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Expansion of the extent of occurrence and potential distribution of the exotic invasive species *Enneapogon cenchroides* (Roem. & Schult.) C.E. Hubb. in Northeast Brazil

Expansão da extensão de ocorrência e da distribuição potencial da espécie exótica invasora *Enneapogon cenchroides* (Roem. & Schult.) C.E. Hubb. no Nordeste do Brasil

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Enneapogon cenchroides (Roem. & Schult.) C.E. Hubb. is an herb native from Africa to India. In Brazil, this species invades areas of the Caatinga in the states of Pernambuco and Bahia. Its ability to affect the germination and development of other species makes it a threat to native flora. This article reports the first record of the invasion of *E. cenchroides* in the state of Sergipe and aims to (i) map the current distribution of this species in Northeast Brazil through Extent of Occurrence (EOO) and (ii) determine its potential distribution in the region through Species Distribution Modeling (SDM). The record of *E. cenchroides* in Sergipe was carried out in a riparian zone in the municipality of Canindé de São Francisco. Georeferenced points of *E. cenchroides* were obtained in its native and invaded environment. The points located in Brazil were used to delimit its EOO through the convex polygon. All points were used to develop the SDM through the Maxent, ANN, GLM, and CTA algorithms. With the new record in Sergipe, the EOO of *E. cenchroides* reached 124,145 km², a value 87.32% higher than that obtained in its first evaluation. According to the SDM, the areas of greatest suitability (0.60–1.0) were concentrated in the states of Bahia, Sergipe, Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte, mainly in the Caatinga. The results indicate that *E. cenchroides* has been invading new areas since its initial introduction. Furthermore, the climatic suitability in Northeast Brazil may favor its spread in new areas.
Keywords: biological invasion, Caatinga, species distribution models.

Enneapogon cenchroides (Roem. & Schult.) C.E. Hubb. é uma erva nativa da África até a Índia. No Brasil, essa espécie invade áreas da Caatinga nos estados de Pernambuco e Bahia. Sua capacidade de afetar a germinação e o desenvolvimento de outras espécies faz dela uma ameaça à flora nativa. Este artigo reporta o primeiro registro da invasão de *E. cenchroides* no estado de Sergipe e tem como objetivos: (i) mapear a distribuição atual dessa espécie no Nordeste do Brasil por meio da Extensão de Ocorrência (EOO) e; (ii) determinar sua distribuição potencial na região através da Modelagem de Distribuição de Espécies (SDM). O registro de *E. cenchroides* em Sergipe foi realizado em uma zona ripária no município de Canindé de São Francisco. Foram obtidos pontos georreferenciados de *E. cenchroides* em seu ambiente nativo e invadido. Os pontos localizados no Brasil foram utilizados para delimitar sua EOO através do mínimo polígono convexo. Todos os pontos foram usados para elaboração do SDM por meio dos algoritmos Maxent, ANN, GLM e CTA. Com o novo registro em Sergipe, a EOO de *E. cenchroides* alcançou 124.145 km², um valor 87,32% superior ao obtido em sua primeira avaliação. De acordo com o SDM, as áreas de maior adequabilidade (0,60-1,0) se concentraram nos estados Bahia, Sergipe, Alagoas, Pernambuco, Paraíba e Rio Grande do Norte, principalmente na Caatinga. Os resultados indicam que *E. cenchroides* está invadindo novas áreas desde sua introdução inicial, além disso, a adequabilidade climática no Nordeste brasileiro pode favorecer sua dispersão em novas áreas.
Palavras-chave: invasão biológica, Caatinga, modelos de distribuição de espécies.

1. INTRODUCTION

Biological invasion is a process that has led to numerous environmental impacts, such as a reduction in native species diversity and the simplification of biota [1, 2]. The impacts caused by invasive non-native species result in economic losses and a decrease in the provision of ecosystem services worldwide [1-3]. In this context, recording new occurrences of an invasive non-native species can provide important information about its ecology and support control efforts [4]. Furthermore, such records can be essential for understanding large-scale invasion dynamics [5]. However, Brazil still lacks information on the distribution of several non-native species.

