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Tayna Sousa Duque [*] , Iasmin Marcella Souza , Débora Sampaio Mendes , Ricardo Siqueira Da Silva , Danielle Piuzana Mucida , Francisca Daniele Da Silva , Daniel Valadão Silva , José Barbosa Dos Santos

Article

Ecological Niche Modeling of Invasive Macrophyte (*Urochloa subquadripara*) and Co-Occurrence with Natives

Tayna Sousa Duque [1,*], Iasmin Marcella Souza [1], Débora Sampaio Mendes [1], Ricardo Siqueira da Silva [1], Danielle Piuzana Mucida [2], Francisca Daniele da Silva [3], Daniel Valadão Silva [3] and José Barbosa dos Santos [1]

[1] Department of Agronomy, Universidade Federal dos Vales do Jequitinhonha e Mucuri, 39100-000, Diamantina, Minas Gerais, Brazil. E-mail: taynaduque24@gmail.com; iasmim.marcella@ufvjm.edu.br;debora.sampaio@ufvjm.edu.br; ricardo.siqueira@ufvjm.edu.br; jbarbosasantos@yahoo.com.br

[2] Department of Forest Engineering, Universidade Federal dos Vales do Jequitinhonha e Mucuri, 39100-000, Diamantina, Minas Gerais, Brazil. E-mail: danielle.piuzana@ufvjm.edu.br

[3] Department of Water and Soil Management, Universidade Federal Rural do Semi-árido, 59625-900, Mossoró, Rio Grande do Norte, Brazil. E-mail: danieleamancio20@gmail.com; daniel.valadao@ufersa.edu.br;

* Correspondence: Tayna Sousa Duque, Department of Agronomy, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina, Minas Gerais, Brazil; CEP: 39100-000, Tel: +55 38 9 9924-2408; E-mail: taynaduque24@gmail.com

Abstract: Invasive macrophytes are considered problematic in natural environments and hydroelectric reservoirs. Climate changes, the occurrence of watercourses, and biotic interactions influence the biological invasion of macrophytes. Native species can correlate with invasives positively or negatively. *Urochloa subquadripara* is an invasive in natural or disturbed habitats co-occurring with the natives *Eichhornia crassipes* and *Salvinia minima*. Aquatic plant communities can be altered by climate change, so species distribution models (SDMs) are important tools for predicting invaded areas. This work aimed to make an SDM for *U. subquadripara* correlating with the potential distribution of native species *E. crassipes* and *S. minima*. Occurrence data for *U. subquadripara*, *E. crassipes*, and *S. minima* were collected from databases and in consultation with the published literature. Parameters encompassing biological information of the species were entered into the CLIMEX software and used to generate the Ecoclimatic Index (EI). The species co-occurrence was performed based on multicriteria decision-making (MCDM), and weights were assigned using the analytical hierarchy process (AHP). It was observed that *U. subquadripara*, *E. crassipes*, and *S. minima* have a higher occurrence in tropical and subtropical regions; however, it is predicted that, from climatic changes, these species may move to high latitudes. According to climate change, the risk of invasion by *U. subquadripara* in the northern hemisphere is mainly in lakes, while in the southern hemisphere, the areas conducive to invasions are rivers and reservoirs. In general, emerging and floating macrophyte species such as *U. subquadripara*, *E. crassipes*, and *S. minima* will be favored, causing suppression of submerged species. Therefore, identifying the potential distribution of these species allows the creation of pre-invasion intervention strategies.

Keywords: biological invasion*; Eichhornia crassipes*; multicriteria decision making; *Salvinia minima*; tenner-grass

1. Introduction

Macrophytes are the primary producers of freshwater ecosystems and are essential for several biotic interactions [1]. These ecosystems have endemic species that move between watercourses, but they are highly invasive due to the high pressure of propagules [2]. In-vasive exotic species can cause

changes in the native community, such as the extinction of macrophytes, amphibians, and fish [1]; it is estimated that spending on biological inva-sions since 1970 in the world has been approximately US$ 1.3 trillion [3].

Urochloa subquadripara (Trin) R.D. Webster, "tenner-grass" (synonymous with *Brachiaria subquadripara*, *Brachiaria arrecta*, and *Urochloa arrecta*) [4–6] is an emergent macro-phyte, rooted near the margins, which has long, floating branches, forming mats on the surface of the water [7,8]. It is a Poaceae native to Africa and invasive in tropical and sub-tropical regions [9].

