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Research Article

Spatial Distribution of *Cedrela Odorata* Smaller Trees Affects Forest Regeneration in Exotic Tree Plantations in Central Côte d'Ivoire

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ABSTRACT
Cedrela odorata L. was introduced as a possible forest restauration species in classified forests at Côte d'Ivoire. Because of its demonstrated invasive behavior in other tropical forests, this study aimed to assess the impact of *Cedrela odorata* on the regeneration of spontaneous plant species in tree plantations. On the base of *Cedrela odorata* larger tree densities, two types of forest plantation were considered: Type I (240 stems/ha) and Type II (176 stems/ha). In these plantations, plots with 0.25 ha were chosen to locate each tree with dbh ≥ 2.5 cm, in an orthonormal reference. The tree density, the basal area, the species richness, the Shannon diversity index and the rank-abundance curves were determined considering smaller and larger trees. The horizontal spatial arrangement and Ripley's K function were performed to understand the spatial relationship between *Cedrela odorata* smaller trees and those of spontaneous species. The results shown lower spontaneous plant species richness (15-20 species) and diversity (1.15 - 1.43); the dominance of *Cedrela odorata* smaller trees (43.02 – 62.95 % of all stems). The *Cedrela odorata* smaller trees and those of other species have dependent spatial distributions; expressed by a spatial repulsion between the two groups up to a distance of 18 m in the most densified forest plantation. This repulsion was related to an aggregated distribution of *Cedrela odorata* smaller trees in plantation with higher tree density. The study suggests a 170-stems/ha (or lower) of *Cedrela odorata* planting density for biodiversity establishment improvement outcomes in forest plantations.

INTRODUCTION
Cedrela odorata L. (Figure 1) is a native of India and America (Global Invasive Species Database 2015). It has been introduced to many countries in Pacific Islands and Africa. While the species was listed on the IUCN Red List of Threatened Species in parts of the Americas, this species paradoxically became an invasive species in Pacific Island including Hawaii and the Galapagos, the South Africa and Tanzania (Pasiecznik 2008; Kilawe et al. 2022).

In Côte d'Ivoire (West Africa), *Cedrela odorata* has been introduced as a timber tree and as a possible forest restoration species since the 1920s (Cintron 1990). This species quickly gained popularity in carrying out industrial reforestation initiatives. The ecological conditions being important to the extensive growth of the species, it has sometimes spread outside the planted areas, modifying abundantly the existing surrounding flora (Vroh et al. 2022).

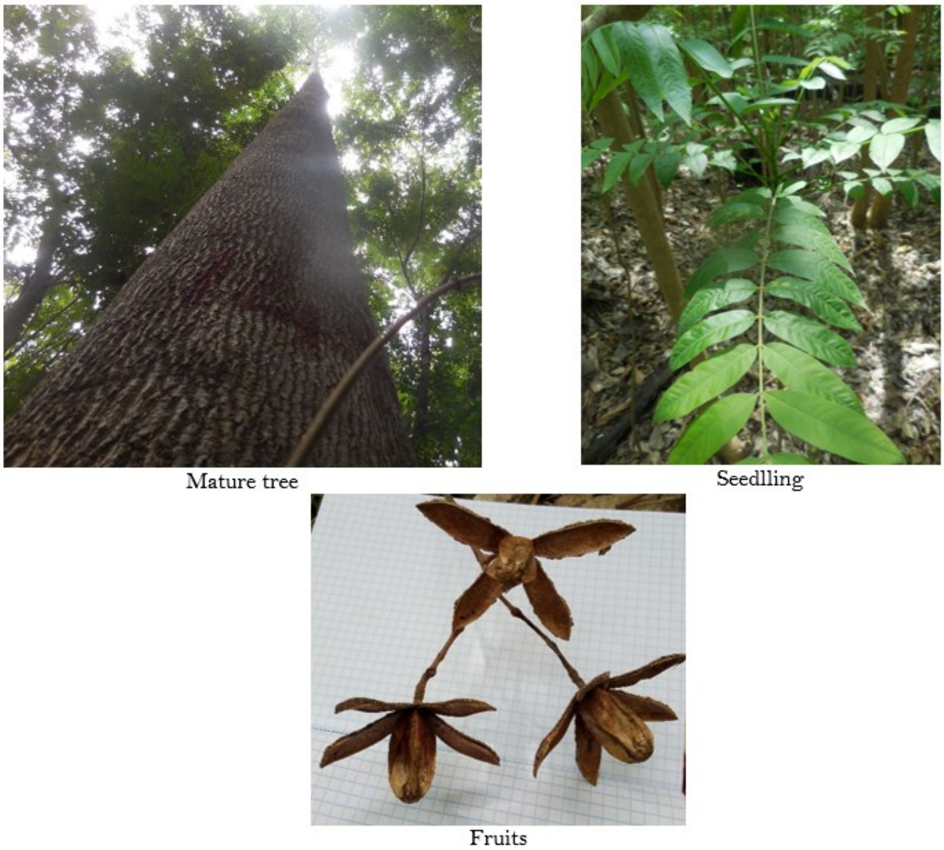

Figure 1. Photographic views of *Cedrela odorata*.

In the country, Classified forests are managed by the government. In this category of protected forest, the forest plantations are authorized for the purpose of reforestation or wood production. Among Ivorian classified forests, the largest areas of the forest plantations are in Téné Classified Forest (TCF). In this area, the exotic species Teck (*Tectona grandis* L.f.), Gmelina (*Gmelina aroborea*, Roxb.) and Cedrela (*Cedrela odorata* L.) represented more than 60 % of the reforested area (Eblin & Amani 2015). In the TCF, *Tectona grandis* was many planted as monoculture; while *Cedrela odorata* and *Gmelina arborea* were mostly associated as mixed-species plantations (Sangne 2009). However, in these mixed-species plantations, *Cedrela odorata* smaller trees had more than 50 % of all sapling and seedling tree species occurrences (Koné & Vroh 2021; Vroh et al. 2022). According to Der Meersch et al. (2021) this concurrency is due to the lasting effects of the wildfire which destroyed more than 65 % of this space in 1980-1981. However, more than 30 years later, in Téné forest, published quantitative data demonstrating the positive or negative effects of exotic tree plantations based on *Cedrela odorata*, on plant diversity establishment, is still limited. Yet, these data are critical in deciding whether tree plantations can be a valuable component in the country's indigenous forest rehabilitation and the Reducing Emissions from Deforestation and Forest Degradation (REDD+) programs.