Understanding the distribution patterns of invasive non-native species in invaded environments is a fundamental step in formulating control and management strategies. In this context, the Extent of Occurrence (EOO) can represent an important tool. EOO can be defined as the smallest continuous imaginary area that can be delineated to encompass all known records of a species [6]. This metric is used to assess the spatial distribution of areas occupied by a species and to categorize it according to its risk of extinction [7]. In the context of biological invasions, the increase in a species' EOO over the years can provide information about the expansion of its distribution [8-10]. Thus, EOO can provide highly relevant information about the spread of an invasive non-native species.

Another tool that can provide important information about the distribution of invasive non-native species is Species Distribution Modeling (SDM). This technique correlates species occurrence records with environmental variables (e.g., precipitation and temperature) to predict suitable environmental conditions through models that can be projected in geographic space [11]. In the field of biological invasions, SDM-generated models are used to characterize the niche of invasive non-native species [12], project the effects of climate change on their distributions [13], and predict invasion risk [14]. Additionally, these models can support the development of public policies [15] and control and management actions for these species [16, 17].

Enneapogon cenchroides, popularly known as Feathergrass and nine-awned grass, is an annual or perennial herbaceous species from the Poaceae family. Its height varies between 15-100 cm, erect or semi-erect, densely covered with glandular glands. It has flat leaves, often involute, ligules with a row of short hairs. Its inflorescence is in a dense panicle [18]. It has solitary spikelets with 3 flowers: a single fertile flower with 9 edges, an upper glume generally with 3 nerves, and a lower glume with 5 to 7 nerves [18]. Its dispersion is anemochorous [19]. This species is native to the savanna regions from Africa to India [20-25]. Currently, there are records of biological invasions in the United States, Spain, and Brazil [25, 26]. In Brazil, this species occurs in the Dry Forest (Caatinga) domains of the states of Pernambuco and Bahia [19, 26]. Some characteristics that favor its invasive behavior include its adaptability to different soil types and conditions [18], as well as its ability to affect the germination and development of other species [19].

This invasive non-native species was recorded for the first time in the Caatinga in 2012 [27]. Some authors speculate that its introduction may have occurred accidentally through aquaculture techniques in the 1970s by the former Companhia de Desenvolvimento do Vale do São Francisco (Codevasf) [27]. Since then, some studies have been conducted recording the species on river islands of the São Francisco River [28], in ruderal, agricultural environments, and degraded natural sites in the Caatinga [29]. However, little is known about its current and potential distribution in the Caatinga and other ecosystems of Northeast Brazil. Thus, this article reports the first record of the invasion of *E. cenchroides* in the state of Sergipe and aims to (i) map the current distribution of this species in Northeast Brazil through EOO and (ii) determine its potential distribution in the region through SDM.

2. MATERIAL AND METHODS

2.1 First record in Sergipe state

The occurrence of *E. cenchroides* in Sergipe was recorded in the municipality of Canindé de São Francisco, in a riparian zone adjacent to the SE-303 highway (9°38'08.5"S; 37°47'23.3"W), classified as a Protected Area. Individuals of the species were photographed (Figure 1), collected, and sent to the Herbarium of the Federal University of Sergipe (ASE), São Cristóvão (SE). To confirm whether this species had already been collected in Sergipe, we reviewed the literature and searched the Global Biodiversity Information Facility (GBIF) [24] and speciesLink [30] databases. The identification of the species was validated by an expert in the family. The taxonomic classification followed the APG IV system [31] and the authors' spelling followed the Flora e Funga do Brasil [26].