Due to the easy propagation by stolons, rhizomes, or fragments that can be trans-ported in water, the invasion of *U. subquadripara* raises concerns about water use and the suppression of biodiversity [8,10]. In addition, the species can grow as an epiphytic life form, rooted on the banks but extending on the surface of the water using floating macro-phytes such as Pistia stratiotes and *Eichhornia crassipes* as support [11].

Urochloa subquadripara colonizes natural and artificial water bodies [12], occurring in Brazil in areas such as the Pantanal [13], Cerrado and Atlantic Forest [14]. In addition, it is problematic in hydroelectric reservoirs such as Barra Bonita (SP) [15], Funil (MG) [16] and Santana (RJ) [17]. The invasive potential of *U. subquadripara* varies according to biotic and abiotic factors [18].

The invasion of *U. subquadripara* correlates with the composition of the native com-munity, varying in different spatial scales [6]. At more minor scales, the similarity be-tween native and invasive species can result in competition; however, at larger spatial scales, the probability of occurrence increases with the richness of native macrophytes [19–21]. The co-occurrence between native and invasive species is explained by the "Theory of biotic acceptance", which suggests that the presence of native species is positively cor-related with the occurrence of invasive species [22,23].

The occurrence of *U. subquadripara* is associated, on a large scale, with emerging and floating native macrophytes, of which the genus Eichhornia and Salvinia stand out [7,19]. *Eichhornia crassipes* is a Pontederiaceae native to the Amazon basin in Brazil and Ecuador, considered an invasive of water bodies and reservoirs worldwide [24]. *Salvinia minima* is a macrophyte native to Mexico, Central, and South America [25], and due to its rapid growth, it is also considered a problematic weed [26].

The distribution of macrophytes is largely related to climatic regions, limited by in-creasing latitude and altitude [27,28]. Climate changes, mainly temperature, and precipi-tation, will influence the regime of water masses, which may reduce the volume and in-crease the water temperature of lakes and reservoirs [28–30]. Thus, climate changes in-terfere with the habitat of macrophytes, altering growth, reproduction, development [31], phenology, distribution, and species migration [32]. Emerging and floating macrophytes such as *U. subquadripara*, *E. crassipes*, and *S. minima* are more prone to impacts related to changes in temperature since they are more exposed than submerged macrophytes [33].

Some approaches, such as species distribution models (SDMs), can be adopted for ecological niche projection considering the climate [34]. SDMs allow for predicting the po-tential distribution of a species using occurrence and climate data [35], being an important tool in preventing the invasion of exotic species in new environments. The CLIMEX soft-ware generates SDMs from the Ecoclimatic Index (EI) based on the growth and stress pa-rameters of the species under study [36]. This methodology has been widely used for modeling the ecological niche of invasive species and weeds [37–41].

Thus, the potential distribution of an invasive species can be determined by paying attention only to the climate, but the integrated understanding of the factor that influences the invasive potential, such as the co-occurrence of species, allows the filtering of suitable   places   [35]. Multicriteria decision-making (MCDM) is an alternative tool combining several criteria in a single index [42]. Within MCDM, the analytical hierarchy process (AHP) is widely used and consists of comparing the criteria, which ensures greater relia-bility in the judgment of assigned weights [43].

Therefore, due to the invasive capacity of *U. subquadripara*, the risk to ecosystems and natural communities, and disturbances in reservoirs, it is necessary to study the potential distribution of the species to develop control strategies to minimize possible impacts. This study aimed to develop a

potential distribution model for *U. subquadripara* using the CLIMEX software. In addition, to determine the potential distribution of *E. crassipes* and *S. minima* and, based on multicriteria decision-making, correlate the climatically suitable areas for native species with areas suitable for the occurrence of the invasive species.

2. Materials and Methods

2.1. Global Distribution of Urochloa subquadripara, Eichhornia crassipes e Salvinia minima

The global distributions of *U. subquadripara*, *E. crassipes*, and *S. minima* were defined from occurrence points collected in the Global Biodiversity Information Facility [44–46] and Invasive Species Compendium [47,48] online databases. New occurrence points were searched in the literature in databases such as Web of Science and Google Scholar and added to the global distribution of the species. Incomplete or duplicate information has been omitted.

The occurrence points of *U. subquadripara* encompassed searches with synonyms of the species, totaling 478 points after filtering 286. The global distribution of *E. crassipes* resulted in 8803 occurrence points and, after data filtering, 2970. *S. minima* resulted in 1594 occurrence points and, after data filtering, 534 (Table S1).

