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Ecological impacts of the invasion of five invasive plant species in agroecosystems of the Lôh-Djiboua region (Côte d'Ivoire)

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Abstract

Biological invasions represent an environmental issue associated with the movement of species beyond their natural distribution range. This phenomenon has intensified with the increased transportation of species over long distances, the intensification of trade, and the development of botanical gardens, horticulture, forestry, etc. This study aims to assess the potential impacts of *Chromolaena odorata*, *Euphorbia heterophylla*, *Fleischmannia microstemon*, *Porophyllum ruderale*, and *Synedrella nodiflora* on the plant communities of agroecosystems in the Lakota department (Côte d'Ivoire). Floristic inventories revealed that all these plants significantly influence the diversity of the agroecosystems they invade. However, this impact is more pronounced for plant communities invaded by *C. odorata* and *S. nodiflora*. Furthermore, the analysis of the current potential distribution shows that *C. odorata*, *E*. heterophylla, and *P. ruderale* have a high probability of presence across almost the entire Ivorian territory, while *F. microstemon* and *S. nodiflora* are confined to the ombrophilic regions of the country. Nevertheless, the distribution range of all these invasive species is projected to shrink by 2050.

Keywords: Invasive species; Agroecosystems; Potential distribution; Côte d'Ivoire

1. Introduction

The extensive expansion of species' distribution areas has given rise to a major ecological issue: biological invasions [14]. According to several studies, Desmoulins and Emeriau [21] ; Gentili *et al*., [32] ; Goudard [33], these invasive organisms threaten the most vulnerable species (reducing abundance and growth rates of native species, etc.), alter ecosystem functioning at various levels (reducing productivity, resilience, and nutrient availability, etc.), and disrupt biotic communities (loss of biodiversity and disturbance of trophic networks, etc.). At the community level, biological invasions can sometimes temporarily increase local species richness [49]. However, this increase is not considered beneficial to the environment, as it may eventually lead to the loss of endemic species or ecosystem dysfunction due to the high density and harmful effects of invasive species [6, 10, 13]. A well-known example is *Chromolaena odorata* (L.) R. M. King & H. Rob., which disrupts vegetation succession by suppressing certain stages during forest establishment. It hinders the development of native pioneer plants and depletes their seed banks [51]. In agriculture, the invasion of spontaneous plants can lead to yield losses, estimated at over 2.2 million tonnes per year in sub-Saharan Africa [58].

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In Côte d'Ivoire, 30 exotic plants (24 terrestrial and six aquatic) are considered invasive [52]. Among these, *Eichhornia crassipes* and *Chromolaena odorata* are deemed the most harmful. Additionally, in recent years, research has focused on the biology and ecology of plants such as *Eichhornia crassipes* (Mart.) Solms. [27], *Chromolaena odorata* (L.) R. M. King & H. Rob. [31], *Tithonia diversifolia* (Helsm.) A.Gray [39, 62], and *Porophyllum ruderale* (Jacq.) Cass. [45, 46]. These studies suggest that the invasive nature of a plant requires specific biological traits, such as rapid growth, high dispersal capabilities, and adaptability to challenging conditions. However, each of these studies focused on a single species without addressing the consequences on biological diversity. Knowledge of the potential impacts of plants is crucial for prioritising them and implementing effective prevention or control methods for each species [47]. Therefore, to combine control and prevention efforts, the evaluation of challenges and risks must adopt a more objective approach. With a predictive and functional perspective, this study aims to evaluate the potential ecological impacts of five invasive plant species in Côte d'Ivoire: *Chromolaena odorata* (L.) R. M. King & H. Rob. (Compositae), *Euphorbia heterophylla* L. (Euphorbiaceae), *Fleischmannia microstemon* (Cass.) R.M.King & H.Rob. (Compositae), *Porophyllum ruderale* (Jacq.) Cass. (Compositae), and *Synedrella nodiflora* (L.) Gaertn. (Compositae). Specifically, the objectives are to (i) evaluate the potential impacts of the five species on the floristic diversity of agroecosystems and (ii) determine their potential distribution.