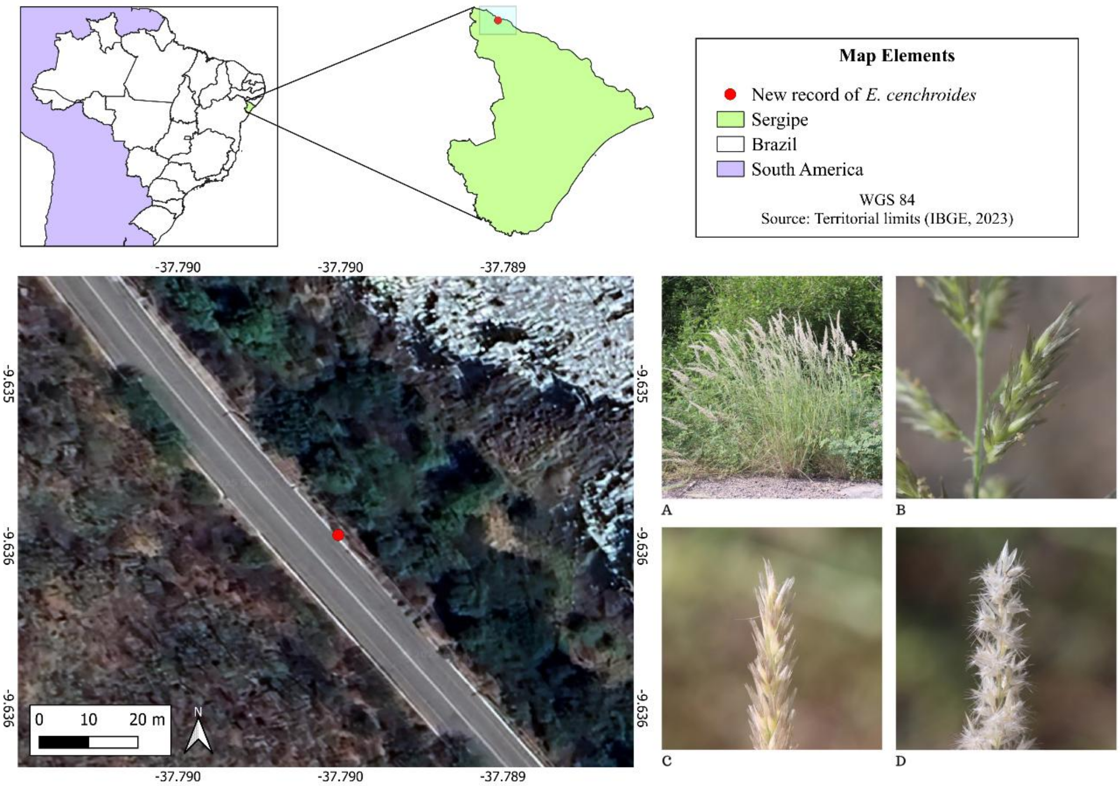

Figure 1: Collection site of Enneapogon cenchroides *(Roem. & Schult.) C.E. Hubb. in the riparian zone of Canindé de São Francisco, Sergipe, Brazil. The photos represent: a) general view of the species; b) spikelets with inflorescence; c) spikelets; d) dense panicle.*

2.2 Extent of Occurrence

Initially, we obtained all georeferenced occurrence points of *E. cenchroides* available in the online databases GBIF [24] and speciesLink [30], regardless of their region of origin (native or invaded), resulting in a dataset of 1,004 records. Subsequently, we created a set containing only the points located in Brazil, totaling 24 occurrences after removing duplicate points and those located in water bodies. This set was used to calculate the Extent of Occurrence (EOO). In this study, we used the Minimum Convex Polygon to calculate the EOO, which corresponds to the smallest polygon that contains all occurrence records of a species in such a way that none of its internal angles exceed 180 degrees [6]. Thus, the total area of this polygon represents the EOO of the studied species [adapted from 7]. To create this polygon, we used the "Minimum Bounding Geometry" function in QGIS 3.32.1 [32].

2.3 Species Distribution Model (SDM)

For the development of the models, we used the initial set of occurrences (native and invaded areas) of *E. cenchroides* obtained from GBIF [24] and speciesLink [30] in the previous step

(Figure 2). This approach encompassed all variations of its climatic niche [33]. To minimize the noise in the models caused by sampling issues with occurrences [34], duplicate coordinates were removed, along with those located in capitals, cities, water bodies, and areas near biodiversity institutes. To avoid overfitting in the models due to the disproportionate number of records between our area of interest (Northeast Brazil) and other environments where the species occurs [33], we chose to perform a rarefaction with a radius of 50 km [15, 35] using the “spThin” package [36] through the software R 2023.06.1 [37]. This also reduced the likelihood that the raster cell of the climatic variable would contain more than one occurrence of the species [38, 39]. As a result of these steps, the number of records used for modeling was 328 points (Figure 2).

The climatic variables used for the analysis were obtained from WorldClim 2.1 [40]. To eliminate variables with high collinearity, we performed a Spearman correlation analysis [41], selecting only the variables with low correlation values (i.e., ≤ 0.7): Bio 3 (Isothermality), Bio 10 (Mean Temperature of Warmest Quarter), Bio 12 (Annual Precipitation) and Bio 15 (Precipitation seasonality). The ecoregions where the species occurs were used to define the calibration area of the model [42; Figure 2]. After that, the generated model was projected onto the Northeast region. The relationship between the probability of occurrence of *E. cenchroides* and the climatic variables used was evaluated through the mean response curves of the generated models.