2.2. CLIMEX

CLIMEX software is used for climate-based species ecological niche modeling [49]. From the known distribution and biological information of the species, it is possible to generate the potential climate distribution [49]. The CLIMEX software is based on Shelford's Law of Tolerance, which determines that the growth of a species has an optimal value according to a given environmental resource, in addition to an upper and lower limit [50]. Climate suitability is defined according to the Ecoclimatic Index, which combines functions adjusted for growth and stress (Equation 1) [38,39]. The Ecoclimatic Index ranges from 0 to 100. Areas with EI = 0 were considered unsuitable; 0>EI>30 with moderate adequacy; and EI>30 highly adequate [39].

$$EI = GI_A \times SI \times SX \qquad (1)$$

Where: EI: Ecoclimatic Index; GIA: annual growth index; SI: annual stress index; SX: interaction between stress indices.

2.3. Parameter Adjustments and Model Validation in the CLIMEX Software

The ecological niche models for *U. subquadripara*, *E. crassipes*, and *S. minima* were generated considering biological information of the species and known distributions. In the CLIMEX software, the "Compare location" function was used, and the biological parameters searched were adjusted so that most of the species occurrence points were inserted in locations considered by the model as highly suitable (EI>30) [39].

Urochloa subquadripara had the African continent and South America as validation regions; e, *E. crassipes*, and *S. minima* in the United States of America, Mexico, and South America; considering native areas and in places invaded by the species.

2.3.1. Subsubsection

2.3.1.1 Growth Indices

Edaphoclimatic characteristics that affect *U. subquadripara* seed germination have already been described [51]. The seed germination begins at 20 – 21ºC, with the optimum at 25ºC [51]. In addition, *U. subquadripara* has been reported to occur in places such as Paragominas (Brazil) [8] and Bantul Yogyakarta (Indonesia) [52], where the minimum and maximum average temperatures are 21 and 34ºC. Therefore, the parameters related to the ideal temperature for the growth of *U. subquadripara* (DV1, DV2) were set at 22 and 35ºC. Research carried out with the species also adopted temperature values within the range established as optimal [53–55].

The lower and upper-temperature limits (DV0, DV3) for the growth of *U. subquadripara* were established at 4 and 39ºC. The lower temperature was defined as reported for species of the same genus, U. panicoides [37], and from the best fit to the global distribution of *U. subquadripara*. The upper temperature was set at 39ºC because the species has a priority distribution in tropical and subtropical regions, with occurrence reported in Autazes (Brazil) [56] and Córdoba (Colombia) [57], where the maximum temperatures reach 38 and 39ºC, respectively.

The lower limit, upper limit, and ideal soil moisture adopted in making the model were defined considering that the species grow in different soil moisture and according to the best fit in the global distribution, being SM0, SM1, SM2, and SM3, 0; 0.1; 8 and 10 respectively (Table 1).

2.3.1.2. Stress Parameters

The temperature limit of cold stress (TTCS) was defined according to the DV0, 4ºC, limiting the potential distribution of *U. subquadripara* in temperate regions without reports of the species. Furthermore, *U. subquadripara* occurs in Naples (United States of America) [51] and Alto Paraná (Brazil) [58], regions with minimum temperatures of up to 7°C. The cold stress accumulation rate (THCS), cold stress degrees threshold (DTCS), and the day cold stress degrees rate (DHCS) were defined at -0.001 week-1, 4ºC, and -0, 01 week-1, respectively.

The temperature limit of heat stress (TTHS) was set at 40ºC because, from that value on, seed germination of *U. subquadripara* is reduced [51](Teuton et al., 2004). The threshold of degrees of heat stress (DTHS) was set at 39°C according to the upper-temperature limit (DV3). The heat stress accumulation rate (THHS) and the degree of heat stress-day rate (DHHS) was set to 0.01 week-1.

Under drought conditions, seeds of *U. subquadripara* show dormancy, and when soil moisture is restored, germination occurs [51]. In modeling the ecological niche, the drought stress threshold (SMDS) and the drought stress accumulation rate (HDS) were considered at 0.1 and 0.005 week-1.

Table 1. Adjusted parameter values for modeling the invasive species *Urochloa subquadripara* (US) and native *Eichhornia crassipes* (EC) and *Salvinia minima* (SM) using CLIMEX.