This study presents an overview of the behavior of *Cedrela odorata* as well as its impacts on the establishment of forest regrowths in forest plantations. We hypothesize that in forest plantations based on *Cedrela odorata*, the establishment of forest regrowths are independent of its spatial structure. The study aimed to assess the impacts of *Cedrela odorata* on

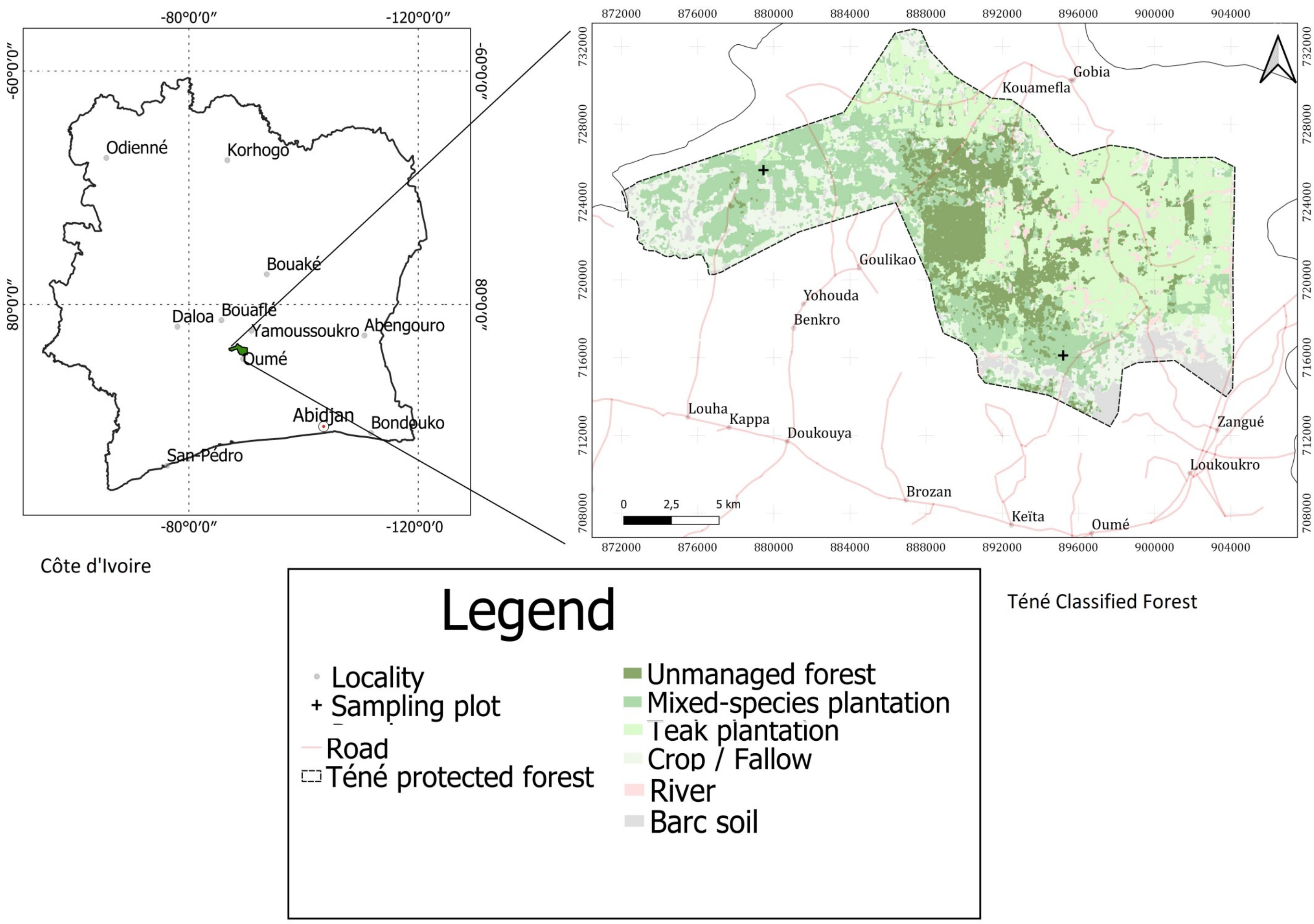

Figure 2. Map of land use type in the Téné Classified Forest in Côte d'Ivoire (Source: Adapted from Sangne 2009).

the regeneration of spontaneous plant species in tree plantations at Téné Classified Forest. Specifically, the study (1) analyzed the floristic and dendrometric characteristics of the forest plantations, (2) characterized the spatial distribution of *Cedrela odorata* trees, (3) defined the interspecific structuring between *Cedrela odorata* and spontaneous sapling and seedling trees.

MATERIALS AND METHODS

Study Area

The study was conducted in the Téné Classified Forest (TCF) managed by the Government agency (SODEFOR) since 1973. The site (Figure 2) is located in the Oumé department (6°27' - 6°37' N and 5°20' - 5°40' W). The TCF is considered the pioneer in timber production and industrial tree plantation development in the country.

The mean annual rainfall in Oumé department was 1,200 mm, while the mean annual temperature is 25 °C (Vroh et al. 2022). The vegetation is dominated by semi-deciduous forests characterized by *Celtis* spp. and *Triplochiton scleroxylon* K. Schum.

