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Assessing the invasive potential of *Azadirachta indica* and its effects on biodiversity in Delta of Saloum National Park, Senegal (West Africa)

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ABSTRACT: Forests represent a vital component of ecosystem services, offering significant benefits. However, these vital habitats are particularly vulnerable to the negative impacts of invasive species. In West Africa, *Azadirachta indica* has been introduced for timber production, the provision of shade, land restoration, etc. This species exhibits traits such as rapid growth, high seed production, etc., which may facilitate its establishment as an invasive species. The objective of this study is to evaluate the potential invasiveness of *A. indica* in the Delta du Saloum National Park, focusing on its abundance, temporal spread, and impact on woody species diversity. The data were collected through floristic inventories conducted in 2012, 2019 and 2022. The results indicated a consistent increase in the sites location, number and density of *Azadirachta indica* over the studied decades. This species demonstrates considerable capacity for natural regeneration, as evidenced by the predominance of young and diminutive individuals. The progressive dynamics of the species observed between 2012 and 2022 remain similar to those predicted for the next 10 years, providing information on future proportions with clear implications for woody flora. The presence of the species has been found to be associated with a decline in richness and diversity, as well as a change in the floristic composition of the forest. The findings of this study offer a management and control instrument that is timely, as it is being developed at a critical juncture when the proliferation of invasive species with severe ramifications typically occurs in an unanticipated manner.

KEYWORDS: Neem, invasive species, protected area, ecosystem dynamic, tree population.

1 BACKGROUND

Biological invasions are widely recognized as a major driver of forest ecosystem degradation and biodiversity loss worldwide [1]. Forest ecosystems play a crucial role in maintaining biodiversity, regulating climate, and supporting livelihoods [2]. However, these ecosystems are particularly vulnerable to potential invasive species due to their high levels of biological diversity [3], ongoing habitat fragmentation, and increasing anthropogenic pressures [4], [5]. Potential invasive species are non-native organisms that possess ecological traits such as rapid growth, high reproductive output, phenotypic plasticity, and efficient dispersal that enhance their ability to establish, spread, and negatively affect native forest communities [6].

In West Africa, among introduced tree species, *Azadirachta indica* A. Juss. commonly known as neem, has gained widespread importance for its socio-economic value but is increasingly suspected of exhibiting invasive behavior in certain forest and savanna-forest transition zones. Native to India, *Azadirachta indica* was extensively introduced across West Africa for shade provision, fuelwood, timber, medicinal uses, and land restoration purposes [7], [4]. Its ecological traits including high seed production, rapid juvenile growth, tolerance to drought and poor soils [8] and effective dispersal mechanisms confer a strong capacity for establishment and persistence [9], [10].

The invasive potential of multipurpose introduced tree species such as *Azadirachta indica* is often underestimated because of their socio-economic benefits. This utilitarian perception may delay ecological risk assessment, particularly in protected areas where introductions initially aim at restoration or shade provision. However, species valued for ecosystem services can simultaneously exert strong competitive pressure on native flora once established beyond managed contexts, leading to unintended ecological consequences [10], [4].

The presence of *Azadirachta indica* in natural forest ecosystems raises concerns regarding its potential impacts on native tree diversity and forest dynamics [11]. *Azadirachta indica* stands out for its remarkable physiological and morphological characteristics, which enable it to withstand and regenerate even in difficult conditions and after numerous cuttings [12]. Its rapid expansion capacity can lead

Azadirachta indica to become invasive in its environment that leads to competition between the species and local species. According to [13], the abundance of *Azadirachta indica* is synonymous with lower floristic richness and natural regeneration potential in woody plant communities. Studies have revealed that the introduction of *A. indica* has already led to the degradation of ancient *Faidherbia albida* parks and risks disrupting the ecological balance of ecosystems in the long term [14].

Such impacts are particularly pronounced in disturbed forests, where canopy openings facilitate the recruitment and spread of non-native species [15]. In Senegal, previous studies have reported the presence of *Azadirachta indica* in the local woody flora [9], [16] such as protected areas [17]. Fathala forest, an integral part of the Delta du Saloum National Park, is one of the protected areas in the Sudanese domain of Senegal, endowed with a rich woody flora that is, however, subject to threats from human disturbances [18], [19]. In the context of human disturbance, it is critical to assess the presence of species that may be considered potentially invasive, and their ecological implications, in order to ensure the sustainable management of protected areas, such as Fathala. Effective management in national parks requires an early detection of invasive species before they become established and cause significant ecological damage.

