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Floristic stability and stratification of ecosystems in the Central Basin: towards a resilience model in Central Africa

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Abstract

Faced with growing anthropogenic pressures in the Central Basin of the Congo, identifying resilient forest groups is imperative to ensure the sustainability of the carbon sink. This study analyses the structure and diversity of 60 permanent plots spread across three contrasting sites: Isangi, Uma and Mambasa. We adopted a refined vertical reading by distinguishing the understorey (diameter at breast height, DBH ≤ 60 cm) from the canopy (DBH > 60 cm). Three dominant assemblages, anchored by Scorodophloeus zenkeri, Staudtia kamerunensis and Cynometra alexandri, were identified. These groups exhibit high alpha diversity (Shannon H' index), inverted J-shaped diameter structures and marked stratification, signs of strong ecological stability. Our results demonstrate that the synergy between floristic diversity and architectural complexity maximises above-ground biomass (AGB). These data provide a robust scientific basis for establishing resilient model forests in the Congo Basin.

Keywords: Congo Basin, floristic diversity, ecological resilience, forest stratification.

1. Introduction

The Congo Basin is the second largest tropical forest complex on the planet and represents one of the world's main reservoirs of biodiversity. These forests also play a decisive role in regulating the global climate through their capacity to store and sequester atmospheric carbon [1], [2]. However, the stability of this ecological function depends not only on the extent of forest cover, but also on the floristic composition, stand structure and ecological dynamics that organise these ecosystems [2], [3].

In the central basin of the Congo, tropical forests are now facing increasing pressures from human activities and climate change. These disturbances affect stand structure, regeneration dynamics and, ultimately, the ability of forest ecosystems to maintain their ecological functions [3], [4]. In this context, understanding the mechanisms that support the ecological stability and adaptability of these forests is becoming a major scientific challenge.

The resilience of forest ecosystems depends largely on their structural organisation and the diversity of the species that compose them. The vertical stratification of tropical forests is a central element of this organisation, as it structures ecological interactions, particularly competition for resources, regeneration processes and forest succession dynamics [5]. Furthermore, the functional diversity of species contributes to the ability of ecosystems to absorb disturbances and maintain their ecological functions over time [6], [7].

Despite the recognised importance of these mechanisms, the relationships between floristic composition, vertical structure of stands and ecological resilience remain insufficiently documented in the forests of the Central African Basin. In particular, few studies have analysed how floristic assemblages are structured according to different forest strata and to what extent this organisation contributes to the ecological stability of tropical forests in the Congo Basin.

From this perspective, the identification of floristic assemblages is a relevant approach for analysing the ecological organisation of tropical forests. The study of species groups and indicator species makes it possible to highlight homogeneous floristic structures and interpret the ecological processes that shape forest landscapes [8].

In order to explore these relationships, this study adopts a structural approach based on the differentiation of two components of forest vegetation: the understorey, consisting of individuals with a diameter at breast height (DBH) of less than or equal to 60 cm, and the canopy, consisting of individuals with a DBH greater than 60 cm. This distinction allows for the joint analysis of the floristic composition, diameter structure and ecological dynamics that characterise forest stands.

In this context, the overall objective of this research is to analyse floristic assemblages and their contribution to the ecological resilience of forests in the Congolese central basin. More specifically, the study aims to: (i) identify homogeneous floristic assemblages within different forest strata; (ii) analyse their diversity and ecological structure; (iii) examine their potential contribution to the stability and resilience of forest ecosystems in different ecological contexts in the Congo Basin.

2. Methodology

This study was conducted at three sites representative of the Congolese Central Basin: Isangi and Uma, located in Tshopo Province, and Mambasa, in Ituri Province. These sites were selected because of their ecological contrasts and their representativeness of the main types of forest formations in the north-east of the Democratic Republic of Congo [9].