2. Methodology

2.1. Data collection

2.1.1. Floristic inventory in invaded agroecosystems

Floristic data were collected through surface inventories conducted in 45 agroecosystems across the villages of Daligoulilié (30N 648995 / 197157), Kahioué (30N 647232 / 193063), and Ligrohoin (30N 648445 / 188215) within the Oparéko Canton, Lakota sub-prefecture. These include cassava, maize, and banana fields, young cocoa plantations, and rubber plantations (eight agroecosystems for each crop), as well as five rice paddies. In each habitat, 16 plots of 25 m^2 (5 m x 5 m) were laid out in parallel transects spaced 10 m apart. Each transect comprised four plots spaced 10 m apart.

In each plot, phytosociological surveys were conducted following the classical [12] method, modified by [25, 26]. This method assigns an abundance-dominance coefficient to each inventoried species (**Table 1**), reflecting the relative space occupied by the species' individuals.

Plant samples were identified using the works of Hawthorne and Jongkind [35], Hutchinson and Dalziel [37] and Johnson [41]. Identified samples were compared to reference specimens from the National Herbarium of Côte d'Ivoire (UCJ) at the National Floristic Centre, the Swiss Centre for Scientific Research (CSRS), and the online Herbarium of the Paris Natural History Museum (https://www.mnhn.fr/fr/collections/ensemblescollections/botanique/plantes-vasculaires). The classification of angiosperm families follows the fourth version of the APG system [7]. Scientific names and authors were updated using the African Plants Database, version 3.4.0 [3] and the International Plant Names Index [38].

Table 1 Correspondence between abundance-dominance coefficients (AD) and mean coverage values (MC) in percentage (%)

	Braun-Blanquet [11]	**Dufrêne [25, 26]**
Abundance-Dominance (AD)	Definition	Mean Coverage (RM) in %
5	Numerous individuals covering more than ¾ of the area	87.5
4	Numerous individuals covering ½ to ¾ of the area	62.5
3	Numerous individuals covering ¼ to ½ of the area	37.5
2	Abundant individuals covering 1/20 to ¼ of the area	15
1	Few individuals with low coverage (<1/20 of the area)	2.5
+	Rare individuals with very low coverage	0.2
r	Very rare individuals with negligible coverage	0.1

2.1.2. Data collection for potential distribution analysis

To analyse the potential distribution of invasive species, locations where C. odorata, *E. heterophylla*, *F. microstemon*, and *S. nodiflora* were collected across the Ivorian territory were identified using Aké Assi [5]. For *P. ruderale*, collection sites were identified through the herbarium of the Botany Laboratory at Nangui ABROGOUA University, as it is a recently introduced species in Côte d'Ivoire. Geolocation of these sites was conducted for each species, generating a matrix containing species and geographical coordinates of their collection sites. Based on this matrix, potential distribution maps for each species were generated using the Maximum Entropy Species Distribution Modelling software [53] or Maxent version 3.3.

2.2. Data analysis

2.2.1. Analysis of agroecosystem floristic diversity

Floristic composition of agroecosystems

The floristic composition encompasses species richness, geographical distribution, biological type, and morphological type of each collected plant. The biological types of the different species were defined according to Raunkiaer's [57] system, modified for tropical zones by Aké Assi [5]. The phytogeographical distribution of the species follows the classification established by Aké Assi [5]. These data were used to establish chorological, biological, and morphological spectra. The main interest of the biological spectrum, for example, is that it reflects vegetation structure and ambient environmental conditions [1]. The spectrum was also established to visualise, through the proportion of herbaceous and lianescent plants, the level of disturbance or openness of the environment [28, 44].