This study aims to assess the potential invasiveness of *Azadirachta indica* in the Fathala classified forest. We suppose *that Azadirachta indica* is (i) one the most abundant plant species of Fathala Classified Forest, (ii) becoming more and more present over time and (iii) it significantly influences the diversity of woody species in the forest. The objectives of this research are to (i) determine the abundance of *Azadirachta indica* in the Fathala classified forest, (ii) analyze the dynamics over time of *Azadirachta indica* in this forest, and (iii) assess the effect of *Azadirachta indica* population on the floristic diversity of the forest.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The Delta du Saloum National Park is located in central-western Senegal. It covers 500,000 hectares and is characterised by a wide variety of aquatic ecosystems [20]. It is also home to the Fathala Classified Forest, which is the main terrestrial part of this National Park, core of the Sine Saloum Biosphere Reserve (Figure 1). Classified in 1935, Fathala forest which covers 7,000 hectares is subject to a Sudanese climate with coastal influences. It is marked by two contrasting seasons: a dry season from November to June and a rainy season from July to October [21].

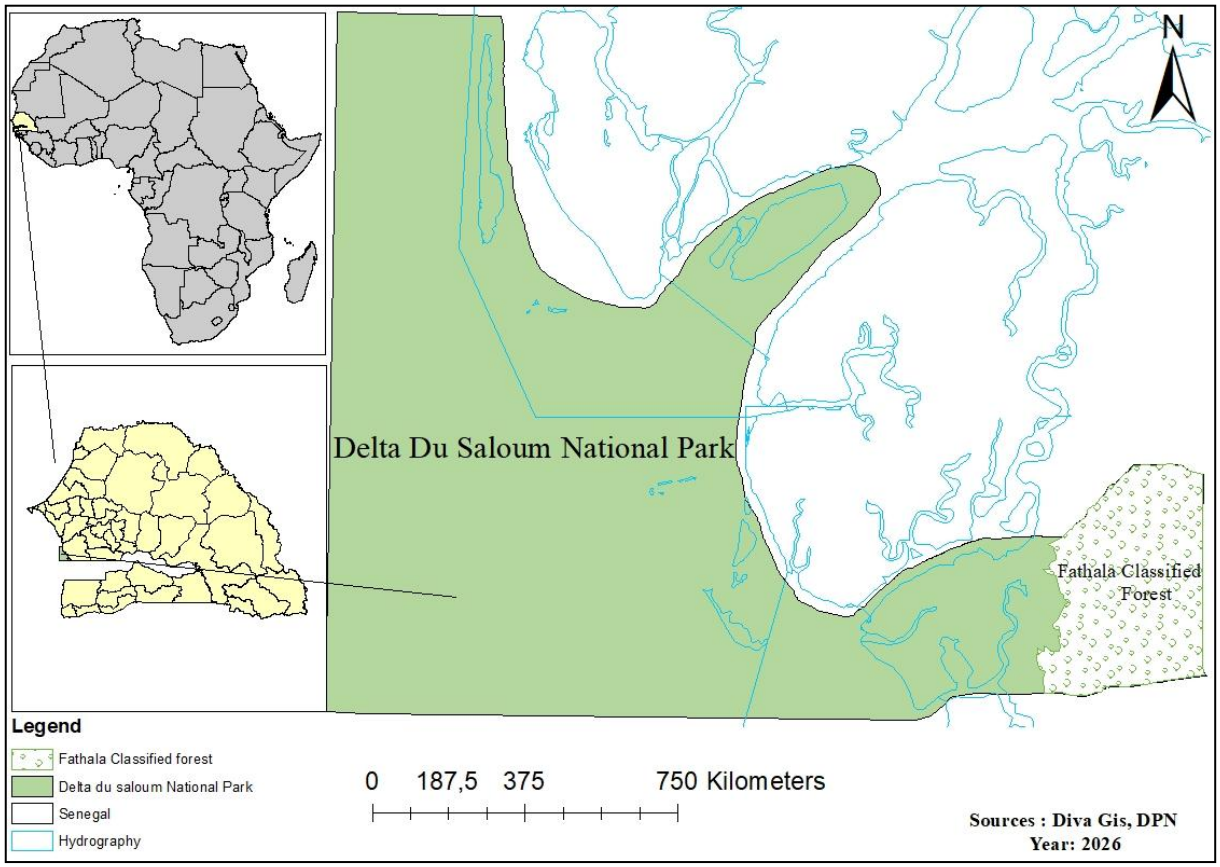

Fig. 1. Location map of the Fathala Classified Forest

2.2 ECOLOGICAL CHARACTERISTICS OF AZADIRACHTA INDICA

Azadirachta indica, which is more commonly known as *Neem* or Margousier, is a tree that is native to India [22]. Neem is a fast-growing, highly resilient tree with significant ecological and agricultural value, including natural pesticide production that modulates insect growth and appetite while exhibiting minimal toxicity towards beneficial organisms [23]). Its rapid growth, regeneration ability, and adaptability render it beneficial but also potentially invasive in certain regions. It is characterized by its rapid and extensive dispersal capacity, which enables it to dominate vast geographical areas [24]. The neem plant is distinguished by its evergreen nature, although it has been observed to undergo a process of leaf abscission during periods of drought. Its pinnate leaves measure 20–40 cm in length and are comprised of 20–30 serrated dark green leaflets. It is noteworthy that the young leaves exhibit a reddish to purplish hue [25]. The tree under consideration is capable of attaining a height of 15–20 m (in some cases, up to 40 m) with a crown diameter of up to 20 m. Its bark is characterized by deeply fissured, cream-colored, fragrant flowers that occur in axillary inflorescences comprising 150–250 flowers per 15–25 cm cluster [25]. Neem has been demonstrated to exhibit a high degree of regenerative capacity. The seeds of this plant are distinguished by their recalcitrant nature, which leads to a swift decline in viability. Fresh seeds have been found to have a germination rate of 70–95% [26], and the tree has been observed to regrow effectively after being cut due to its deep root system [27]. From an ecological perspective, Neem has been shown to exhibit significant resilience, with the capacity to adapt to a range of climatic and topographical conditions [28]. Neem is increasingly being regarded as invasive in certain regions, a consequence of its capacity for resilience and adaptability [24].