The Isangi and Uma sites belong to the low-altitude dense rainforest domain, characterised by evergreen formations with strong vertical stratification. In contrast, the Mambasa site corresponds to an ecological transition zone towards the submontane formations of the eastern Congo Basin. The annual rainfall in these regions generally varies between 1,600 and 2,000 mm, with moderate seasonality typical of humid equatorial forests [10], [11].

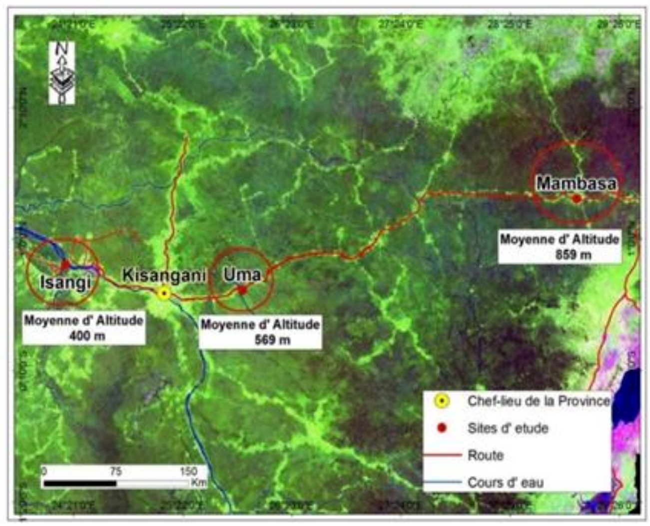

Figure 1 – Map showing the location of the study sites

Each site has a dominant forest physiognomy characterised by certain structuring species: Scorodophloeus zenkeri in Isangi, Staudtia kamerunensis in Uma and Cynometra alexandri in Mambasa. These formations reflect specific ecological and edaphic conditions that influence the floristic composition and structure of forest stands.

Furthermore, the levels of anthropogenic pressure vary between sites. The forests of Isangi and Mambasa are subject to greater pressure, linked in particular to population density, shifting agriculture and artisanal logging, whi, the Uma site remains relatively undisturbed.

2.1 Experimental design and data collection

The study is based on a forest inventory system involving the establishment of 60 permanent plots of 0.25 ha (50 m × 50 m), distributed evenly across the three study sites, i.e. 20 plots per forest area. This type of system is commonly used in tropical ecological studies to characterise the structure and composition of forest stands [12].

In each plot, all trees with a diameter at breast height (DBH) greater than or equal to 10 cm were inventoried. For each individual, the following variables were recorded: the botanical identity of the species; the diameter at breast height (measured at 1.30 m above the ground) and the total height of the tree.

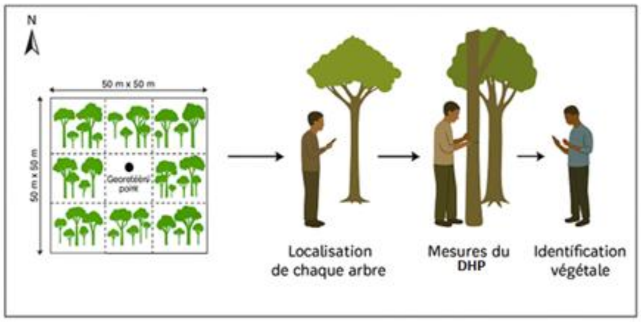

Figure 2 – Field data collection diagram

Measurements were taken in accordance with standard tropical forest inventory protocols. In sloping terrain, the necessary corrections were applied using the methods described in the tropical forest inventory methodology guides.

In order to analyse the vertical stratification of forest stands, the individuals inventoried were divided into two functional classes according to their diameter:

- Understory: trees with a diameter at breast height (DBH) less than or equal to 60 cm;

- Canopy: trees with a diameter at breast height (DBH) greater than 60 cm.

This segmentation makes it possible to assess the dynamics of regeneration and structural continuity between the different strata of the forest stand.

