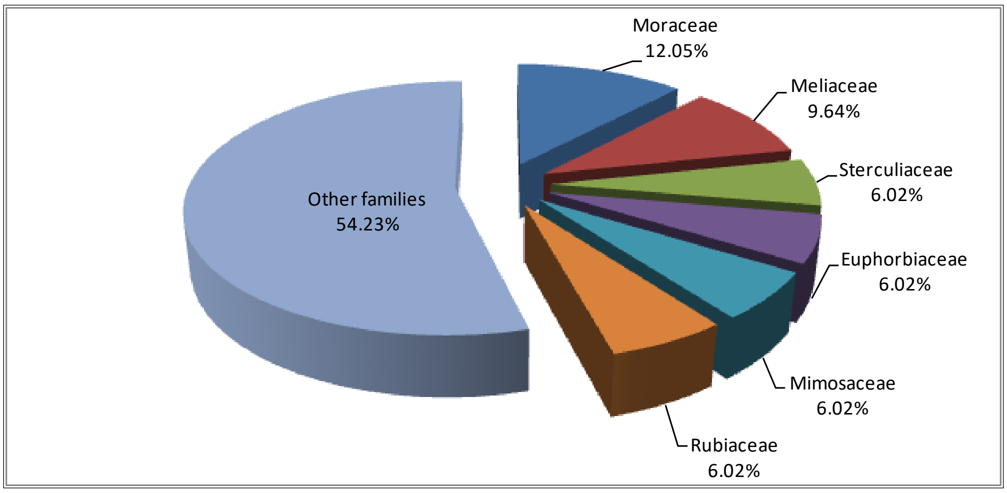

Figure 2 Proportion of trees families in number of species

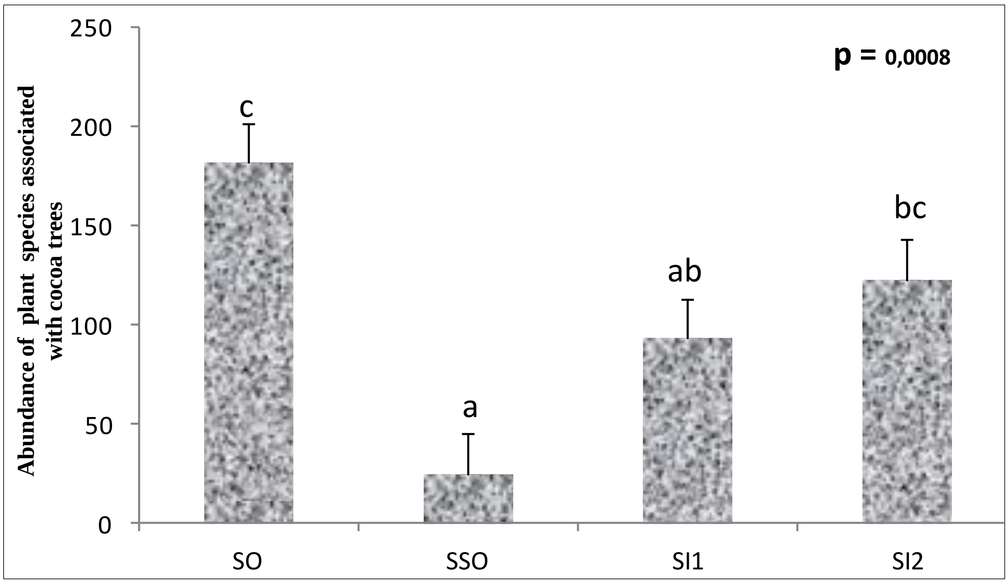

Figure 3 Abundance of trees associated with cocoa trees

SSO : Full sun system ; SI1 : intermediary system 1 ; SI2 : intermediary system 2 ; SO : Shaded system;Means followed by the same letter are not different (Tukey test, p = 0.05).

3.2. Distribution of individuals by diameter class

The distribution of individuals by diameter class decreases exponentially in forest species and fruit trees (Figure 4). For forest trees, the trend is irregular, with high values in the [10 - 20],] 20 - 30] and] 30 - 40] classes. The graph shows that the [10 - 20] diameter class is the most represented in the two types of shade tree. These two types of tree have a decreasing structure, with the number of stems decreasing as the diameter increases.