2.3 DATA COLLECTION

Floristic data were collected in 2012, 2019 and 2022 in the Fathala classified forest. Data collection is based on stratified random sampling [29], [30]. The forest area is divided into grids of 250 m x 250 m, based on a stratification using Landsat images [31]. Each stratum (vegetation type) is divided into grids of 250 m x 250 m and the number of grids was determined by the size of the strata. Grids exhibiting homogeneity in terms of vegetation type were selected randomly. Within each selected homogeneous grid, eight plots measuring 20 m x 20 m were installed randomly along the medians and diagonals of the grids. In each plot, all trees with a circumference of at least 9.5 centimeters at a height of 1.3 meters were encountered and their total height estimated. Trees with a circumference of less than 9.5 cm at a height of 1.30 meters above ground level are considered to be part of natural regeneration and have been enumerated. Identification of individuals was based on the flora of Senegal [32] and the book Trees, shrubs and lianas of West Africa [33].

2.4 DATA ANALYSIS

The analytical framework adopted in this study integrates descriptive, inferential and predictive approaches in order to capture both current patterns and future trajectories of invasion of *Azadirachta indica* and its effects on biodiversity. Such combined frameworks are increasingly recommended in invasion ecology, as they allow the identification of early warning signals while accounting for temporal inertia in population dynamics [1], [6], [34]. The frequency and density per year were calculated. Predictions were made using linear regression models, with 95% confidence intervals calculated. Thereafter, species richness and the Shannon index were calculated. Plots with and without *Azadirachta indica* were compared using non-parametric (Wilcoxon test). The results were then visualized using box plots, with p-values displayed to indicate the significance of the differences. Principal component analysis (PCA) was performed to explore the variation in floristic composition between plots with and without *Azadirachta indica*. PERMANOVA was applied to statistically test whether species composition differed significantly depending on the presence of the species. Simple and multiple linear regression models were used to predict changes in frequency, density, DBH and height over time. Confidence intervals (95%) were calculated for each prediction. The coordinates of the plots were then utilized to visualize *Azadirachta indica* spatial distribution over time through using mapping software (ArcGIS). All statistical analyses were performed using R Studio software.