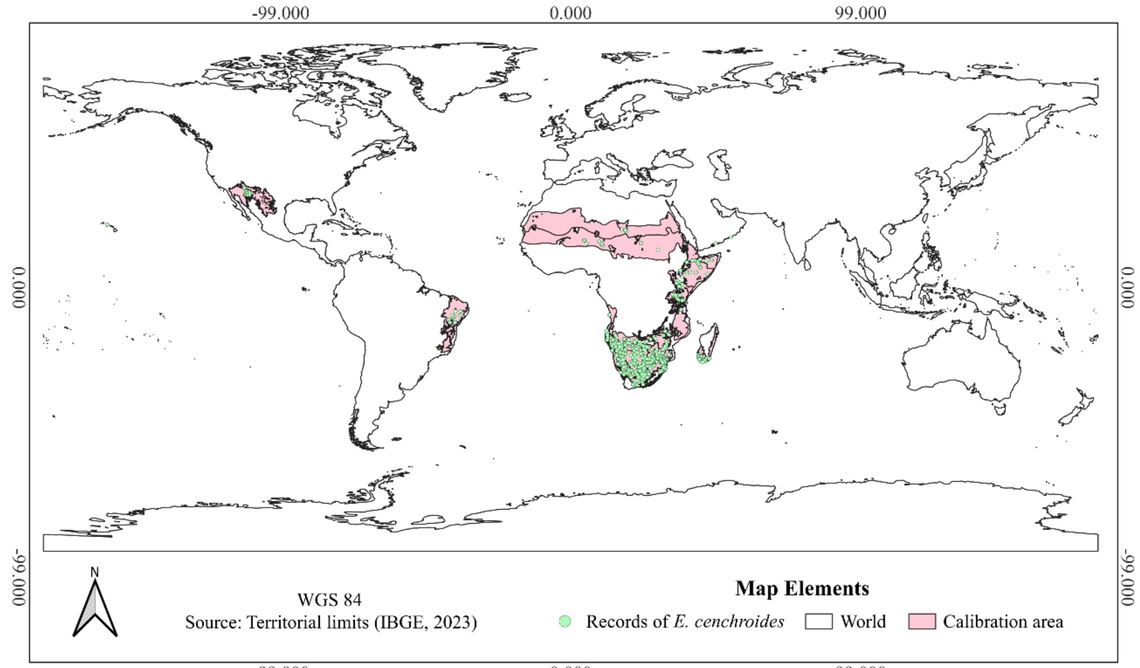

Figure 2: Records of Enneapogon cenchroides *(Roem. & Schult.) C.E. Hubb. and calibration area of models.*

The entire model development process was carried out in the “Biomod2” package [43] through the software R 2023.06.1 [37]. We conducted a preliminary modeling using all algorithms available in “Biomod2” and retained only those that presented satisfactory initial results. Thus, the algorithms used for the modeling stage were Maximum Entropy (Maxent), Generalized Linear Model (GLM), Classification Tree Analysis (CTA), and Artificial Neural Network (ANN). The models generated by each algorithm were validated using the True Skill Statistic (TSS) and Area Under the ROC Curve (AUC) metrics. In the TSS, models with values close to or equal to 1 indicate a satisfactory prediction and less than or close to -1 indicate low prediction capacity [44]. In general, models with TSS values above 0.5 are considered acceptable [44]. According to the AUC, models with values of 0.8 are considered good [45]. The background and pseudo-absence points were generated using the "disk" strategy with a distance of 10 km from the occurrence points to reduce the risk of spatial autocorrelation [46]. A total of 10,000 pseudo-absence points were generated for the models implemented using the GLM and ANN algorithms and 10,000 background points in Maxent [47]. For the models generated with CTA, an equivalent number of pseudo-absences to the presences was used [47].

The species occurrence points were separated into a proportion of 75% for training and 25% for testing. This separation was repeated 10 times, while the pseudo-absence/background sampling was repeated five times for each algorithm, totaling 200 models (10 x 5 x 4). These models were then reprojected for the entire extent of Northeast Brazil. To obtain more reliable results, models that obtained TSS values equal to or above 0.5 were merged using the ensemble technique [48]. The resulting model was separated into four suitability classes, namely: No suitability (0-0.20), Low suitability (0.20-0.40), Moderate suitability (0.40-0.60), and High suitability (0.60-1.0).