In all diameter classes, the number of forest trees is greater than that of fruit trees. Individuals with diameters greater than 80 cm are poorly represented in the forest trees and non-existent in the fruit trees. The graph also shows an abundance of young trees of diameter [10 - 20] in the plots.

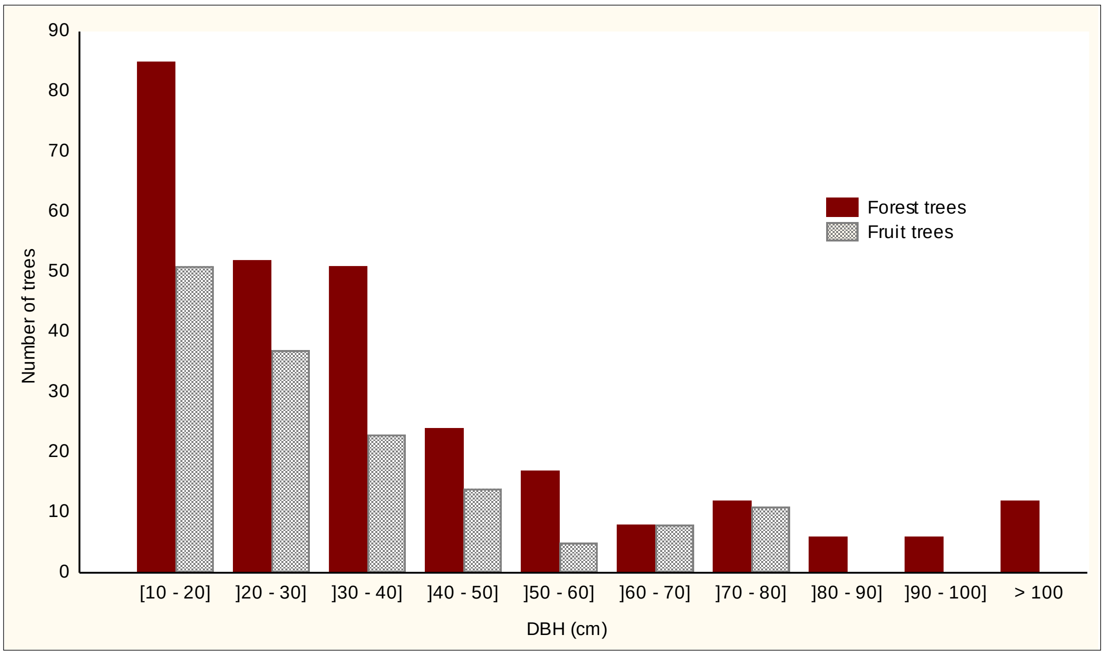

Figure 4 Distribution of shade tree abundance by diameter class

3.3. Distribution by height class of plant species associated with cocoa trees

The distribution of woody plants in the different SAFc is dominated by individuals from the upper tree stratum, followed by individuals from the emergent stratum and the medium tree stratum (Figure 5). In the upper tree stratum, the most represented individuals are from the shaded system, followed by individuals from the intermediate systems. Individuals from the full sun system are less represented in the upper tree layer. The middle tree layer is dominated by a high number of trees from the shaded system, while large trees (> 32 m tall) are in greater proportion in the intermediate systems than in the others. The vertical structure of the stand shows that in the shaded system, tree species are predominantly between 8 and 16 meters tall, while in the intermediate systems the stand is dominated by individuals taller than 8 meters. As for the full sun system, it is characterized by a mixture of individuals from the three strata in similar proportions.