3 RESULTS

3.1 STAND DENSITY AND STRUCTURE OF AZADIRACHTA INDICA

Figure 2 illustrates the evolution of the abundance and structure of *Azadirachta indica* between 2012 and 2022. The species exhibits continuous increase in both density and the number of individuals on an annual basis from 2012 to 2022 (Figures 2a and 2b). This trend is indicative of the species' gradual spatial expansion and an active regeneration as shown in Figures 2c and 2d. These two figures illustrate the distribution of DBH classes and that of the height of *Azadirachta indica* trees. This structure is characterized by a dominance of young trees, with a marked concentration of individuals in the small diameter classes (approximately 5 to 25 cm) and low height classes (5 to 10 m). Beyond this range, there is a rapid and drastic decrease in the size and height of the trees. These trends indicate a low representation of large-diameter and tall trees, becoming almost non-existent for diameters greater than 75 cm. This asymmetrical distribution indicates that *A. indica* stand possess significant natural regeneration potential.

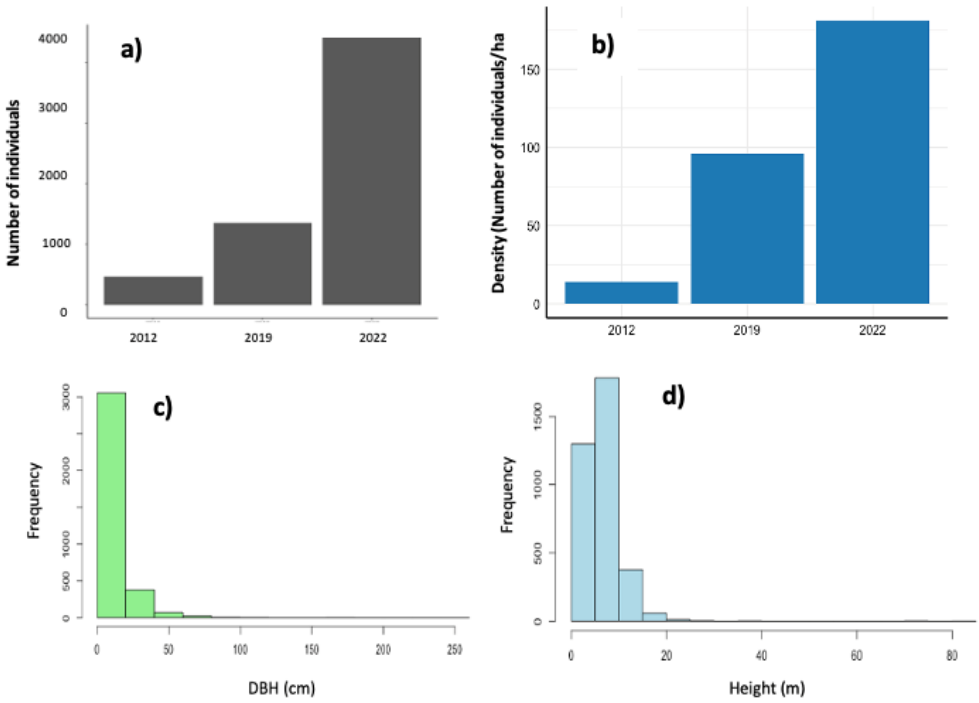

Fig. 2. Azadirachta indica stand density (a), total individuals numbers (b), DBH diameter classes (c) and height classes (d) from 2012 to 2022

3.2 RANGE EXPANSION OF AZADIRACHTA INDICA

Figure 3 illustrates the spatio-temporal dynamic of *A. indica* occurrence in Fathala forest from 2012 to 2022. The results indicate a continuous and accelerated increase in the species' presence over time suggesting a positive dynamic of occupancy and an expansion of its location sites in Fathala classified forest, main terrestrial part of Delta du Saloum National Park (Figure 3).