The TCF covers 29,400 ha, of which 22,000 ha are forest plantations. Currently in the site, there are two forest plantation types: the monospecific *Tectona grandis* forests and the mixed-species tree forests based on *Gmelina arborea* and *Cedrela odorata* (Figure 2). These two tree plantation types are intended especially for commercial use. The plantations under 10 years old (young plantations) are subject to regular cutting operations while in those with more than ten years (10-40 years), thinning and selective tree cutting are done (SODEFOR 2014). For 40 years, awaiting for the timber exploitation, the plantations are abandoned without any cutting operations.

For this study, only mixed-species plantations based *on Cedrela odorata* and *Gmelina arborea*, over 40 years were chosen. Indeed, in these plantations, cutting effects are reduced and natural regeneration is provided without human disturbance.

Two types of mixed-species plantations of more than 40 years were chosen based on botanical inventories carried out by Koné & Vroh (2021) and Vroh et al. (2022) in the Téné Classified Forest. According to these authors, in the TCF, the average density of mature stems (dbh ≥ 10 cm in adult plantations) of the target species (*Cedrela odorata*) was 234.95 stems/ha. Thus, for the forest plantation Type I, we selected a plot with 240 stems/ha as planting density of *Cedrela odorata.* This plantation type was considered closer to average across the Téné Classified Forest. For the forest plantation Type II, the planting density of *Cedrela odorata* was 176 stems/ha. This latter type was considered as a plot where the planting density is low compared to the average in the TCF. Also, this density of Cedrela odorata in the forest plantation Type II is closer to the standard which is 120–150 stems/ha according to Lemmens (2008). Thus, inventories were carried out in one plot per forest plantation Type.

Sampling Design and Data Collection

The sampling design was adapted from the classic method described by Picard & Gourlet-Fleury (2008). The size of the plots was 2500 m^2; i.e. 50 m x 50 m. Many authors have used this plot size (0.25 ha) as observation units in the analysis of spatial patterns (Nicotra 1998; Fonton et al. 2011; Havyarimana et al. 2013). In addition, this plot size significantly reduced the errors accumulation during the distance measurement between trees (Boose et al. 1998).

Each plot was subdivided into four (4) sub-plots of 625 m^2; i.e. (25m x 25m). Data collection consisted of locating each individual of Cedrela odorata and other tree species in an orthonormal reference (o, i, j). Only trees with at least 2.5 cm diameter at breast height (dbh ≥ 2.5 cm) were considered and their cartesian coordinates were read following a grid. In practice, an origin of the axes (x0, y0) has been defined for each plot of 2500 m^2.

Data Analysis

Firstly, in the identified stand, two size classes of trees were defined: 2.5 cm ≤ dbh < 10 cm as smaller trees (sapling and seedling) and dbh ≥ 10 cm as larger trees (mature). In each forest plantation type and for each tree size class, the total tree density (N), the basal area, the species richness (S) and the Shannon diversity index (H') were estimated. Also, rank-abundance curves (Kindt & Coe 2005; Marcon 2018) of tree species were constructed to highlight the most abundant species. All these diversity indices permitted to know the quality and the quantity of the forest regrowths affected by *Cedrela odorata* smaller trees.

Secondly, we determined the horizontal spatial arrangement of *Cedrela odorata* (smaller and larger trees) through the distribution maps using the coordinates (xi; yi). Then, Ripley's K function (Ripley 1977) was performed to confirm the distribution mode observed through the maps (He & Duncan 2000; Fonton et al. 2011). This Ripley's function is widely used in spatial pattern analysis and offers the advantage of integrating information on all inter-point distances (Diggle 1983). In application, the Ripley's function K(r) is estimated for an area with circular radius r. However, Kiêu & Mora (1999) demonstrated that the function K

(r) is biased for trees located at the border of the plot area. To address this issue, Besag (1977) recommended linearized function L(r). This function is the local bias correction method of Ripley (1981) which yields more robust results and is easier to interpret than K(r).

If L(r) was equal to zero for a given value of r, the null hypothesis was accepted; that meant that the trees have a random distribution. For non-random distributions, a Monte Carlo approach was used with 1,000 random runs for all trees in the plot. A 95% confidence interval was generated for a given value of r, with r increasing from 1 to 25 m in 1-m increments (Diggle 1983). The distance limit of 25 m corresponded to half the observation plot and represented the scale of analysis considered (Ripley 1977). If L(r) was greater than the upper confidence limit (positive) there was an aggregated distribution. In contrast, if L(r) was smaller than the lower confidence limit (negative), there was an overdispersed distribution (Abdourhamane et al. 2017).

Thirdly, Ripley's L12(r) intertype function was used to understand the spatial relationship between Cedrela odorata smaller trees (group 1) and those of spontaneous species (group 2). Indeed, the L12(r) function permitted to quantify the degree or type of spatial relationship between the two groups (Haase et al. 1996). The 95% confidence interval for L12 (r) was also calculated using a Monte Carlo simulation. In order to understand the establishment of spontaneous species, each simulation consisted of randomly assigning new coordinates to given trees in group 2 while coordinates of group 1 were left unchanged (Goreaud & Pélissier 2003). For this intertype function, the null hypothesis was that groups 1 and 2 have independent spatial distributions. If the value of L12(r) was significantly different from zero up to distance r, this null hypothesis was rejected. When L12(r) was statistically larger than zero, the parameter indicates spatial attraction between the two groups up to distance r. In contrast, when L12(r) was statistically smaller than zero, the parameter indicates spatial repulsion between the two groups up to distance r.

All the horizontal spatial arrangement maps and Ripley's spatial distribution analyses were performed using Programita software (Wiegand & Moloney 2004).