2.2 Data analysis and assessment of ecological resilience

Aboveground biomass (AGB) was estimated using the pantropical allometric equation developed by Chave et al. [13] for tropical rainforests:

$$AGB = 0.0673 \times (\rho \times D^2 \times H)0.976 \qquad (1)$$

where ρ is wood density (g/cm³), D is DBH (cm) and H is height (m). Individual AGBs were then aggregated by plot and converted to t/ha.

This allometric formula is now considered one of the most robust for estimating biomass in tropical forests.

Wood density values were extracted from international databases compiling the functional properties of tropical tree species [14]. When the specific density of a species was not available, the average tropical value of 0.58 g/cm^3 was used, in accordance with methodological recommendations for biomass estimates in tropical forests [15].

2.3 Statistical analyses

All statistical analyses were performed using R (v. 4.2.3). Diversity α was quantified using the Shannon (H'), Simpson (D) and Pielou's equitability (J') indices. To identify floristic groupings, we used an unsymmetrical correspondence analysis (USCA) coupled with K-means classification, whose ecological robustness was confirmed by the IndVal method. Spatial dissimilarities were examined using NMDS and PCA ordinations based on Bray-Curtis distance, with the significance of composition differences validated by PERMANOVA.

Comparisons of means between strata (canopy vs. understory) and sites were based on ANOVA or the Kruskal-Wallis test, depending on the normality of the distributions. To model above-ground biomass (AGB), we developed generalised linear mixed models (GLMM) using the MuMIn package, incorporating site as a random effect to capture contextual variability. All tests were interpreted at a significance threshold of $p < 0.05$.

3. Results

3.1. Homogeneous floristic groups by site and stratum

The floristic analysis conducted on the plots surveyed at the three sites made it possible to distinguish, for each forest stratum (canopy and understory), well-defined groupings structured around characteristic dominant species. These configurations reflect the combined influence of edaphic and topographic factors and anthropogenic pressures specific to each environment.

In order to highlight homogeneous floristic assemblages, an Asymmetric Correspondence Analysis (ACA) coupled with a K-means classification was applied to each of the sites studied, systematically distinguishing between the canopy and the understorey.

The results are illustrated in the group of six figures (Figure 3) below. For each site (Isangi, Uma and Mambasa), the canopy is shown on the left and the understorey on the right.

These six sub-figures project the plots onto the two main axes of inertia, while grouping them according to their floristic affiliation, determined by the dominant species of the group.

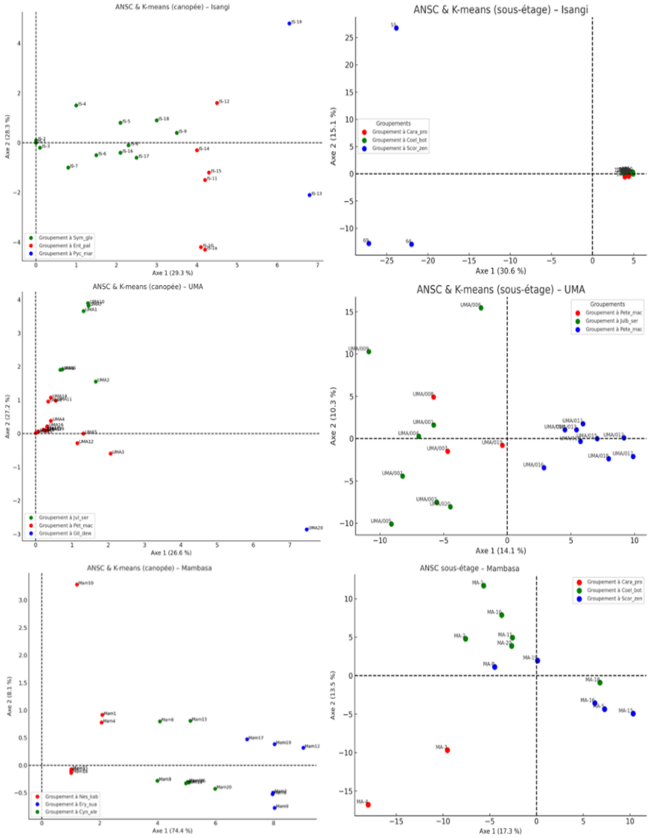

Figure 3 – ANSC along axes 1 and 2 of the floristic data and K-means classification of canopy and understorey plant communities at three study sites.