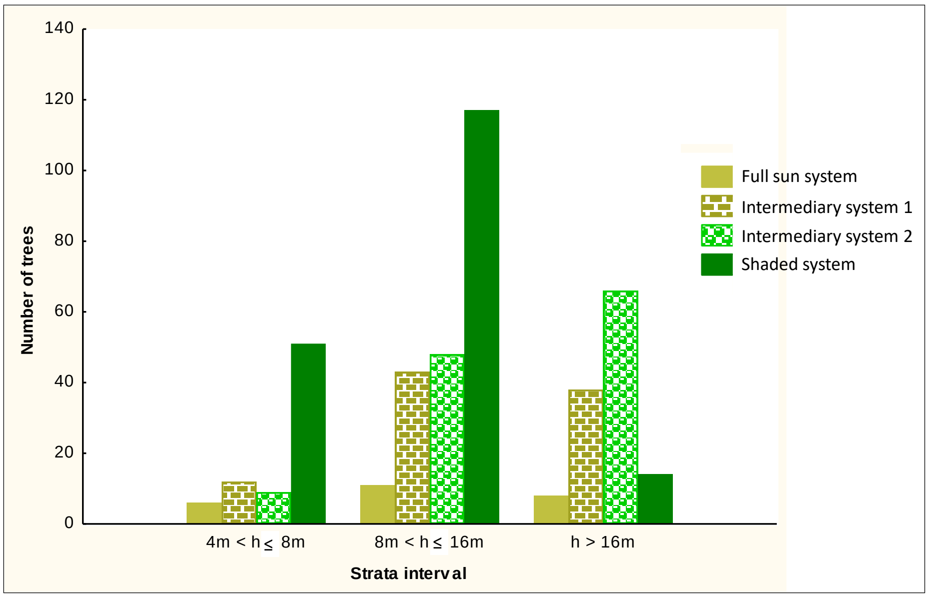

Figure 5 Distribution of trees abundance by height class

h : Height

3.4. Basal area, density of associated trees and quantity of biomass

The average basal area of the intermediate systems is estimated at 15.5 m^2 / ha for intermediate system 1 and 13.21 m^2 / ha for intermediate system 2 (Table II). The shaded system and the full sun system have the lowest basal areas, with 12 m^2 / ha and 3.59 m^2 / ha respectively.

In the shaded system, the number of trees associated with cocoa trees is 11 per 900 m^2, giving an average density of 126 trees / ha. This system has the highest average density. The average densities in the intermediate systems are respectively 6 trees / 900 m^2 and 8 trees / 900m^2 for intermediate system 1 and intermediate system 2, i.e. 65 trees / ha and 85 trees / ha. The full sun system has the lowest density (2 trees / 900 m^2 or 17 trees / ha). As basal area is a function of diameter at breast height, the value of 12 m^2 / ha obtained in the shaded system with a higher density indicates the presence of a young stand in this agroforestry system.

Above-ground biomass is estimated at 1903.18 tones/ha and 933.88 tones/ha for intermediate systems 1 and 2. The corresponding below-ground biomasses are 456.76 tones/ha and 224.13 tones/ha. These biomasses are the highest in the SAFc studied. In the full sun system, however, the biomass is the lowest (24.17 tones/ha).

Table 2. Basal Area, Average Density, and Biomass of Trees Associated with Cocoa Trees

Shade systems	Basal Area (m^2 / ha)	Average Density (number of stems / 900 m^2)	Aerial Biomass (t / ha)	Root biomass (t / ha)
SSO	3.59	2	24.17	5.80
SI1	15.5	6	1903.18	456.76
SI2	13.21	8	933.88	224.13
SO	12	11	79.73	19.13

SSO : Full sun system ; SI1 : intermediary system 2 1 ; SI2 : intermediary system 2 ; SO : Shaded system

3.5. Biomass quantity and carbon sequestration rate in different agroforestry systems

Estimates of total biomass in the different SAFc evolve with those of above-ground biomass. The intermediate system 1 has the highest total biomass, with a value of 2359.95 t/ha (Table III). This biomass corresponds to a sequestered carbon rate of 1179.97 t / ha, equivalent to a monetary value ranging between 12979.70 and 60571.95 euros (between 8501686.29 and 39674546.91 CFA francs) depending on the market. The lowest total biomass is estimated for the full sun system, with 29.97 t/ha and a sequestered carbon rate of 14.98 t/ha. Between these two extreme average values, intermediate values are observed within the other systems.

Table 3 Total Biomass, Sequestered Carbon Quantity, and Equivalent Costs

Shade systems	Individuals	Total biomass (t / ha)	Carbon stock (t / ha)	CO_2 (t)	CDM carbon price (€)	Voluntary Carbon Market price (€)	REED+ carbon price (€)
SSO	25	29.97	14.98	54.94	164.81	258.21	769.13
SI1	93	2359.95	1179.97	4326.57	12979.70	20334.87	60571.95
SI2	123	1158.01	579.01	2123.03	6369.08	9978.22	29722.37
SO	182	98.86	49.43	181.25	543,74	851.85	2537.44

SSO : Full sun system ; SI1 : intermediary system 1 ; SI2 : intermediary system 2 ; SO : Shaded system