Parameters	Index	Unit.	US	EC	SM
Lower temperature threshold	DV0	ºC	4	0.5	5
Lower optimum temperature	DV1	ºC	22	25	23
Upper optimum temperature	DV2	ºC	35	30	30
Upper optimum threshold	DV3	ºC	39	36	39
Lower soil moisture threshold	SM0	--	0	0	0.1
Lower optimum soil moisture	SM1	--	0.1	0.1	0.2
Upper optimum soil moisture	SM2	--	8	8	8
Upper soil moisture threshold	SM3	--	10	10	10
Cold stress temperature threshold	TTCS	ºC	4	0.5	5
Cold stress temperature rate	THCS	Week-1	-0.001	-0.0003	-0.0003
Cold stress degree-day threshold	DTCS	ºC day	4	----	----
Cold stress degree-day rate	DHCS	Week-1	-0.01	----	----
Heat Stress Temperature threshold	TTHS	ºC	40	37	39
Heat Stress Temperature rate	THHS	week-1	0.01	0.001	0.1
Heat Stress Threshold	DTHS	ºC dia	39	----	35
Heat Stress Degree-day rate	DHHS	week-1	0.01	----	0.1
Dry Stress Threshold	SMDS	--	0.1	0.02	----
Dry Stress rate	HDS	week-1	0.005	-0.005	
Degree-days threshold	PPD	ºC dia	----	1916	----

2.3.2. *Eichhornia crassipes*

2.3.2.1. Stress Parameters

Ecological niche modeling for *E. crassipes* was performed, but the authors considered only places where the species is considered naturalized [39]; in addition, new occurrences were reported [45]. Therefore, the new modeling was generated with adjustments in the parameters of the old one to encompass most of the current distribution points. The modeling proposed by Kriticos and Brunel [39] and the current distribution of *E. crassipes* is presented in Figure S1.

The ideal lower (DV1) and higher (DV2) temperatures were maintained at 25 and 30ºC, as defined by [39]. The lower (DV0) and upper (DV3) temperature limits have been changed. The DV0 was defined at 0.5ºC because the species is sensitive to frost [39], and from air temperatures close to 0.5ºC, damage to the leaf blades occurs [59].

The DV3 was defined at 36ºC because research carried out in tanks suggests that, in water temperatures above 34ºC, the death of *E. crassipes* occurs [59]. However, other reports demonstrate that the species can withstand temperatures up to 43ºC [60,61]; therefore, an intermediate value was established.

In addition, to create the new model, humidity and degree days (PDD) parameters were inserted. The maximum leaf area of *E. crassipes* occurs between 1800 and 2000 ºC days; therefore, the defined PDD value was 1916 ºC days [62].

Eichhornia crassipes is a macrophyte; thus, the species is highly dependent on water in the soil [39]. However, other factors such as water salinity [63,64] and pH [65] influence the occurrence. The lower limit, upper limit, and ideal soil moisture adopted in making the model were defined considering the suitability for high moisture values and according to the best fit in the global distribution, with SM0, SM1, SM2, and SM3, 0; 0.1; 8 and 10 respectively (Table 1).

2.3.2.2. Stress Parameters

The temperature limits of cold stress (TTCS) and heat stress (TTHS) were maintained at 0.5 and 37ºC according to the methodology proposed by [39]. The accumulation rate of cold stress (THCS) and heat stress (THHS) were defined as -0.001 week $^{-1}$ and 0.001 week $^{-1}$, respectively.

The drought stress threshold (SMDS) (0.02) and the drought stress accumulation rate (HDS) (-0.005 week-1); were adopted in this model because, under progressive drought, there are reductions in the photosynthesis of *E. crassipes*; however, the defined values were low because the species tolerates conditions of up to 6% of the volumetric content of water in the soil [66] ((Table 1).

2.3.3. *Salvinia minima*

2.3.3.1. Growth Indicess

Research on the influence of climatic factors on the development of *S. minima* is scarce, so the minimum and maximum temperature values were based on studies carried out with *Salvinia molesta*. The species have a similar global distribution [46,67], so such a comparison is valid.

The development of *S. minima* is maximized at temperatures of 23 and 35ºC, and at 15ºC, there is a decline in growth and chlorophyll production [68]. In addition, experiments with *S. minima* adopted the average temperature range of 20 – 25ºC [69,70]. Therefore, the temperature range established as ideal for the growth of *S. minima* (DV1, DV2) was 23 – 30ºC.

The minimum temperature values for *S. molesta* vary between 5 and 10.7ºC [71,72]; and those with maximum temperature between 39 and 43ºC [61,71–73]. The definition of the lower limit (DV0) and the upper-temperature limit (DV3) was carried out considering the best adjustment to the occurrence data of *S. minima*, being 0.5 and 39ºC, respectively.

The lower and upper limits and the ideal soil moisture adopted in the making of the model were defined considering the best fit in the global distribution, being SM0, SM1, SM2, and SM3, 0.1; 0.2; 8, and 10, respectively (Table 1).

2.3.3.2. Stress Parameters

The cold stress temperature threshold (TTCS) was set at 5ºC per the DV0, and the cold stress accumulation rate (THCS) was established at -0.0003 week-1.