3. RESULTS AND DISCUSSION

3.1 Extent of Occurrence

Through literature research and information from experts, it was possible to verify that the record of *E. cenchroides* made in the present work is the first for the state of Sergipe. With this new record, the EOO of *E. cenchroides* reached 124,145 km² (Figure 3).

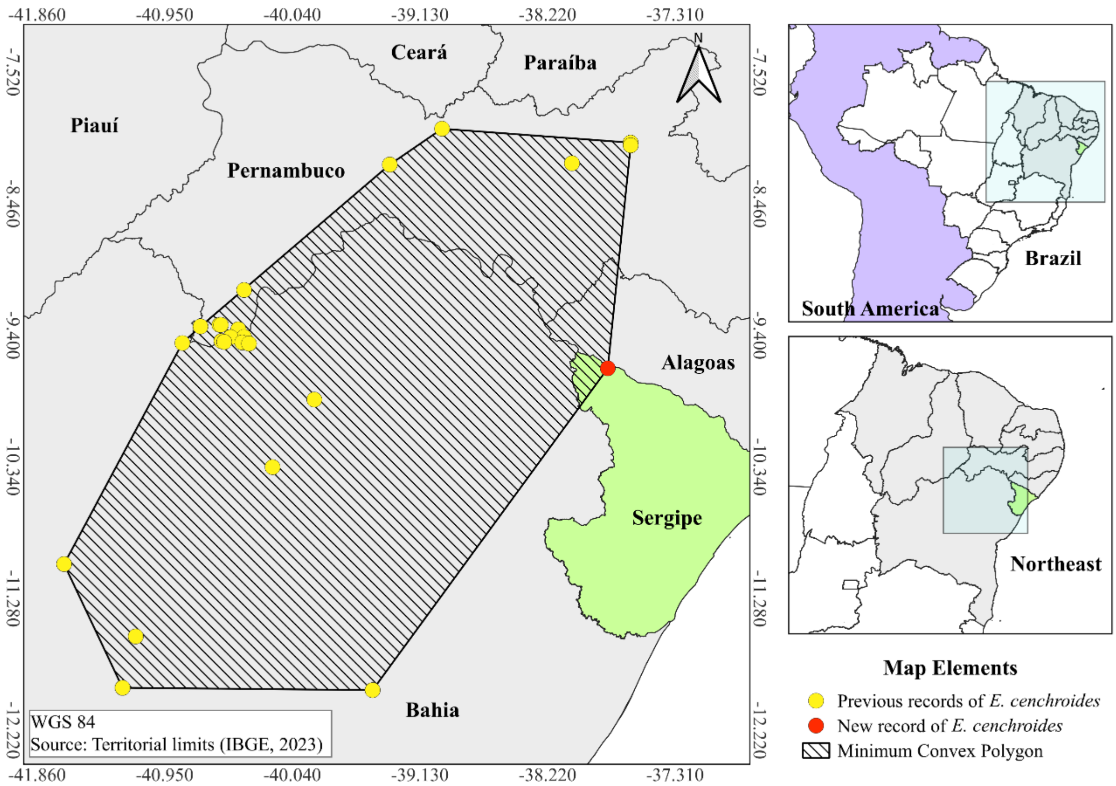

Figure 3: Records and Extent of Occurrence (EOO) of Enneapogon cenchroides *(Roem. & Schult.) C.E. Hubb. in Brazil.*

3.2 Species Distribution Model

The mean TSS and AUC values of the models used to generate the ensemble were 0.54 ± 0.01 and 0.82 ± 0.01, respectively, indicating acceptable predictive capacity. According to our ensemble, climatic suitability in Northeast Brazil ranged from null (0-0.20) to high (0.60-1.0). High suitability areas were concentrated in the states of Bahia, Sergipe, Alagoas, Pernambuco, Paraíba, and, to a lesser extent, Rio Grande do Norte. The states of Piauí, Ceará, and Maranhão predominantly exhibited areas with null and low suitability (0.20-0.40). Regarding the ecosystems of Northeast Brazil, most areas with moderate (0.40-0.60) and high suitability were restricted to the Caatinga domain. In the other ecosystems (Amazon, Central Brazilian Savanna a.k.a Cerrado, and Atlantic Forest), null and low suitability areas were more prominent (Table 1; Figure 4).