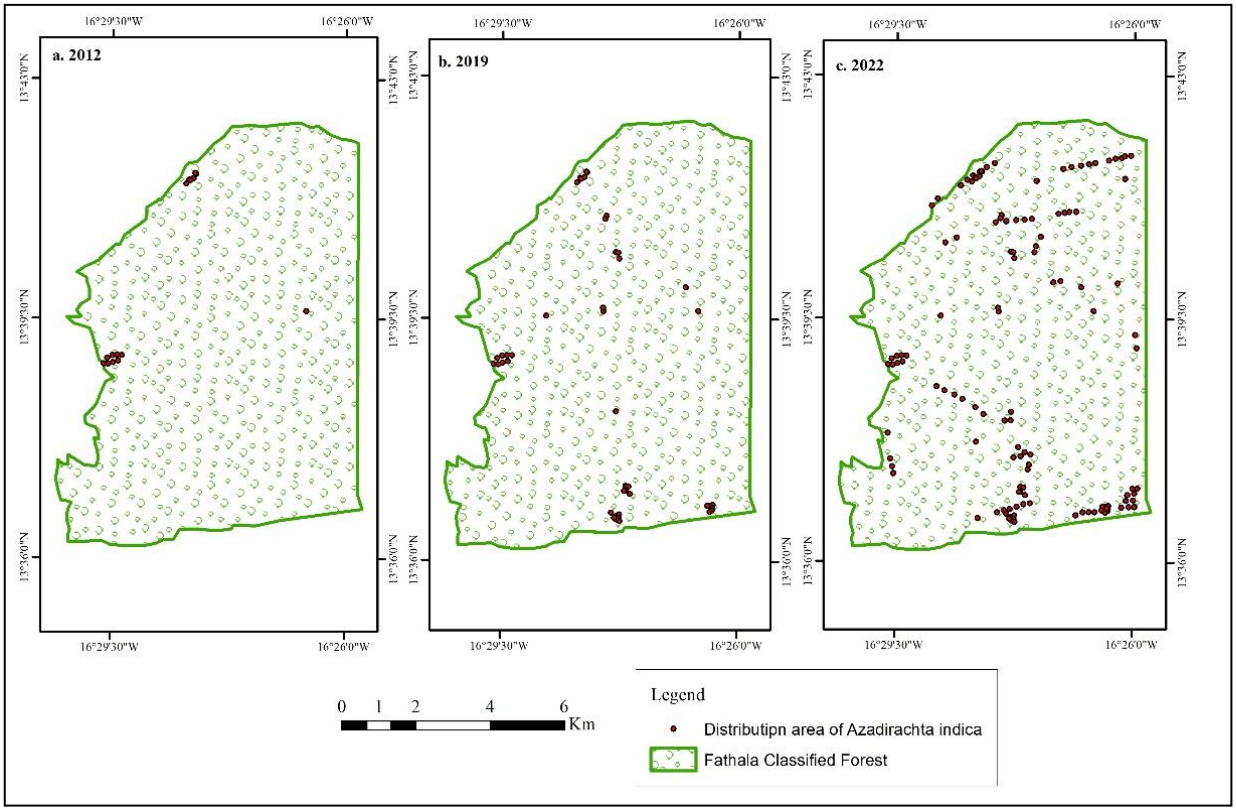

Fig. 3. Spatio-temporal dynamics of Azadirachta indica occurrence in Fathala forest from 2012 to 2022

Fig. 4. Young individuals (a) and mature tree (b) of Azadirachta indica in the Fathala forest (Source, URENE, 2026)

3.3 PREDICTING THE EXPANSION POTENTIAL OF AZADIRACHTA INDICA

The findings of the predictive analyses indicate a sustained expansion of the species marked by a gradual increase in its probability of occurrence on a yearly basis (Figure 5). This tendency is associated with a considerable contraction in the confidence interval to 95%, indicating a diminution in the uncertainty surrounding the estimations and an enhancement in the precision of the predictions. These predictions indicate a proliferation of the species in the short and medium term, reflecting the same dynamics observed over the last decades. All the structural parameters assessed show a gradual increase in their values between 2022 and 2032, despite some variations. The estimates predict a quasi-linear, fairly steady increase in the diameter and frequency of the *Azadirachta indica* species. However, the growth dynamics of density appear to be less pronounced between 2027 and 2030, when the increase in height is expected to slow slightly at the end of the period, suggesting a gradual future dynamic.