This visual representation highlights a clear differentiation between sites, revealing specific floristic signatures and dominance dynamics that vary significantly depending on the stratum analysed.

At Isangi, three floristic groups were identified in the canopy: (i) a group dominated by Carapa procera DC. and associates, characteristic of undisturbed low-altitude forests; (ii) a second group centred around Coelocaryon botryoides VERM.; and (iii) a third group dominated by S. zenkeri, a species indicative of relatively mature drylands. These dominances are also reflected in the understorey, although some slower-growing species are more prevalent there, indicating differentiated regeneration according to stratum.

The Uma site also reveals three distinct canopy groups: dominated respectively by Gilbertiodendron dewevrei J. LÉONARD, Petersianthus macrocarpus LIBEN and Julbernardia seretii TROUPIN. These species reflect an ecological gradient ranging from more open areas of light to dense old-growth forests. In the understorey, the presence of S. kamerunensis and Polyalthia suaveolens ENGLER & DIELS highlights the importance of slow-regenerating species in the constitution of the lower stratum.

The submontane forests of Mambasa have a differentiated floristic structure between the canopy and the understorey. While some taxa such as C. alexandri are found both among the large trees and in the young DHP classes, others such as Erythrophleum suaveolens BRENAN or Alstonia boonei DE WILD show a notable absence of regeneration. This contrast suggests that floristic resilience is not homogeneous across groups: some appear dynamic and regenerative, while others appear senescent or in decline. Increasing anthropogenic pressure in the region could accentuate this structural heterogeneity and affect the sustainability of dominant species in different ways.

3.2. Diversity, structure and resilience potential of forest communities

For floristic diversity, diameter structure and resilience potential of the communities identified in each stratum and site, three axes are prioritised: (i) alpha diversity indices, (ii) diameter structures (pyramids) and (iii) indicator species revealing ecological stability. Together, these allow the functional robustness of the sampled forests to be assessed.

Table 1 - Comparative ecological characteristics of the dominant forest communities identified by site

Site	**Stratum**	**Group**	**Indicator species**	**Diversity (H')**	**Diametric structure**	**Stratification**	**Resilience potential**
Isangi	Canopy	Scorodophloeus zenkeri	S. zenkeri, Carapa procera	2.9	Inverted J	Well marked	Strong
	Sub-storey	Coelocaryon botryoides	C. botryoides, S. kamerunensis	2.7	Regular	Moderate	Medium
Uma	Canopy	Staudtia kamerunensis	S. kamerunensis, J. seretii	3.1	Inverted J	Well marked	Strong
	Sub-storey	Polyalthia suaveolens	G. dewevrei, P. suaveolens	2.8	Regular	Moderate	Medium
Mambasa	Canopy	Cynometra alexandri	C. alexandri,	3	Inverted J	Well marked	Strong

			Diogoa zenkeri				
	Sub-storey	Scorodophloeus zenkeri	Santiria trimera, C. mildbraedii	2.6	Unstable	Low	Low

3.2.1. Alpha diversity indices

The Shannon (H'), Simpson (1-D) and Pielou's evenness (J') indices show marked inter-site variability. In the canopy, the Mambasa groups have the highest Shannon values (H' > 2.8), reflecting greater species diversity. Uma, although less floristically rich, reveals high evenness, suggesting a balanced distribution of dominant species. In the understorey, Isangi stands out with moderate indices, indicating average but stable diversity. These results suggest that the diverse Mambasa communities and balanced Uma stands are better able to absorb disturbances without losing their functional integrity.