Table 1: Suitability classes (km²) for the occurrence of Enneapogon cenchroides *(Roem. & Schult.) C.E. Hubb. in Northeast Brazil.*

Suitability Classes	**Area (km²)**
No suitability	659,937
Low suitability	506,245
Moderate suitability	218,497
High suitability	167,330

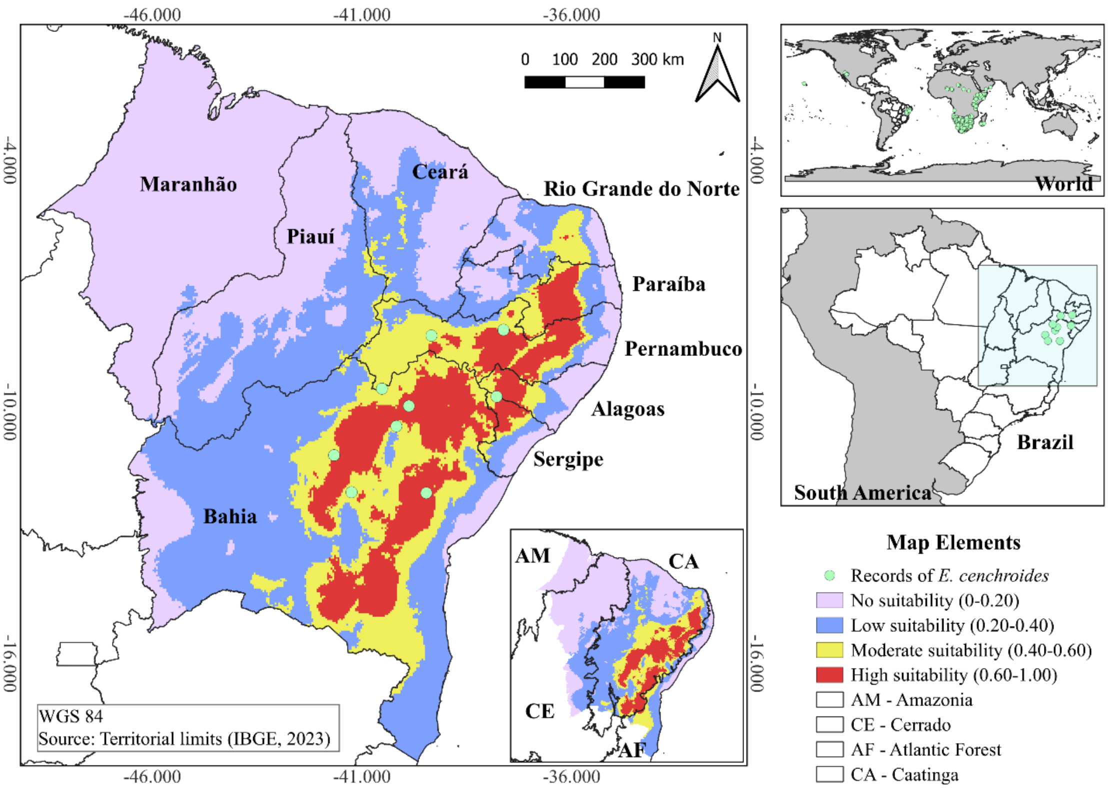

Figure 4: Environmental suitability of Enneapogon cenchroides *(Roem. & Schult.) C.E. Hubb. in Northeast Brazil.*

According to the response curves, *E. cenchroides* exhibited higher suitability in environments where Isothermality (Bio 03), which represents the ratio of daily temperature variation to annual variation, ranged between 50% and 65%. For the variable Mean Temperature of the Warmest Quarter (Bio 10), the species began to show a decline in suitability at around 25°C. Annual Precipitation (Bio 12) and Precipitation Seasonality (Bio 15) indicated that the species exhibits higher suitability in environments with lower precipitation levels and more stable rainfall patterns, respectively (Figure 5).