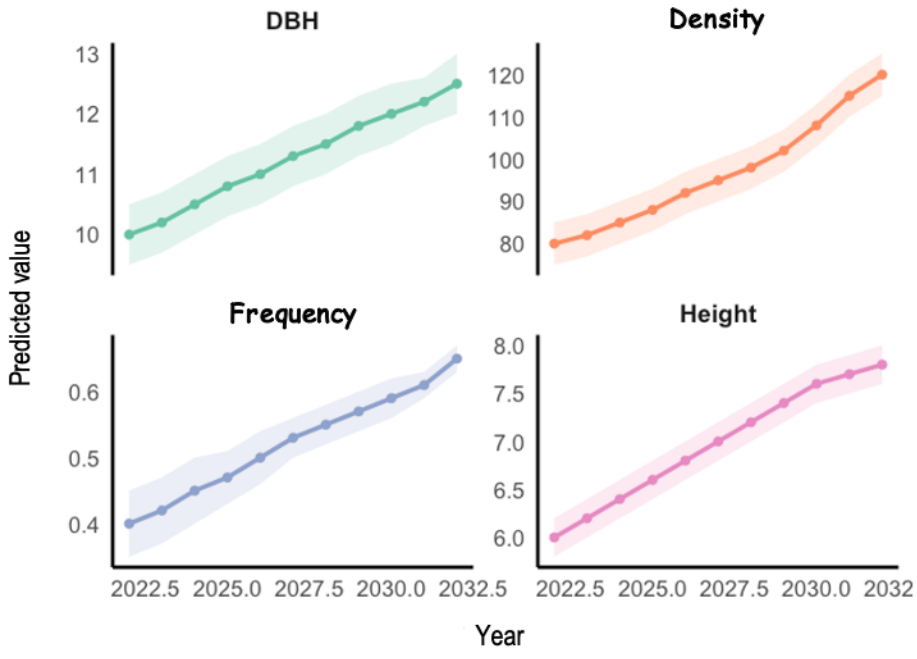

Fig. 5. Prediction of frequency, density, DBH and height of Azadirachta indica in the Fathala forest

3.4 EFFECTS OF AZADIRACHTA INDICA EXPANSION ON FLORISTIC DIVERSITY AND COMPOSITION

Figure 6 shows that the presence of *Azadirachta indica* in the Park's tree population significantly influences species richness and diversity (p-value <0.05). Species richness and Shannon diversity index are much higher in the absence of *Azadirachta indica* in the surveyed plots. This indicates a negative correlation between species abundance and the evolution of *A. indica* in the forest. Thus, the lowest values for species richness and Shannon diversity index are observed in the presence of *Azadirachta indica,* suggesting a decline in other species.

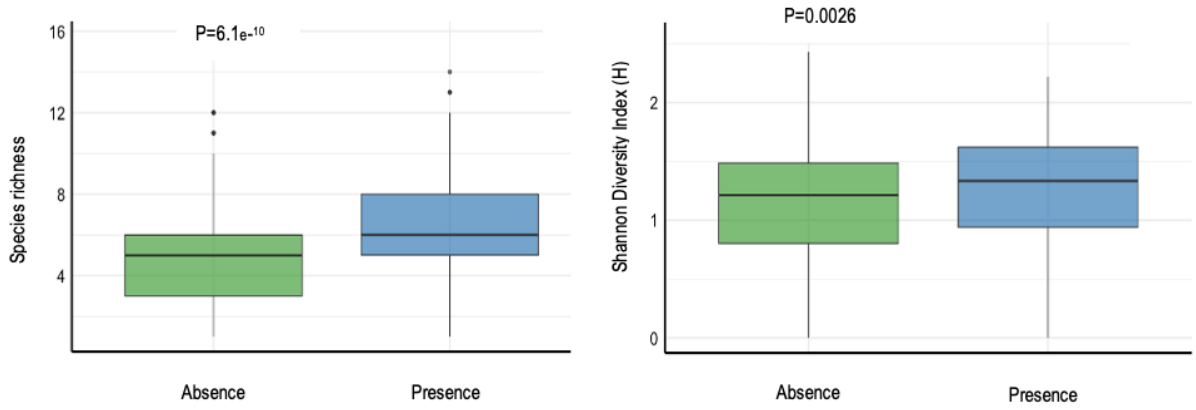

Fig. 6. Contribution of Azadirachta indica to variation in species richness (A) and diversity (B) in the forest

The analysis of figure 7 indicates that the floristic composition of the forest is influenced by the presence or absence of the species *A. indica*. In plots where *A. indica* is not present, species demonstrate comparable patterns as they evolve in close association, despite the presence of certain differences noted in some species. This group of species demonstrates a stronger affinity with axis 2. Conversely, the presence of *A. indica* has been associated with varying pattern among species. The latter are distributed around the two axes in a relatively dispersed pattern.