RESULTS AND DISCUSSION

As a reminder, two types of mixed-species forest plantations were chosen based on the density of the larger trees (dbh ≥ 10 cm) of the target species, *Cedrela odorata*: plantation Type I with 240 stems/ha and plantation Type II with 176 stems/ha.

Floristic and Dendrometric Characteristics of The Forest Plantations

From 15 to 20 trees species were recorded per plot (Table 1), with more species represented in smaller trees (13 to 17 species; 2.5 cm ≤ dbh > 10 cm) than in larger trees (8 to 9 species; dbh ≥ 10 cm). The lower richness observed for larger trees could be related to the cutting and thinning activities realized by the SODEFOR agencies until 40 years after the creation of the plantations.

The forest plantation Type I, with 20 species, was the richer than the Type II. The Shannon diversity index values varied from 1.15 (forest plantation Type I) to 1.43 (forest plantation Type II) for all trees, and lower for each category of trees. These results shown that the tree species diversity was very low. This reflected a dominance phenomenon of one or a few species (Marcon 2019) in the two forest plantation types.

Overall tree density in the stand varied from 3372 to 4456 stems/ha respectively in forest plantations Type I and Type II; the corresponding densities of smaller trees represented 70.5 – 81.4 %. The basal area in the stand varied from 44.1 m2/ha (forest plantation Type II) to 48.8 m^2/ha (forest plantation Type II); the corresponding basal areas of larger trees represented 86.2 – 89.9 % (Table 1). These results shown that the lower density of larger trees in the forest plantation type II, favored a higher density of tree regrowth. Indeed, forest regrowth does not generally tolerate significant shade (Avalos 2019).

In the two forest plantation types, the larger tree class in the stand was dominated by *Gmelina arborea* with 600 stems/ha (Type II) and 724 stems/ha (Type I). The second most abundant species was *Cedrela odorata* with 176 and 240 stems/ha respectively in forest plantations Type II and Type I (Figure 3).

The smaller trees which result in natural forest regrowth, were dominated by *Cedrela odorata* as shown in Figure 4. The density of the species represented 43.02 and 62.95 % of the overall densities respectively in forest plantations Type I and Type II. This means that *Cedrela odorata* had the most represented abundance of the overall species. Also, the abundance of *Cedrela odorata* was higher in forest plantations where the larger trees density was lower. This result is similar to those demonstrated by Muellner et al (2010). According to these authors, the saplings of *Cedrela odorata* do not tolerate heavy shade.

The other species had lower abundances in both forest plantation types (Figure 3). For forest plantation type I, *Newbouldia laevis* with 8 stems/ha in the larger trees class, was represented by 48 stems/ha (2.02 %) in the smaller trees class. This tropical native species, grows usually in Guinean savannas to dense forests and secondary forests areas (Adomou et al. 2018). In many Ivorian ecological areas, this species is well adapted to the highly anthropized habitats like the Téné Classified Forest area.

For forest plantation Type II, *Cassia siamea* is the third most abundant species with 28 (3.4 %) and 596 stems/ha (16,4 %) respectively for larger and smaller trees. This alien species, native to Asia, was introduced into Téné Classified Forest for ornamental and decorative purposes of the forest police camp. However, it spread very quickly in several forest plantations at TCF.

Native species like *Baphia nitida*, *Milicia excelsa*, with a wide range of distribution in Guineo-Congolian area, were less well represented in the two plantation types. This confirms that in previous years, natural stands have faced disturbances either from human-induced or related to competition with planted species (Meyer et al. 2021).

Table 1. Summary of floristic and structural parameters in the two plantation types.

Groups	Density (stems/ha)		Richness		Shannon		Basal area (m^2 / ha)	
	Type I	Type II	Type I	Type II	Type I	Type II	Type I	Type II
Larger trees (dbh ≥ 10 cm)	992	828	8	9	0.19	0.18	43.9	38
Smaller trees (2.5 cm ≤ dbh > 10 cm)	2380	3628	17	13	0.88	1.10	4.8	6.1
Total	3372	4456	20	15	1.15	1.43	48.8	44.1

Note: Type I = forest plantation with 240 stems/ha as *Cedrela odorata* density; Type II = forest Plantation with 176 stems/ha as *Cedrela odorata* density.