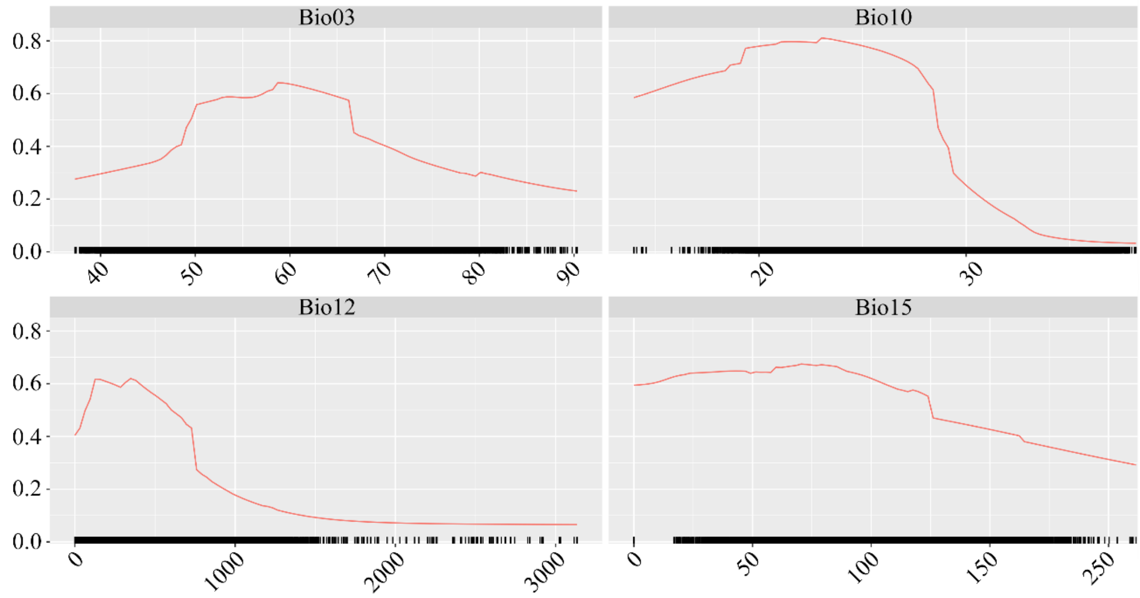

Figure 5: Response curves of the variables used in the development of the Species Distribution Model of Enneapogon cenchroides *(Roem. & Schult.) C.E. Hubb.*

4. DISCUSSION

The record of *E. cenchroides* for Sergipe increased the number of non-native species present in the state to 84 [49]. Silva et al. (2013) [19] indicated that the EOO of this species in Brazil was 142 km², a value substantially low compared to that obtained in the present study. The addition of this new record for Sergipe, along with occurrences recorded after the study by Silva et al. (2013) [19], resulted in a considerable 87.32% increase in the EOO of *E. cenchroides* between the evaluations conducted in 2013 and 2025. This result may indicate the high spread capacity of *E. cenchroides* and illustrates how the invasion process of this species has advanced since its first record in Brazil, registered by Fabricante and Siqueira-Filho in 2012 [27].

Despite the observed increase, the EOO should be considered with caution. In the case of species introduced in multiple locations, large areas without populations of the species may be included within the EOO, leading to an overestimation of the occupied area [50]. This may be the case for *E. cenchroides*, since its initial introduction possibly occurred accidentally through pisciculture [27]. Thus, it is likely that there are areas with discontinuous occurrences of the species within its EOO [51]. Nevertheless, this metric can contribute to the control and management of the studied species, as it aids in resource allocation and strategic planning of management actions [8, 9]. Furthermore, we recommend that the EOO of *E. cenchroides* be continuously monitored and updated with new information so that its spread rate can be measured more accurately [8].

As in the record made in Sergipe, a considerable portion of the occurrence points of *E. cenchroides* in Brazil are located in riparian areas or close to them. This raises the possibility that this type of environment may be important for the invasion process of the species in the country. In general, riparian environments tend to act as pathways for the dispersal of invasive non-native species [52]. Furthermore, the dynamics and conservation conditions of this environment favor the establishment of these species [53]. Considering the length of the São Francisco River, it is likely that *E. cenchroides* is already invading areas beyond the one where it was sampled in the present study. However, it is important to highlight that the areas suitable for its occurrence are not limited to riparian zones, as demonstrated in the species distribution model (Figure 4).