4. Discussion

4.1. Diversity and composition of trees associated with cocoa trees

Our study revealed a significant species richness in cocoa agroforestry systems in the Nawa region, with 83 tree species distributed among 62 genera and 32 botanical families. The most represented families are Moraceae (12.05%), Meliaceae (9.64%), followed by Euphorbiaceae, Fabaceae, Sterculiaceae and Rubiaceae (6.02% each). The floristic diversity was particularly high in the shaded system (52 species) and intermediate system 2 (40 species). These results are similar to those of Gockowski and Sonwa (2011) [33], who observed high diversity in West African cocoa agroforests. However, our observations differ from those of Zigbé (2021) [34], who inventoried only 41 species in the Bonon locality in west-central Côte d'Ivoire. Our results also differ from those observed by Mbade (2012) [35] and Laird *et al*. (2007) [36] in cocoa-based agroforests in Cameroon, with 45 and 59 woody species respectively.

Some of the forest species present in most of the plantations in the study area, such as *Albizia adianthifolia*, *Ceiba pentandra*, *Ficus exasperata*, *Funtumia elastica*, *Hevea brasiliensis*, *Spathodea campanulata*, *Spondias mombin* and *Terminalia superba* had been identified in agroforests in other regions of Côte d'Ivoire by several authors, including Assiri *et al*. (2012) [37], Vroh *et al.* (2015) [38] and Adou Yao *et al.* (2016) [39]. The dominant presence of Moraceae and Meliaceae highlights the importance of certain families in the composition of shade trees, which may be linked to their functional traits favourable for agroforestry systems [19, 17].

The higher species richness in shaded systems may be explained by less intensive management and greater conservation of forest species [40, 41]. Furthermore, in terms of species richness, an increase is observed when moving from full sun system to shaded systems. However, the species richness of forest species is higher than that of fruit trees in shaded and intermediate systems. This may be explained by the awareness campaigns carried out by certain organisations such as ICRAF, WCF and CNRA in the study area to encourage the introduction of trees into plantations. In addition, the structures in charge of supervising cocoa producers in these zones generally provide, for shade in plantations already in production, forest species, most of which have medicinal, artisanal, traditional and/or customary value for farmers or for the management of environmental conditions in their plantations.

The significant variation in the abundance of woody species between the different agroforestry systems indicates that management practices influence floristic composition. Forest species such as *Albizia adianthifolia*, *Ceiba pentandra* and *Terminalia superba* are frequent, suggesting their adaptation and usefulness in cocoa agroforests [42]. Fruit species such as *Mangifera indica* and *Persea americana* offer additional economic benefits to producers, reinforcing the multifunctionality of agroforestry systems.

4.2. Structural characteristics of trees associated with cocoa trees and ecological consequences

The distribution of individuals by diameter class follows an exponentially decreasing curve, with a predominance of young trees in the [10-20] cm diameter class. This type of distribution is characteristic of regenerating stands, where the majority of individuals are of small diameter [24]. This trend was also observed by Deheuvels et al (2012) [43] and Edelstein et al. (2023) [44] in cocoa agroforests, highlighting a dynamic of stand renewal. The absence or scarcity of trees with a diameter greater than 80 cm suggests the felling of large trees during the establishment of cocoa plots or selective logging of mature trees. This may have implications for the provision of certain ecosystem services, such as long-term carbon sequestration and wildlife habitat [18]. Nevertheless, the conservation or introduction of forest species in cocoa plantations is to be welcomed and could be linked to farmers' awareness of the new Ivorian forestry code adopted in 2014. Indeed, this new code recognises the ownership of trees for landowners, which could encourage them to allow forest trees to proliferate or to introduce them into plantations in the hope that, in addition to the environmental services they provide to the plantation, these trees could be used without any constraints.

The vertical structure shows a dominance of the upper tree stratum (8 to 16 m) in the shaded system, while the intermediate systems have a higher proportion of large trees (>16 m). According to Isaac et al. (2007) [19], this stratification influences the canopy microclimate, affecting temperature, humidity and light levels, which are essential for optimal growth of cocoa trees [45]. Shaded systems, with a denser canopy, may offer better protection against thermal and water stress, thus improving the resilience of cocoa trees to climatic variations [46, 16]. However, Tscharntke et al. (2011) [47] and Niether et al. (2020) [18] suggest that excessive shading can also reduce cocoa photosynthesis and reduce yields in the short term.