Estimation of agroecosystem floristic diversity index

The Shannon-Wiener diversity index [61] is one of the most commonly used indices to measure floristic diversity [60]. It quantifies species composition within a community based on the number of species and their abundance [30, 48]. According to these authors, diversity is considered low when H' is less than 3, moderate when H' ranges between 3 and 4, and high when H' is equal to or greater than 4. This index varies from 0 (a single species present) to log2S (all species present with the same abundance). The index is calculated using equation (1):

$$H' = -\sum_{i}^{n} Pi \log_2 Pi \qquad \text{..........}(1)$$

where $\boldsymbol{H'}$ *represents the Shannon index, ,* $\boldsymbol{Pi} = (\boldsymbol{ni}/\boldsymbol{N})$ *is the frequency of species i within the community, and* $\boldsymbol{N}$ *is the total number of collected plants.*

The calculation of the Shannon-Weaver index is accompanied by that of Piélou's equitability [54]. This index translates the way individuals are distributed among species. It reaches its maximum value when individuals are evenly distributed across species and varies from 0 (one species has a very high abundance) to 1 (all species have equal importance). It is determined using equation (2):

$$E = \frac{H'}{\log_2 S} \text{...............} (2)$$

where ***E*** *is equitability,* ***H'*** *is the Shannon-Weaver index, and S is the average number of species.*

Invasive plant communities were compared based on the Shannon index and equitability. This comparison aimed to determine which species had the most detrimental impact on plant diversity. One-way analysis of variance (ANOVA 1) was performed after verifying the normality and homogeneity of variables. This analysis was conducted using R software version 3.6.1 [56].

Analysis of community similarity in sampled sites

To assess similarity between floristic compositions of different invaded agroecosystems, a Non-Metric Multidimensional Scaling (NMDS) ordination analysis was applied to the species recurrence data. The closer two habitats are in terms of species composition, the closer their polygons appear on the graphical representation. Subsequently, an Analysis of Similarity (ANOSIM) was used to test the validity of the retained groups [15]. These analyses were conducted using PAST software version 3.11 [34].

Identification of indicator species in sampled communities

In this study, the analysis of indicator species was limited to species pairs, as suggested by De Cáceres and Legendre [19]. According to these authors, this approach minimises complexity in identifying indicator species, avoids an excessive number of possibilities that could reduce the reliability of the analysis, and ensures efficient processing. To achieve this, indicator species pairs within sampled plant communities were determined by calculating the Group Indicator Value index (Equation 3). The calculation was performed using R software version 3.6.1. Furthermore, 9999 permutations (Monte Carlo test, p < 0.05) were used to test the significance of the results.

$$\text{IndValGroupe k. Espèce j} = \text{Akj} \times \text{Bkj} \times 100 \qquad \ldots\ldots\ldots (3)$$

In this formula, **IndValGroup k.Species j** *represents the indicator value of species j in group k*, **Akj** *represents the specificity of species j in group k, while* **Bkj** *corresponds to the fidelity of species j to group k.*

2.2.2. Analysis of Potential Distribution of the Studied Species

To generate distribution maps for the studied species, a matrix containing species and their respective geographical coordinates was established. All these data, after being converted from Excel files into CSV format (semicolon separator), were processed using Maxent software, version 3.3 [53], to produce potential distribution maps. Environmental variables were obtained from WorldClim [36]. These variables span the period from 2000 to 2050, comprising 19 factors that influence species distribution. The software performs 1000 iterations before predicting potential species ranges, considering the most determining environmental variables for each species.

Finally, Quantum GIS (QGIS) software version Lyon 2.1.2.3 was used to generate maps delineated according to the geographical boundaries of Côte d'Ivoire. The obtained results provide valuable insights into species ecology and enable more reliable predictions.

3. Results

3.1. Plant diversity in invaded agroecosystems

3.1.1. Species richness observed, biogeographical distribution, and morphological types

A total of 263 plant species were recorded across all sampled agroecosystems. These species belong to 191 genera distributed among 67 families, the most numerous being the Fabaceae (37 species), Rubiaceae (20 species), Apocynaceae (17 species), Compositae and Poaceae (14 species each), Combretaceae, Euphorbiaceae, and Malvaceae (11 species each), Sapindaceae (eight species), and Commelinaceae and Lamiaceae (seven species each). This flora is dominated by herbaceous plants (38.78%), followed by lianescent plants (35.74%) and arborescent plants (25.48%).