The high suitability in Caatinga areas aligns with the known distribution of the studied species. *E. cenchroides* naturally occurs in arid and semi-arid climates from Africa to India [20-25]. This environmental preference is also maintained in other invaded areas, such as the United States [54, 55]. Thus, our model demonstrates ecological coherence by indicating that the Caatinga, an ecosystem with a predominantly semi-arid climate [56], presents suitable conditions for the invasion of this species, even in areas without occurrence records. The response curve result for the variable Mean Temperature of Warmest Quarter (Bio 10; Figure 5) showed that temperatures above 25 ºC may reduce the probability of *E. cenchroides* occurrence. To some extent, this trend may have influenced the reduction in suitability in some areas of the Caatinga, given that the annual average temperature in this ecosystem varies between 25º and 30ºC [57].

Precipitation is another important factor shaping the ecological aspects of plants in arid and semi-arid regions [58, 59]. In the generated model, most areas with medium and high suitability are located in the eastern portions of the Caatinga, a region with low precipitation variability [60]. Accordingly, areas with high precipitation seasonality may decrease the probability of *E. cenchroides* occurrence, as evidenced by the response curve result for the variable Precipitation Seasonality (Bio 03; Figure 5). Similarly, the pattern observed in the variable Annual Precipitation (Bio 12; Figure 5) shows that higher rainfall levels may also reduce the probability of occurrence of this species. This may explain the null or low suitability observed across most of the territory of other ecosystems in the Brazilian Northeast. Unlike the Caatinga, the Amazon and Atlantic Forest are humid forests with high annual precipitation levels ranging between 2000-3000 mm and 700-3120 mm [61, 62], respectively. The Cerrado, although a savanna, has annual precipitation between 600-2000 mm [63]. Thus, it is likely that the invasion of *E. cenchroides* in the ecosystems of the Brazilian Northeast is being climatically limited by these factors.

The existence of areas with moderate and high suitability (Figure 4) but without *E. cenchroides* occurrence records in the Brazilian Northeast are concerning, as these regions may be invaded in the future or may already harbor unrecorded populations due to undersampling. Among the northeastern states with these conditions, Alagoas stands out because, in addition to bordering the three states where the species has already been recorded (Bahia, Pernambuco, and Sergipe), it is marginally crossed by the São Francisco River. We suggest conducting new expeditions in Alagoas and other states to gain a better understanding of the invasion process of *E. cenchroides* in Brazil. Obtaining new species records in areas identified as suitable serves as a robust test of the model's predictive capacity and can aid in improving its results [64, 65].

The presence of anthropogenic environments, as is the case in much of the ecosystems of the Brazilian Northeast [66], may facilitate the dispersal and establishment of this species in new areas [67]. The environmental conditions in these habitats may exclude native competitor species, creating vacant niches that facilitate the occurrence of invasive exotic species [67, 68]. Additionally, anthropogenic disturbances can shape the niche of introduced plants, allowing them to occur in regions with suboptimal climates [e.g., 69-71]. Therefore, the possibility of *E. cenchroides* forming viable populations even in environments with climatic conditions considered less suitable or unsuitable in the model presented in this study should not be ruled out. Furthermore, it is important to highlight that, unlike other non-native species, *E. cenchroides* can invade even well-preserved environments, as already reported in the Caatinga [29].

We highlight the need for studies aimed at evaluating the population dynamics and impacts of *E. cenchroides* in invaded environments in Northeast Brazil. Despite its importance, information of this kind is still scarce in the literature for a large number of non-native species present in Brazilian territory [72]. Furthermore, considering the expansion of its area of occurrence in the last decade and the probability of invading new environments, the control of this species is extremely necessary. Otherwise, *E. cenchroides* will likely continue to disperse to adjacent areas, potentially becoming as problematic as other African grasses, such as *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs and *Urochloa brizantha* (Hochst. ex A. Rich.) R.D. Webster [73], which currently invades not only the Northeast region but several environments throughout Brazil.

5. CONCLUSION

Our study updates the list of non-native plants in Sergipe by providing the first record of the invasive exotic species *Enneapogon cenchroides* (Roem. & Schult.) C.E. Hubb. in Sergipe. We observed that this species has been expanding its Extent of Occurrence in Northeastern Brazil and invading new areas since its introduction. Furthermore, a considerable part of this region remains suitable for the invasion of *E. cenchroides* due to the presence of areas with climatic conditions suitable for its occurrence, particularly in the Caatinga ecosystem. These findings are crucial for understanding the invasion dynamics of *E. cenchroides* in Brazil and may serve as a basis for efforts aimed at its management and control.

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