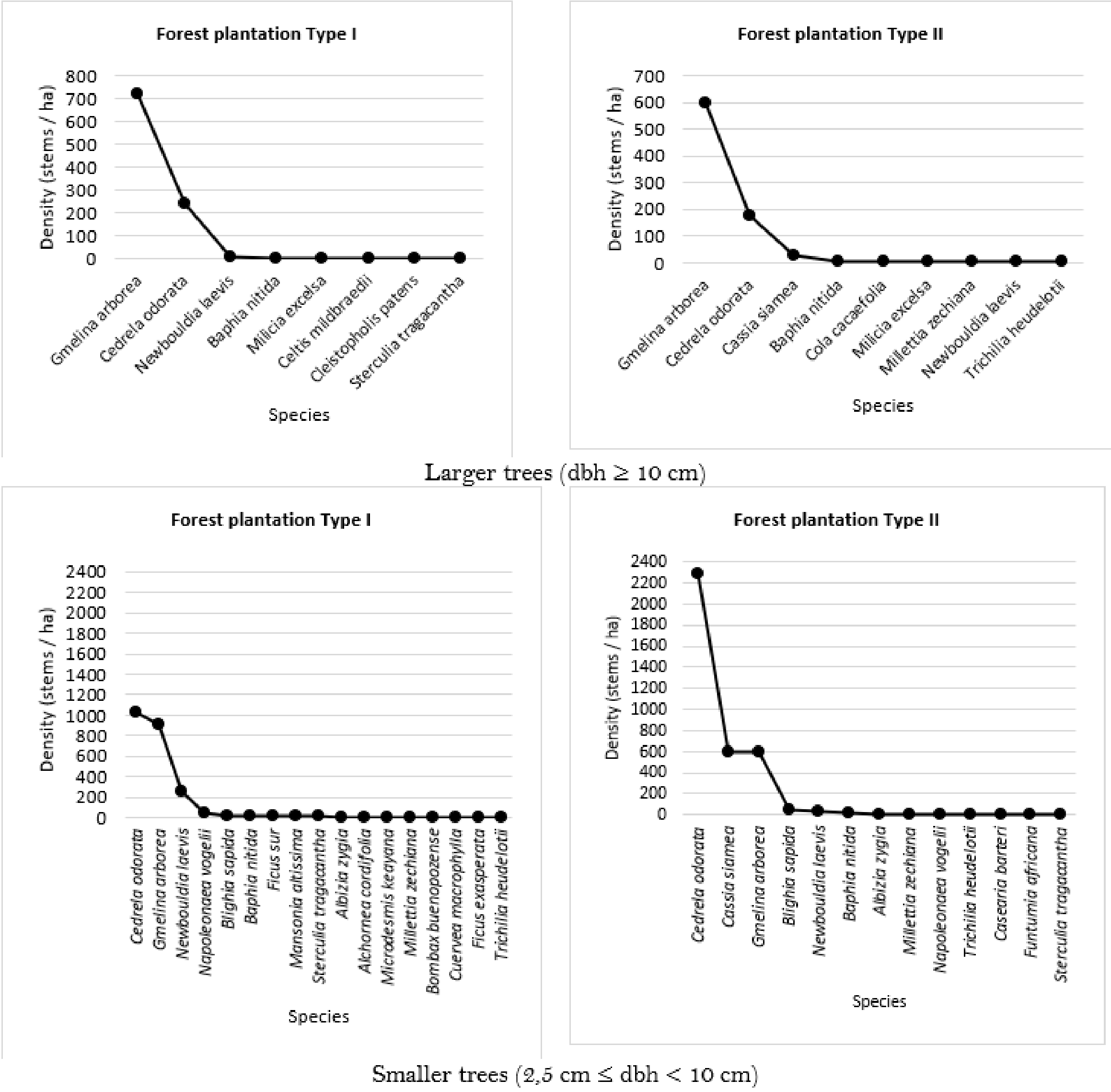

Figure 3. Abundances of recorded species in the two forest plantation types. Type I = forest plantation with 240 stems/ha as *Cedrela odorata* density; Type II = forest Plantation with 176 stems/ha as *Cedrela odorata* density.

Figure 4. A view of Cedrela odorata smaller trees abundance level in a forest plantation.

Spatial Structure of *Cedrela Odorata*

The overall spatial distribution of *Cedrela odorata* (larger and smaller trees) presented a significant aggregate radius of more than 24 m in forest plantation Type I (Figure 5). In the forest plantation Type II, the spatial distribution was also, characterized by a significant aggregate radius of 13 m. However, beyond 13 m, the distribution was random in this plantation type. The size of the aggregates is therefore greater for higher plantation density of *Cedrela odorata.* The large size of the aggregates is related to the wind dispersion of *Cedrela odorata* propagules (Muellner et al 2010).

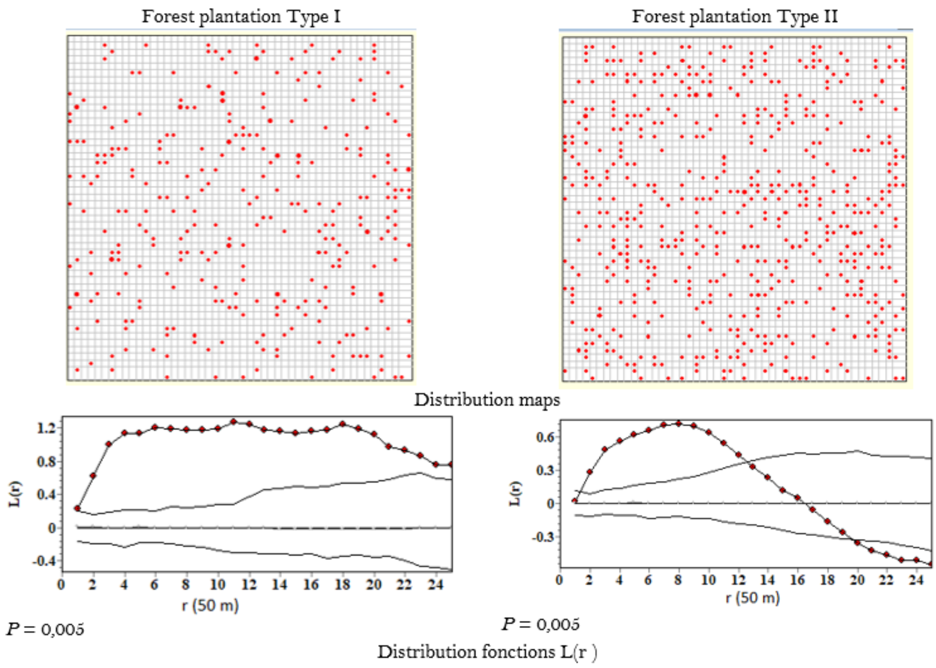

Figure 5. Spatial distribution maps and functions of larger and smaller stems of *Cedrela odorata* in the two forest plantation types. Type I = forest plantation with 240 stems/ha as *Cedrela odorata* density; Type II = forest Plantation with 176 stems/ha as *Cedrela odorata* density.

When the two categories of trees are considered separately, we observed a random distribution of the *Cedrela odorata* larger trees (Figure 6). This distribution attested to the homogeneity of the larger trees; resulting in the history of cutting and thinning activities effects. By contrast, the spatial structure of *Cedrela odorata* smaller trees was characterized by an aggregated distribution in the two forest plantation types (Figure 7). In the forest plantation Type I, the *Cedrela odorata* smaller trees presented a clump of 17 m radius, with two aggregation peaks, at 6 and 24 m. In the forest plantation Type II, the spatial distribution of *Cedrela odorata* smaller trees presented a clump withe radius of 13 m.