3.2.2. Diametric structure of communities

Analysis of diameter pyramids reveals variable profiles between sites. In Isangi, hydromorphic forests dominated by E. palustre show an irregular distribution, with an overrepresentation of middle classes, reflecting discontinuous recruitment. In Uma, S. kamerunensis stands have a bell-shaped structure, symptomatic of active regeneration but also moderate exploitation. Mambasa offers an inverted J distribution, typical of dynamic forests, characterised by abundant recruitment in young diameter classes, an indication of good resilience. These variations reflect contrasting ecological dynamics and differential capacities to respond to disturbances.

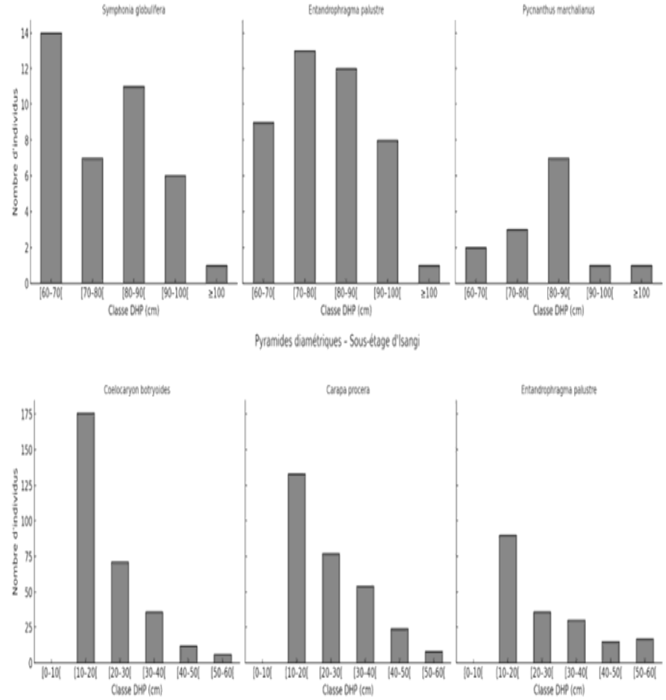

Figure 4 - Diametric structure of forest communities in Isangi (top = canopy and bottom = understorey)

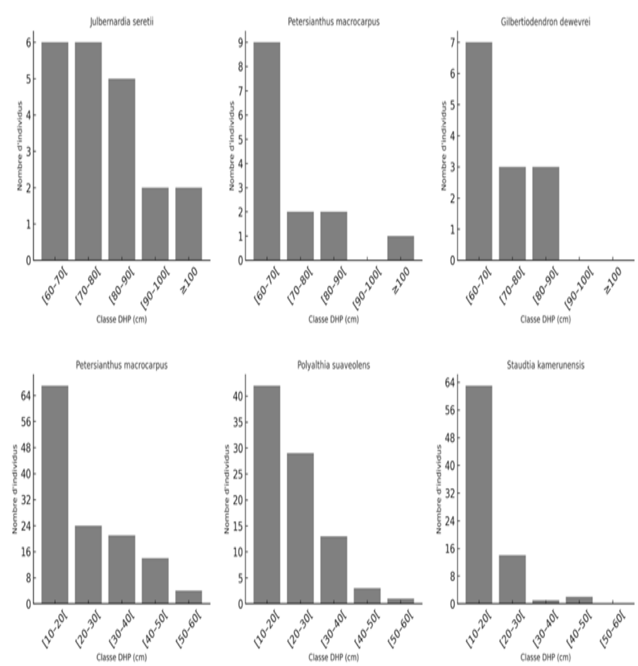

Figure 5 - Diameter structure of forest stands in Uma (top = canopy and bottom = understorey)