4.3. Biomass and carbon sequestration of SAFc

The results show that intermediate systems 1 and 2 have the highest above-ground and below-ground biomass, with 1903.18 t/ha and 933.88 t/ha respectively for above-ground biomass. These systems also have the highest sequestered carbon rates, notably 1179.97 tC/ha for intermediate system 1. These values exceed those reported by Saj et al. (2017) [14], who also highlighted the potential of cocoa agroforests for carbon sequestration. The high carbon sequestration capacity in intermediate systems may be due to an optimal combination of tree species, allowing high biomass without significant impact on cocoa production [48, 17]. Full sun systems recorded the lowest biomass and sequestered carbon rates, confirming that the absence of trees reduces the ability of plantations to contribute to climate change mitigation [49, 18].

4.4. Economic value of trees associated with cocoa

The economic evaluation carried out in the SAFc studied reveals that the quantity of carbon sequestered in these systems can generate a substantial monetary value, ranging from 12,979.70 and 60,571.95 euros per hectare for intermediate system 1, depending on the carbon markets considered. Our results are in line with the observations of Chenost et al (2010) [31], who highlighted the financial potential of carbon credits for small-scale producers. The sale of carbon credits can provide farmers with an additional source of income, while encouraging them to adopt sustainable agroforestry practices [32, 50]. In addition, the presence of marketable fruit species in intermediate systems enhances income diversification and household food security in rural communities [33].

4.5. Implications for sustainable cocoa production

The results of our study suggest that intermediate SAFc offer an optimal balance between cocoa productivity, biodiversity conservation and ecosystem services such as carbon sequestration. Tscharntke et al (2011) [47] point out that by integrating a diversity of tree species, these systems improve the resilience of plantations to environmental stresses and contribute to the overall sustainability of cocoa farming. Farmers should therefore benefit from adapted agroforestry management, favouring tree species with beneficial functional traits, such as rapid growth, nitrogen fixation or high commercial value fruit production [17]. This approach addresses environmental concerns linked to deforestation and offers fairly attractive economic prospects for farmers [16].

4.6. Limitations of the study

This study has a number of limitations. The measurement of underground biomass was estimated using standard coefficients [30], which may introduce a margin of error. Direct measurements or estimated using local allometric equations could improve the accuracy of the estimates. Furthermore, as the study was limited to the Nawa region, generalising the results to other regions with different ecological conditions may be problematic [51, 42].

Recommendations

In the light of the results obtained in this study, we can recommend the promotion of intermediate agroforestry systems in cocoa production in Côte d'Ivoire. Agricultural policies should encourage the adoption of agroforestry practices, by offering economic incentives such as access to carbon markets [31]. Training programmes for producers on the selection and management of tree species could also improve system performance [43, 44]. In-depth research into the functional traits of shade trees and their impact on specific ecosystem services is also necessary to optimise the benefits of cocoa agroforests [19, 17]. Finally, extending the study to other regions of Côte d'Ivoire and a conducting long-term analysis would validate and reinforce our conclusions.

5. Conclusion

This study highlighted the importance of trees associated with cocoa trees in agroforestry systems in the Nawa region of Côte d'Ivoire. With a species richness of 83 trees spread across 62 genera and 32 botanical families, cocoa-based agroforestry systems show significant biodiversity, particularly high in shaded and intermediate systems. The structural characteristics of the shade trees, in particular the distribution of stems by diameter and height classes, revealed a predominance of young trees, suggesting an active regeneration dynamic. Vertical stratification, with a dominance of the upper tree stratum in shaded systems, has a favourable influence on the microclimate and contributes to the resilience of cocoa trees to environmental stresses.

Estimates of biomass and carbon sequestration showed that intermediate systems have the highest values, attesting to their potential for mitigating climate change. The economic valuation of the carbon sequestered highlighted significant financial opportunities for producers. This underlines the economic value of associated trees, not only as a source of additional products such as fruit and timber, but also as providers of ecosystem services.

In sum, the results of this study suggest that intermediate agroforestry systems offer an optimal balance between cocoa productivity, biodiversity conservation and the provision of ecosystem services. Widespread adoption of this agroforestry practice could therefore contribute to the sustainable development of the cocoa-growing sector in Côte d'Ivoire, while meeting the global challenges of climate change and food security.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that the research complies with the ethical standards established by the journal and that there is no conflict of interest that could have influenced the results or interpretations of the work. .

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