These results shown that the aggregated distribution of *Cedrela odorata* is due to smaller trees. Also, the clumped radius was greater when the planting density was higher. The standard planting density (120-150 stems/ha) as recommended by Lemmens (2008) could then, reduce the clumped radius of *Cedrela odorata* smaller trees. In the two forest plantation types, the aggregate spatial distributions of *Cedrela odorata* smaller trees can be interpreted as reflecting variations in the characteristics of the environment (Dajoz 2003). The species aggregated in places where environmental conditions are favorable for its development (Thammanu et al. 2021).

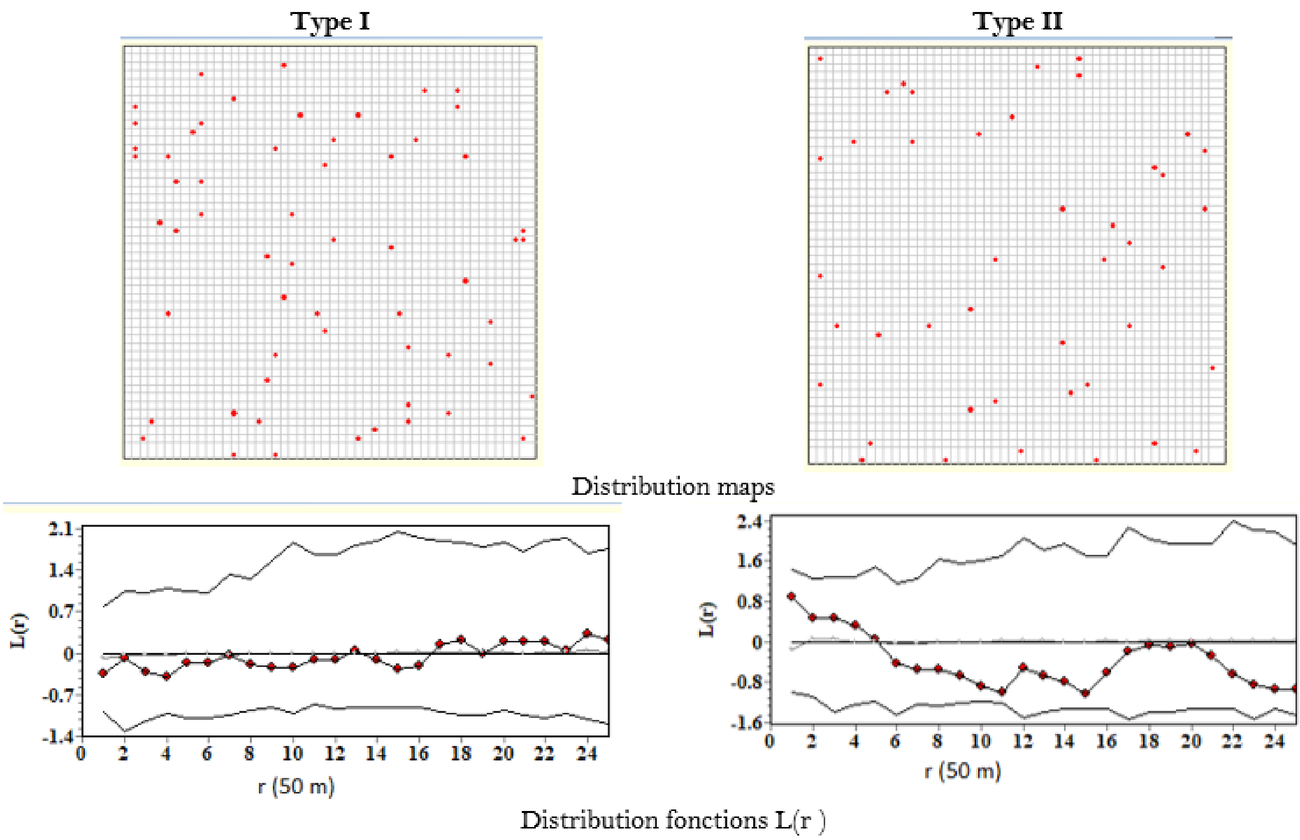

Figure 6. Spatial distribution maps and functions of *Cedrela odorata* larger trees in the two forest plantation types. Type I = forest plantation with 240 stems / ha as *Cedrela odorata* density; Type II = forest Plantation with 176 stems / ha as *Cedrela odorata* density.