Furthermore, the phytogeographical distribution indicates that more than half of the species (54.37%) belong to the Guineo-Congolian region (GC). Additionally, 18 species (6.84%) are restricted to West Africa (GCW), and two species are endemic to Côte d'Ivoire (*Leptoderris miegei* Aké Assi & Mangenot and *Salacia columna* N. Hallé).

The agroecosystems invaded by *C. odorata*, *E. heterophylla*, *F. microstemon*, *P. ruderale*, and *S. nodiflora* recorded 113, 88, 152, 137, and 130 plant species, respectively. Thus, environments dominated by *F. microstemon* exhibited the highest species count, followed by those with *P. ruderale* and *S. nodiflora*. The environments with the lowest species counts were those invaded by *E. heterophylla*.

3.1.2. Variability in diversity index across different agroecosystems

The values of biocoenotic indices (Shannon diversity and Piélou's evenness) were very low across all sampled environments (Table 2). However, these two indices varied significantly between plant communities (p < 0.001). Agroecosystems invaded by *C. odorata* and *S. nodiflora*, which exhibited the lowest biocoenotic indices, were the least diverse plant communities.

Table 2 Biocoenotic indices of invaded environments

	Shannon-Wiener Index	**Piélou's Evenness**
Environments with *Chromolaena odorata*	0.41 ± 0.03[a]	0.2 ± 0.01[a]
Environments with *Euphorbia heterophylla*	0.79 ± 0.03[bc]	0.4 ± 0.01[c]
Environments with *Fleischmannia. microstemon*	0.67 ± 0.04[b]	0.3 ± 0.02[b]
Environments with *Porophyllum. ruderale*	0.88 ± 0.06[c]	0.41 ± 0.02[c]
Environments with *Synedrella nodiflora*	0.46 ± 0.03[a]	0.22 ± 0.01[a]
Paramètres statistiques	*F=20.02*	*F=21.49*
	p<0.001	*p<0.001*

3.1.3. Floristic affinity of the different sampling environments

A global comparison of communities based on their species composition, using the Non-Metric Multidimensional Scaling (NMDS) method, shows that the sampled communities are distinct (Figure 1). The Analysis of Similarity (ANOSIM) between the five communities indicates an overall floristic similarity of 30.29% (R = 0.98; p = 0.0001), which is below 50%.