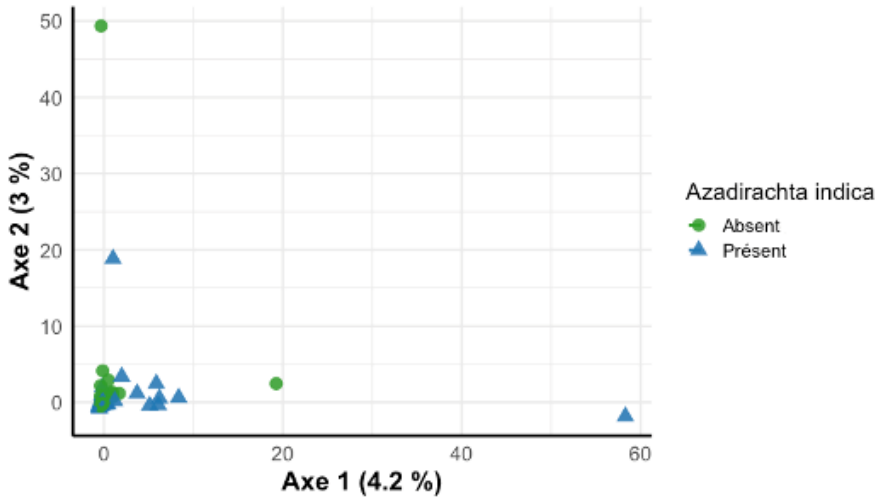

Fig. 7. Principal component analysis of floristic composition based on the presence and absence of Azadirachta indica

4 DISCUSSION

It is postulated that *Azadirachta indica* manifests an increase in abundance over time, attributable to its elevated reproductive capacity and competitive advantage over indigenous flora. It is further proposed that the spatial expansion of the species is accelerated in Fathala forest. It is anticipated that the presence of this species will have a negative effect on biodiversity, through competition for resources and alteration of habitat structure. The findings demonstrate a rapid expansion of the Neem and an adverse effect on native species in the Delta du Saloum National Park.

4.1 Evidence Of The Invasive Spread Of Azadirachta Indica

This study demonstrates a substantial expansion of *Azadirachta indica* within the Fathala classified forest in Delta du Saloum National Park. There is a demonstrable increase in both the quantity of individuals and the geographical location of species, thus reflecting a strong capacity for regeneration. Authors such as [9] have reported comparable trends in the natural region of Sine, located in the Groundnut Basin, where Neem is spreading rapidly to the point of being among the dominant species of woody vegetation. This species has been identified as the most prevalent invasive species in a total of thirteen forests that were surveyed by [24] in Togo. The rapid and substantial expansion of *Azadirachta indica* was cited by [35], who contended that the biological capabilities of the species enable it to prevail in stands and become invasive. This dynamic is further emphasised by the substantial and rapid rate of fruit production [25], [36]. Its abundance is also attributed to its effective seed dispersal mechanisms, namely barochory and ornithochory, in addition to its high fruit production [13]. It has been argued by some authors that the rapid spatial expansion of invasive species is dependent on their dispersal capabilities [34], which are influenced by the existence of long-distance dispersal events and the selection of dispersing phenotypes [37], [38].

Furthermore, the results of this study demonstrate that *A. indica* populations are predominantly young, with individuals ranging in diameter from 5 to 25 cm and in height from 5 to 10 m, with small individuals. This demographic structure, characterized by the prevalence of diameter and height classes, is indicative of a stable population in a phase of establishment and active expansion. The results obtained in this study are comparable to those previously reported by [39]. The latter researchers found that young stands, estimated to be approximately fifteen years of age, exhibited diameters ranging from 1.30 m to 9.9 cm, with heights ranging from 3.62 m to 5.36 m. The observed similarity in the results substantiates the notion that neem possesses a pronounced regenerative capacity and exhibits accelerated growth in analogous ecological settings. The preponderance of juveniles within this species was observed in the research conducted by [11] in the peanut basin.