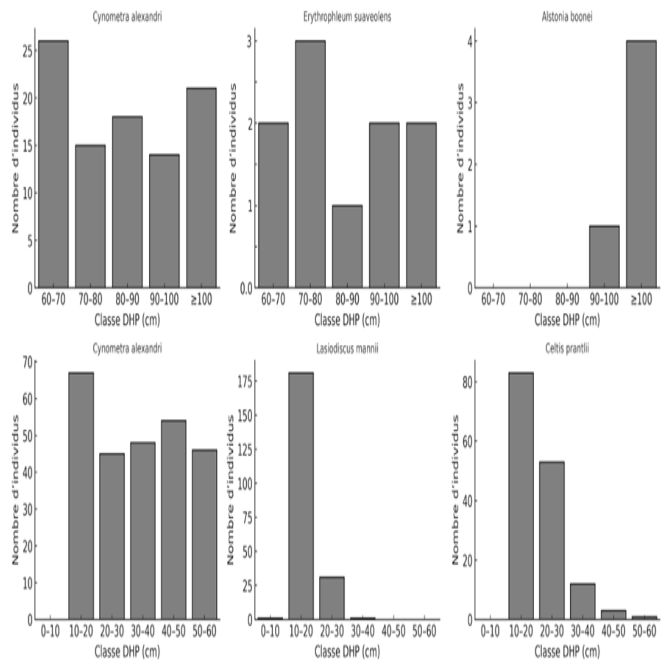

Figure 6 - Diameter structure of forest communities in Mambasa (top = canopy and bottom = understorey)

3.2.3. Indicator species and ecological stability

IndVal analyses reveal, for each site and stratum, species that are highly representative of their ecological environment. In Isangi, S. zenkeri dominates on dry land, while E. palustre characterises flooded areas. At Uma, S. kamerunensis and P. suaveolens are distinguished by their strong affinity with mature understores. At Mambasa, C. alexandri occupies a central position in both the canopy and understore, reflecting a marked ecological specialisation.

The recurrence of these taxa, combined with high floristic diversity and a stratified structure, demonstrates functional robustness in the face of disturbances. These attributes give the forests of Uma and Mambasa strong potential for resilience-, making their communities prime candidates for modelling ecologically stable forests in the central Congolese basin.

3.3. Operational lessons for model forests in the Congo Basin

A comparative analysis of the forest communities studied reveals the need for a nuanced approach to the design and management of model forests in the Congolese central basin. Three major lessons emerge from this study, offering concrete avenues for ecological and pragmatic forest planning.

3.3.1. Prioritise ecologically stable and well-structured groups

The formations dominated by S. zenkeri in Isangi, S. kamerunensis in Uma and C. alexandri in Mambasa are distinguished by a balanced diameter structure, high floristic diversity and well-developed vertical stratification. These attributes are generally recognised as indicators of ecological maturity and resilience to disturbance. As a result, these communities are prime candidates for model forest initiatives, as conservation cores, forestry research hubs or sustainable management pilot sites.

3.3.2. Integrating the ecological and anthropogenic constraints specific to each site

Some groups, particularly those located on hydromorphic soils in Isangi (E. palustre) or the impoverished secondary formations of Uma, have lower diversity and an altered structure, reflecting past or present disturbances. While these forests are of local or functional interest, their ecological fragility calls for particular vigilance. Their integration into a model forest approach must be accompanied by targeted interventions: floristic enrichment, control of anthropogenic pressures, and restoration of ecosystem functions.

3.3.3. Designing model forests as adaptive ecosystem mosaics

The juxtaposition of groups with distinct floristic and structural identities within the same landscape highlights the value of modular model forests that integrate the diversity of local ecological units. Such a configuration would better reflect the complexity of the Congo Basin's forests and preserve their multiple functions. However, it requires differentiated planning according to edaphic, topographic and sociocultural conditions, as well as the active involvement of local communities in forest governance and use. The experience gained from the Isangi, Uma and Mambasa sites thus provides a relevant empirical basis for guiding the implementation of model forests in this strategic region.

4. Discussion

4.1. Differentiated floristic structure and ecological identities

The forests of the Congolese central basin show marked floristic differentiation depending on the site and stratum. In Isangi, Staudtia zenkeri dominates the dryland forests; in Uma, Staudtia kamerunensis structures the mesomorphic stands with balanced stratification; while in Mambasa, Cynometra alexandri characterises the submontane formations. This distribution reflects a subtle and localised ecological adaptation, confirming the observations of Fayolle et al. on the biogeographical regionalisation of African flora [16] and those of Droissart et al. on Central African ecological gradients [17]. These strong floristic identities are a relevant criterion for the selection of reference sites in the context of model forests.