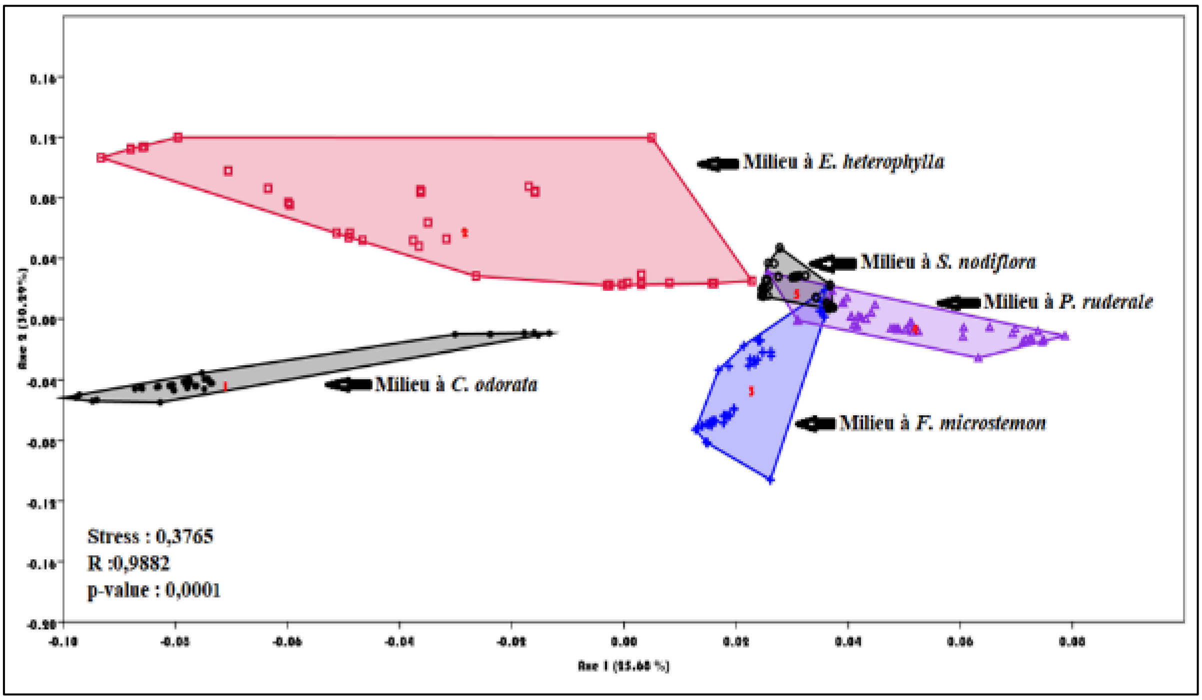

Figure 1 Floristic similarity of the sampled plant communities using NMDS
The polygons represent the sampled plant communities, while the points represent the survey plots

3.1.4. Plant associations within the sampled communities

An analysis of floristic surveys shows that *C. odorata*, *Euphorbia heterophylla*, *Fleischmannia microstemon*, *Porophyllum ruderale*, and *Synedrella nodiflora* are associated with three, eight, five, six, and one species, respectively (Table 3), with significant indicator values (IndVal > 0.5). The various species pairs formed exhibit both specificity and fidelity values greater than 0.5.

Table 3 Indicator Value (IndVal) of taxon combinations with the studied species

Taxon	**A**	**B**	**IndVal**	**p**	**Sig**
Environments with *Chromolaena odorata*					
Chromolaena.odorata + Axonopus.compressus	0.982	0.583	0.757	0.001	***
Chromolaena.odorata + Desmodium.adscendens	0.963	0.52	0.708	0.001	***
Chromolaena.odorata + Mallotus.oppositifolius	1	0.5	0.707	0.001	***
Environments with *Euphorbia heterophylla*					
Euphorbia heterophylla + Mitracarpus scaber	0.935	0.791	0.861	0.001	***
Euphorbia heterophylla + Salacia owabiensis	0.755	0.937	0.841	0.001	***
Euphorbia heterophylla + Ageratum conyzoides	0.998	0.687	0.828	0.001	***
Euphorbia heterophylla + Synedrella nodiflora	0.982	0.666	0.809	0.001	***
Euphorbia heterophylla + Pueraria phaseoloides	0.646	0.604	0.625	0.001	***
Euphorbia heterophylla + Digitaria horizontalis	0.591	0.645	0.618	0.001	***
Euphorbia heterophylla + Passiflora foetida	0.696	0.52	0.602	0.001	***
Euphorbia heterophylla + Phyllanthus amarus	0.335	0.52	0.418	0.007	**
Environments with *Fleischmannia. microstemon*					
Fleischmannia microstemon + Synedrella nodiflora	0.918	0.729	0.818	0.001	***
Fleischmannia microstemon + Porophyllum ruderale	0.741	0.895	0.815	0.001	***
Fleischmannia microstemon + Rauvolfia vomitoria	0.716	0.5	0.599	0.001	***
Fleischmannia microstemon + Mallotus oppositifolius	0.681	0.5	0.584	0.001	***
Fleischmannia microstemon + Centrosema pubescens	0.652	0.52	0.583	0.001	***
Environments with *Porophyllum. ruderale*					
Porophyllum ruderale + Rottboellia cochinchinensis	0.855	0.875	0.865	0.001	***
Porophyllum ruderale + Synedrella nodiflora	0.868	0.77	0.818	0.001	***
Porophyllum ruderale + Mitracarpus scaber	0.952	0.604	0.758	0.001	***
Porophyllum ruderale + Pueraria phaseoloides	0.869	0.604	0.725	0.001	***
Porophyllum ruderale + Centrosema pubescens	0.595	0.583	0.589	0.001	***
Porophyllum ruderale + Mallotus oppositifolius	0.514	0.625	0.567	0.001	***
Environments with *Synedrella nodiflora*					
Synedrella nodiflora + Chassalia kolly	0.617	0.708	0.661	*0.001*	***