Projections indicate a substantial increase in the frequency, density, diameter and height of *Azadirachta indica* stands by the year 2032. These findings are consistent with those of [40] who found that tropical and subtropical regions exhibit a propensity for an augmentation in the distribution range of *Azadirachta indica*. A considerable body of literature posits the hypothesis that such incursions are set to rise in the coming years [41], [42]. The capacity of Neem to disseminate rapidly may be attributed to its capacity to thrive in challenging soil and climatic conditions [22]. The results of the present study are analogous to those of [43], who utilised modelling to demonstrate the expansion of *Azadirachta indica* populations over time and space. This finding thus demonstrates the remarkable resilience of *A. indica* to climate change [43]. This high resistance to change is all the more remarkable given that the survival period of the species' seeds exceeds four months [8], highlighting its rapid germination and growth. These characteristics, when considered in conjunction with its capacity to reproduce in a variety of climatic conditions and its ability to adapt to diverse soil types, have given rise to concerns regarding its potential impact on local biodiversity, thus leading to its classification as an invasive species [28]. In order to limit their impact on biodiversity loss, predicting which forest species are likely to become invasive following their introduction represents a major challenge [42], [44], [45].

4.2 Ecological Implications Of Azadirachta Indica Invasion

The primary purpose of protected areas is the conservation and protection of biological resources. However, these areas continue to face various pressures. The issue of biological invasions, which primarily impact ecological functions, is becoming increasingly significant in national parks, which are the primary areas for species confinement. In the context of the Saloum Delta National Park, the ongoing proliferation of *Azadirachta indica,* an exotic species, poses a significant threat to native species conservation and ecological stability of this ecosystem.

The introduction of invasive species is a well-documented phenomenon with the potential to cause significant and long-lasting changes to local biodiversity. This study highlights a correlation between the proliferation of *A. indica* and the concurrent decline in species richness and diversity. As posited by [28], the introduction of *A. indica* has been demonstrated to have a deleterious effect on many ecosystems, characterized by a decline in species and a homogenization of natural habitats. This phenomenon can be attributed to the rapid occupation of the most fertile environments by *A. indica,* particularly in the vicinity of trees, which provide optimal conditions for species development [46]. Furthermore, *A. indica* exhibits low tolerance for other plant species in its immediate environment, a property that facilitates its establishment and replacement of local vegetation [47], [48]. The allelopathic effect of *A. indica* on native species could be a potential mechanism that hinders rooting, which could have long-term consequences for forest succession and balance [49]. As posited by the author, one of the consequences of this phenomenon of allelopathy is alterations in ecosystem processes and the structure of species communities.

This present study demonstrates also that the tree species composition in the Fathala forest is influenced by the presence of the *A. indica*. A comparable situation was documented by [11], who contend that the aggregative distribution of *A. indica,* in conjunction with its invasive character, which is deleterious to other plant species, signifies a shift in the floristic composition of the *Cordyla pinnata* agroforestry park. Previous studies such as those by [44] adopt a congruent perspective, elucidating that the incursion of woody species exerts a more substantial influence on the functionality of ecosystems and the preservation of biodiversity. for this purpose, [50] attribute

these facts not only to the importance of their biomass and their competitiveness with other biological types, but also to their undeniable potential to transform environments. However, it is important to consider that in this context of ecological change induced by the rapid expansion of *A. indica,* the emergence of various factors often acting in synergy is striking. The consequences of climate change and human disturbance are evident in the increased incidence of invasive species, resulting in the establishment of generalist invasive species that compete with local species populations, thereby weakening and undermining them [45], [51]. For instance, human activities are a primary driver of the adverse ecological impact of an invasive species, as they facilitate its ability to traverse barriers that previously constrained its dispersal and reproduction, resulting in accelerated population growth and rapid spatial expansion [1].

5 CONCLUSIONS

The combination of high frequency, high density, and significant expansion over time indicates that *Azadirachta indica* exhibits invasive characteristics in Fathala forest, the main terrestrial part of Delta of Saloum National Park. Predictive analysis suggests that the rate of increase in *A. indica* populations is likely to continue in the short to medium term, indicating an increase in density, frequency, DBH and height over the next decade. Furthermore, this study highlights a compromise in floristic diversity and composition due to the presence of *Azadirachta indica,* which could have ecological impacts on native species and forest future composition. In a context of management, these findings emphasize the importance of careful monitoring to control the expansion of *Azadirachta indica* and its negative effect on local biodiversity, particularly in this national park where the main aim is to protect native species. It is imperative that the authorities of the Delta du Saloum National Park develop clear management plans to control the expansion of *Azadirachta indica* before it causes significant and irreversible ecological damage. An understanding of a species' reproductive strategies is imperative for evaluating its dynamism and adaptability. The comprehension of these strategies enables the prediction of population growth rates and critical periods for their management.

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