4.2. Diversity, vertical structure and demographic stability: indicators of resilience

Groups with high floristic richness, a diametric "inverted J" distribution, and clear stratification between the understorey and canopy reflect stable and regenerative stands. This convergence of indicators—diversity, structure, and stratification—corresponds to the functional criteria of stability and resilience proposed by Elmqvist et al. [18] and Mori et al. [19]. These elements provide a robust diagnosis for prioritising sites according to their ecological resilience potential.

4.3. Indicator species and IndVal: towards adaptive management

Analysis of indicator values (IndVal) has identified structuring and diagnostic species, such as S. zenkeri, S. kamerunensis and C. alexandri, which are capable of accurately representing homogeneous habitats. Within the framework of MRV for REDD+ [20], monitoring these species is an operational tool for detecting ecological dynamics, guiding adaptive management and anticipating the impacts of anthropogenic and climatic pressures.

4.4. Ecological mosaic and model forest design

The heterogeneity observed between forest types (terrestrial, mesomorphic and submontane) calls for a mosaic approach to model forests, in line with the recommendations of de Wasseige et al. [21]. By composing multifunctional forest complexes adapted to edaphic conditions and local uses, this approach optimises landscape resilience while meeting the socio-economic needs of local communities.

4.5. Community governance and territorial co-construction

Field data show that the most resilient groups often coincide with traditional practices compatible with conservation. The integration of local communities in participatory monitoring and the promotion of indigenous knowledge is essential to the sustainability of model forests, in line with the recommendations of the RRI [22] and the observations of Sunderland et al. [23]. This collaborative governance strengthens both the ecological sustainability and social legitimacy of interventions.

4.6. Implications for REDD+ and climate policies

The stable clusters identified have strong potential for REDD+ initiatives, thanks to their ability to store biomass and maintain a resilient floristic composition [24, 25]. Comparable experiences in Central Africa illustrate this dynamic: in Gabon, the Lopé and Abeilles forests demonstrate the robustness of ecosystems dominated by Aucoumea klaineana [26, 27], while in Cameroon, the Dja and Campo-Ma'an forests highlight the importance of structured monodominances such as Gilbertiodendron dewevrei for ecological resilience [28, 29].

The integration of floristic, structural and spatial criteria appears to be essential for the designation of model forests at the regional level. The methodology adopted, combining diversity, structure and stratification, provides a functional and operational interpretation of forest resilience. Despite certain limitations, such as the lack of detailed soil data and the short monitoring window, this approach provides a solid basis for differentiated management strategies and for strengthening forestry and climate policies in the Congo Basin.

Conclusion

This study has demonstrated that the above-ground biomass and resilience of forests in the central Congolese basin result from a dynamic interaction between floristic richness and vertical stratification. The methodological approach adopted, distinguishing the understorey from the canopy at a threshold of 0.60 m DBH, revealed that the stability of carbon stocks is intrinsically linked to the functional complementarity between these two strata.

We identified emblematic groupings anchored by Scorodophloeus zenkeri, Staudtia kamerunensis and Cynometra alexandri, which have high resilience potential thanks to an "inverted J" structure and well-defined stratification. Conversely, areas subject to high anthropogenic pressure or hydromorphic constraints show a break in inter-stratum continuity, signalling increased vulnerability to disturbances.

Operationally, the superiority of integrated mixed models (conditional $R^2 = 0.82$) confirms, that species diversity acts as an amplifier of biomass storage capacity determined by structure. These results provide a robust scientific basis for refining REDD+ monitoring systems and guiding the designation of resilient model forests in Central Africa.

Ultimately, biodiversity conservation should no longer be seen as an isolated objective, but as the guarantor of the sustainability of the carbon sink in the Congo Basin.

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