(A = Specificity, B = Fidelity, Sig. = Significance level); Significance codes: 0 ***' 0.001 **' 0.01 `*' 0.05.

3.2. Potential distribution of the studied plants

The present study on potential distribution shows that *C. odorata*, *E. heterophylla*, and *P. ruderale* have a relatively high probability of presence across almost the entire Ivorian territory, whereas *F. microstemon* and *S. nodiflora* are confined to the ombrophilous sector of the country. However, the distribution range of all these invasive species is expected to decline by 2050, with an increase in the density of *E. heterophylla* in the agroecosystems it will occupy (Figure 2).

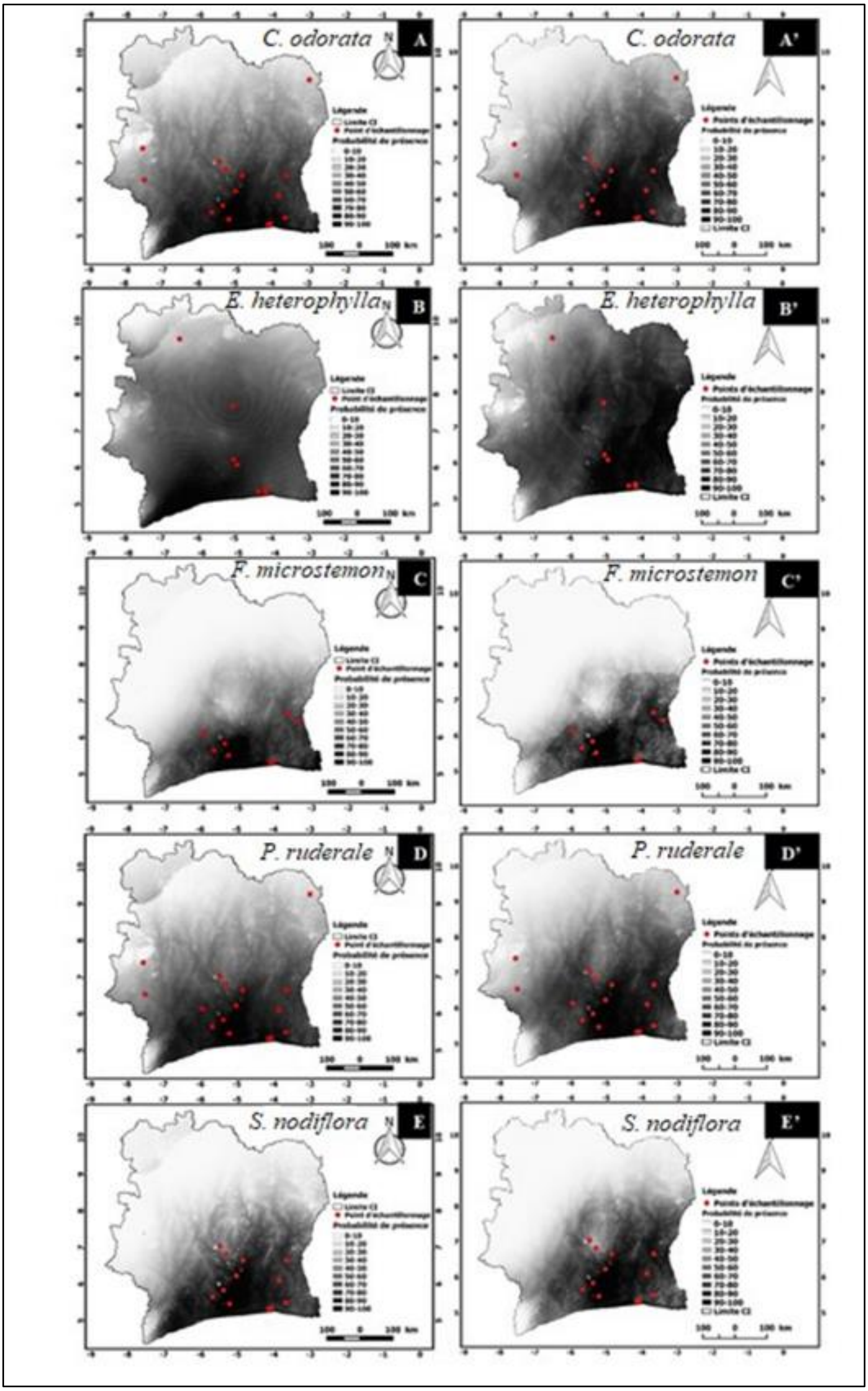

Figure 2 Potential distribution map of the five studied plant species
A, B, C, D, and E: respective present potential distribution; A', B', C', D', and E': respective future potential distribution

4. Discussion

Chromolaena odorata, Euphorbia heterophylla, Fleischmannia microstemon, Porophyllum ruderale, and *Synedrella nodiflora* are five invasive plant species found in agroecosystems in Côte d'Ivoire [24, 52]. However, according to several authors such as Evangelista [29], and Pinar [55], Vilà *et al*. [63],), biological invasions induce ecological disturbances that propagate at all levels of biological organisation within the recipient ecosystems. For instance, *Rhododendron ponticum* L. significantly reduces the diversity of forest patches it invades [18].

In this case study, research findings indicate that species richness varies depending on the sampled environments. Indeed, the highest number of plant species (152 species) was recorded in communities invaded by *F. microstemon*, whereas those invaded by *E. heterophylla* were the least species-rich (88 species). This variation in floristic composition may be explained either by the specific ecological conditions of each sampled environment or by the increased use of herbicides in certain areas. According to Déat [20], weed flora is specific to ecological parameters and agricultural practices. Mangara *et al*. [50] also affirm that intensive and regular herbicide use reduces floristic diversity by selectively eliminating certain weeds.