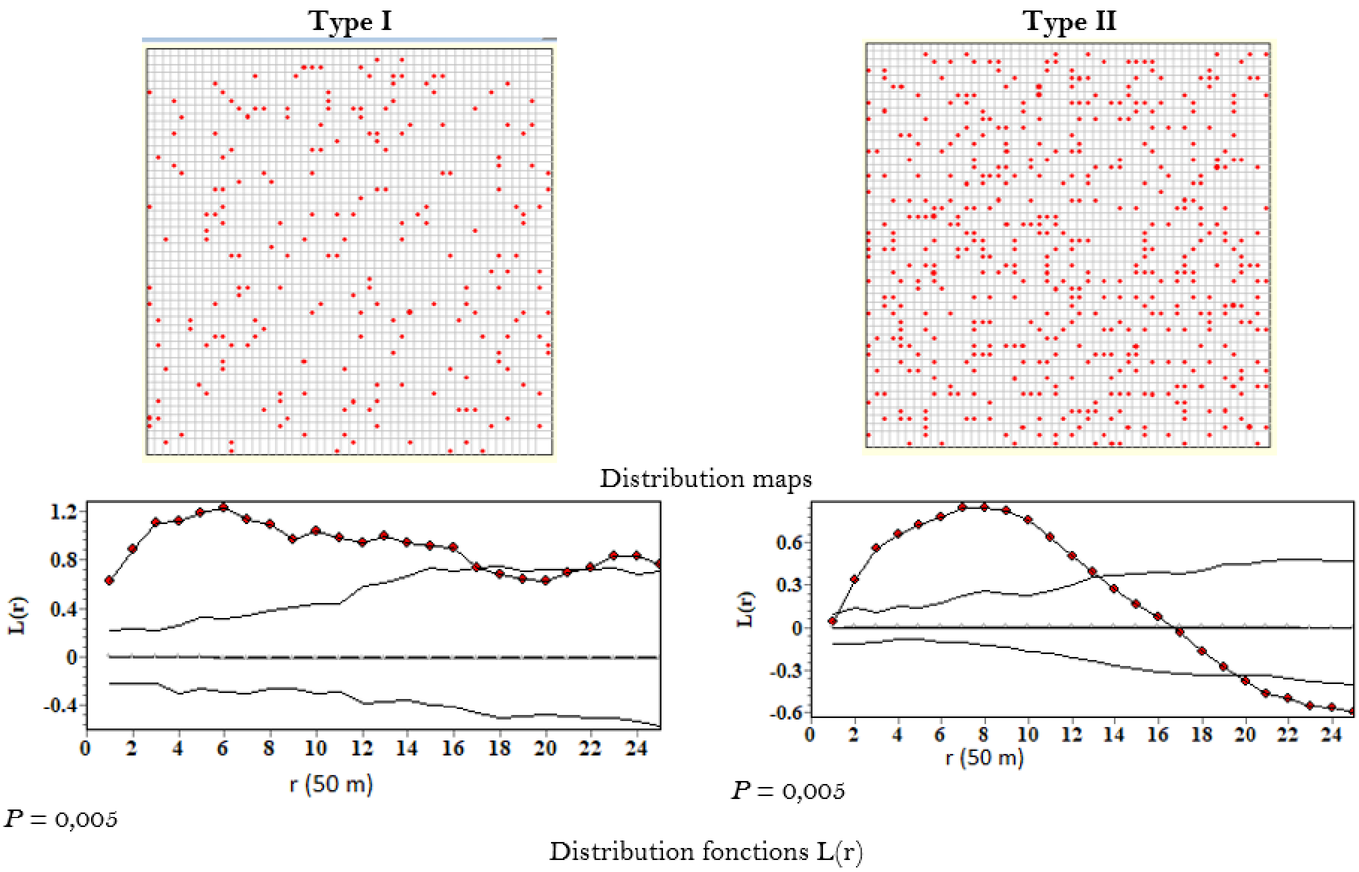

Figure 7. Spatial distribution maps and functions of *Cedrela odorata* smaller trees in the two forest plantation types. Type I = forest plantation with 240 stems/ha as *Cedrela odorata* density; Type II = forest Plantation with 176 stems/ha as *Cedrela odorata* density.

Effect of *Cedrela Odorata* Smaller Trees on Forest Regrowths

The L12 function assessed the spatial association between *Cedrela odorata* and the spontaneous species (Figure 8). In the forest plantation Type I, the value of L12(r) is significantly different from zero up to a distance of 18 m. This meant that, in this plantation type, *Cedrela odorata* smaller trees and those of other species have dependent spatial distributions. Indeed, the L12(r) function is statistically smaller than zero, indicating a spatial repulsion, between the two groups up to distance 18 m. By contrast, the association between these two groups was random for all values of r in plantation Type II (Figure 8). When the larger trees (adults) density was reduced, there was an independent distribution between *Cedrela odorata* smaller trees and those of spontaneous forest regrowth. The observed repulsion of spontaneous species is therefore eliminated when the density of *Cedrela odorata* larger trees is reduced to around 170 stems/ha or lower.

In the plantation type with around 240 stems/ha, the abundance and dominance of *Cedrela odorata* smaller trees could be linked to ecological niche specialization (Stoll & Bergius 2005). As demonstrated by many authors (Le Maître et al. 2011; Pearson et al. 2018; Dydersky & Jagodziński 2020), the spatial repulsion of a species trees can restrict the establishment of spontaneous species and promote changes in species composition and community structure. Indeed, the local dominance expressed by an aggregate distribution of a tree species can reduce the diversity (Havyarimana et al. 2013).