The most representative botanical families across all sampled plant communities are the Fabaceae, Rubiaceae, Compositae, Euphorbiaceae, Poaceae, Apocynaceae, and Malvaceae. These families are among the world's major weed families [43]. However, the Fabaceae family contains the highest number of species recorded in each environment. This dominance of Fabaceae is not unique to this study, as Diouf *et al*. [22] also reported their prevalence in the weed flora of cotton crops in Eastern Senegal and Upper Casamance. Moreover, according to Aubréville [8], the dominance of Fabaceae is common in most tropical zones.

Furthermore, the most widespread morphological types in the studied agroecosystems are herbaceous species, followed by liana species. The predominance of herbaceous and liana species is explained by their higher number of viable seeds in the understorey of agroecosystems [44]. These are also pioneer species, meaning they are the first to colonise disturbed environments [42, 64]. Additionally, their typically heliophilous nature at all stages of development (seedlings, young trees, mature trees) [6] enables them to thrive in open environments. Consequently, herbaceous and liana species are the best adapted to agricultural environments, as they have short life cycles, high seed production capacity, and significant germination potential. Indeed, according to Ipou Ipou [40], herbaceous plants take advantage of any opening in the forest or clearing to establish themselves and are capable of regenerating and persisting in agroecosystems.

The sampled plant communities exhibit low biocenotic indices (Shannon index and Piélou's evenness), suggesting they are not highly diverse. The evenness indices close to zero indicate the dominance of certain species in these environments. This suggests that the five species (*C. odorata, E. heterophylla, F. microstemon, P. ruderale*, and *S. nodiflora*), which have the highest mean coverage (above 70%) in the sampled agroecosystems, are the species that influence their diversity. Indeed, any invasive plant species has a negative impact on local flora, leading to biodiversity loss, disruption of natural succession, and facilitation of other invasive species' establishment [4]. Similar observations were made by Adingra and Kassi [2] regarding *C. odorata*. According to these authors, *C. odorata* is capable of forming impenetrable thickets reaching up to 3 metres high, with nearly 100% coverage.