In plantations with more *Cedrela odorata* large trees (Type I), an

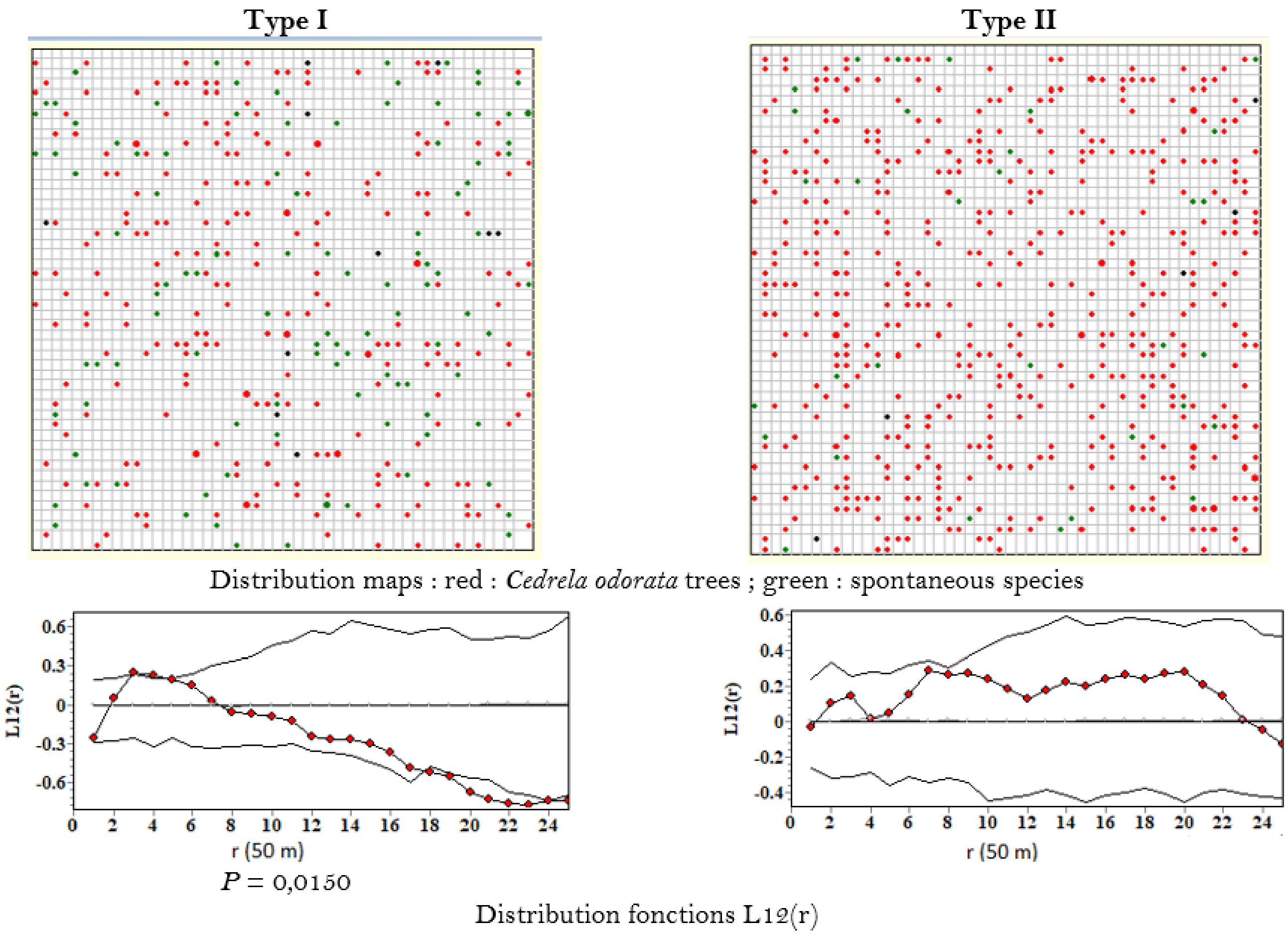

Figure 8. Distribution maps and bivariate functions of spatial association between smaller trees species in the two forest plantation types. Type I = forest plantation with 240 stems/ha as *Cedrela odorata* density; Type II = forest Plantation with 176 stems/ha as *Cedrela odorata* density.

interspecific repulsion was observed, between the two groups of smaller trees, up to a distance of 18 m. To take into account *Cedrela odorata* behavior (repulsion between smaller trees), we suggest to SODEFOR two planting strategies based on this species. If SODEFOR maintains the density of *Cedrela odorata* larger trees around 240 stems/ha (forest plantation type I), then a minimum spacing of 18 m between *Cedrela odorata* smaller trees could be adopted throughout the planting process. With this spacing, spontaneous species could better establish in order to improve plant diversity. But this strategy could evidently demand more labor effort. The second strategy (less costly) would consist to reduce the *Cedrela odorata* larger trees in plantations to 170 stems/ha (or less); which could favor the establishment of spontaneous species. This last management strategy favors a good canopy openness which is an important factor influencing understory richness and light to forest regrowths establishment (Lemenih & Teketay 2005; Carnus et al. 2006).

However, although resulting from the different analyzed processes, the suggested spacing of *Cedrela odorata* smaller trees and density of larger trees may not be optimal for many purposes. Indeed, these suggested spacing and densities may depend on sapling and seedlings mortality rates, ecological zones, given the great climatic variation in Côte d'Ivoire. Other studies could then, take into account more forest plantation sites (based on *Cedrela odorata*) with different biotics and abiotic parameters to confirm and improve the spacing and densities. We must consider also the associated species used for polyculture plantation.

To improve plant species outcomes of plantations established on previously forested lands, the Government Agency SODEFOR could also leave remnant native trees during harvest, managing plantations on longer rotations, avoiding intensive site preparation. Other factors will be necessary: the proximity to native forest (Goldman et al. 2008), the best adaptation of exotic species to increased light (Herault et al. 2004), canopy cover provided (Battles et al. 2001). Further experiment works and field inventories would help to clarify these points.

CONCLUSIONS

This study tested the relationships between forest regrowths distributions in plantations based on *Cedrela odorata*. For ecological characteristics, the main results shown lower native plant species richness and diversity related to the cutting and thinning activities. *Cedrela odorata* smaller trees abundance was higher when the density of the larger trees of the species was lower.

For spatial structure, the results shown an aggregated distribution of *Cedrela odorata* smaller trees. The clumped radius of these smaller trees was greater when the larger trees density was higher. The smaller trees of *Cedrela odorata* and other species have dependent spatial distributions; expressed by a spatial repulsion between the two groups up to a distance of 18 m in forest plantation with higher planting density. To improve biodiversity outcomes of plantations established, we recommend to SODEFOR a 170-stems/ha (or lower) of larger trees density of *Cedrela odorata*; this density will eliminate or reduce the spatial repulsion between the forest regrowths and smaller trees of this species. However, further experiment works and field inventories would help to clarify the suggested *Cedrela ododrata* larger trees density.

AUTHOR CONTRIBUTION

V.B.T.A. and K.A. contributed to the study conception and design. Material preparation, data collection and analysis were performed by the two authors. The first draft of the manuscript was written by V.B.T.A. and commented by K.A. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

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