However, the results show a significant difference between the diversities of the plant communities. The least diverse environments are those invaded by *C. odorata* and *S. nodiflora*, as they have the lowest Piélou's evenness values (0.2 ±0.01 and 0.22 ±0.01). This could be due to the versatility of these two species. Indeed, these plants allocate resources simultaneously towards growth, reproduction, and defence, whereas the other three species allocate resources only towards growth and reproduction [23]. *C. odorata* and *S. nodiflora* may therefore have a higher competitive ability than the other species. Moreover, the dense thickets formed by these species on fertile soils in humid areas prevent light from reaching the ground [2]. As a result, this reduces the germination potential of seeds and the growth of other plants in their habitat. According to Combes *et al*. [17], light plays a crucial role in fundamental plant development processes such as germination, growth, and flowering. The ability of *C. odorata* and *S. nodiflora* to allocate resources towards growth, defence, and thicket formation is likely the main reason for the reduction in the number of associated species. Indeed, plant communities evolve based on available light [9].

Thus, this study reveals that *C. odorata* is generally associated with three plant species (*Axonopus compressus, Desmodium adscendens*, and *Mallotus oppositifolius*), while *S. nodiflora* is associated with only one species (*Chassalia kolly*). In contrast, the other three species are typically accompanied by more than five plant species. The thickets formed by *C. odorata* and *S. nodiflora* suggest that the associated weeds are sciaphilous species, meaning they can grow in vegetation with low light penetration.

Moreover, the current potential distribution study shows that *C. odorata, E. heterophylla*, and *P. ruderale* have a high probability of presence across the entire Ivorian territory. This suggests that these plants have a broad ecological amplitude, meaning they can adapt to varying edaphic and abiotic factors. Species with a wide spatial distribution also reproduce easily in different climates, vegetation types, and soils. For example, *C. odorata*, like most weeds, has a common characteristic: it thrives on a wide range of tropical soils (pH 4 to 8) and adapts to different climates [16]. Kpla *et al*. [45] showed that *P. ruderale* occupies 71.64% of Côte d'Ivoire's territory.

In contrast, *F. microstemon* and *S. nodiflora*, although invasive in Côte d'Ivoire, have a very low probability of presence in the mountainous western and Sudanese sectors of the country. These species likely have a narrower ecological amplitude, which may be due to several factors such as climatic variation, soil factors, and human activities.

According to Schnell [59], many species once had much larger ranges but failed to adapt to rapid climatic changes, which could explain their absence in certain areas. Moreover, the current humid equatorial climate in Côte d'Ivoire is highly favourable for the development of these five species. Assuming that current conditions are optimal for these ecotypes, a reduction in rainfall could make the currently highly favourable regions (humid equatorial zones) less suitable by 2050.

5. Conclusion

This study has shown that *Chromolaena odorata, Euphorbia heterophylla, Fleischmannia microstemon, Porophyllum ruderale*, and *Synedrella nodiflora* strongly influence the diversity of the agroecosystems they invade. However, this impact is most significant in plant communities invaded by *C. odorata* and *S. nodiflora*. Additionally, these two invasive species, due to their versatility in resource allocation and dense thicket formation, are associated with very few species.

Moreover, the current potential distribution study shows that *C. odorata, E. heterophylla*, and *P. ruderale* have a relatively high probability of presence across almost the entire Ivorian territory, whereas *F. microstemon* and *S. nodiflora* are confined to the ombrophilous sector of the country. However, by 2050, all these invasive species are expected to see a decline in their distribution range, with an increase in their density within invaded agroecosystems. Consequently, they will have greater ecological and agronomic impacts in their respective distribution areas.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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