The temperature limit of heat stress (TTHS) was 39ºC, according to the established DV3, and because the maximum temperature for the growth of *S. molesta* is 39.6ºC [72]. Values for heat stress accumulation rate (THHS), heat stress degree threshold (DTHS), and heat stress degree rate-day (DHHS) were defined as 0.1 week-1, 35°C, and -0.1 week-1, considering the global distribution of *S. minima*.

Salvinia minima, when exposed to periods of drought, manages to return to its primary state due to its morphology that forms a mat, protecting the apical meristem and allowing the re-establishment of the species when the humidity conditions are adequate [74,75]. This tolerance occurs because, in the native area of the species, there is exposure to floods but also long periods of drought [75]. Therefore, drought stress was not considered in modeling the ecological niche of *S. minima* (Table 1).

2.4. Climate Data, Models, and Scenarios

Modeling of *U. subquadripara*, *E. crassipes*, and *S. minima* were carried out using climatic data on a Climond 10' grid. The files contain weather data on average minimum and maximum temperatures, precipitation, and monthly relative humidity. Data from 1961 to 1990, centered on 1975, represented the historical climate [76].

2.5. Multicriteria Decision-Making and Analytical Hierarchy Process

The use of multicriteria decision making (MCDM) based on GIS (Geographic Information Systems) has as basic units layers represented by polygons (vectors) or pixels (raster) (Figure 1); it allows the combination of weights of a large number of criteria [77] and obtaining results on spatial scales [42,78].
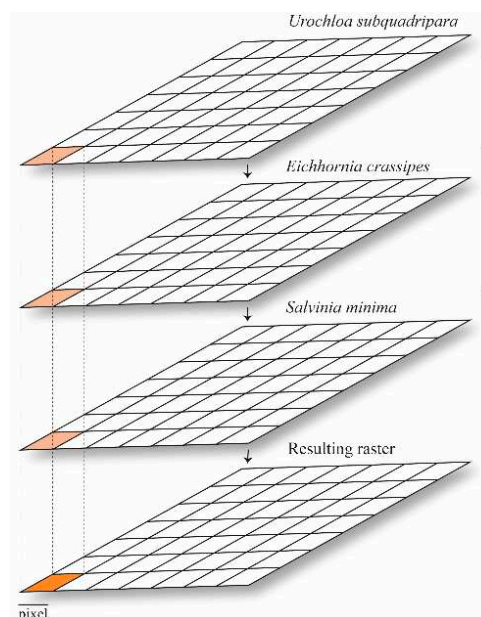

Figure 1. Weighted combination of criteria matrix datasets.

The criteria for making the multicriteria decision were based on the modeling results for the invasive species (*U. subquadripara*) and native species (*E. crassipes* and *S. minima*). Each criterion was divided into classes considering the Ecoclimatic Index; the values of the classes were normalized so that they were on a scale between 0 and 1 (Table 2).

Table 2. Criteria used in multicriteria decision-making, classes, and normalized values.

Criteria		
Criterion	**Description**	
Criterion 1	Ecological niche for *U. subquadripara*	
Criterion 2	Ecological niche for *E. crassipes*	
Criterion 3	Ecological niche for *S. mínima*	
Criteria Classes		
Description	**Classe**	**Normalized value**
EI = 0	0	0
0>EI>30	1	0.5
EI>30	2	1

The analytical hierarchy process (AHP) is widely used in MCDM to determine the weight of each criterion [78–80]. The AHP method uses a square preference matrix, in which all criteria are compared to each other based on the intensity of importance, where value 1 expresses "equal importance" and value 9 "extreme importance" over another factor (Table 3) [81,82].

Considering the theory of biotic acceptance, the foundation used to determine the importance of each criterion was the relevance in the potential distribution of *U. subquadripara*. For example, the ecological niche for *U. subquadripara* (criterion 1) was considered of substantial or essential importance to the ecological niche for *E. crassipes* (criterion 2); therefore, the value 5 was assigned to the corresponding position in the matrix. The transposition position obtained the reciprocal value, in this case, 1/5, equivalent to 0.20 (Table 3).

Table 3. Paired comparison matrix describing preferences between the criteria identified in table 2.

	Criterion 1	**Criterion 2**	**Criterion 3**
Criterion 1	1	5	5
Criterion 2	0.2	1	1
Criterion 3	0.2	1	1

The intensity of importance: 1 (equal importance); 3 (moderate importance of one factor over the other); 5 (strong or essential importance); 7 (very strong importance); 9 (extreme importance); 2,4,6,8 (intermediate values); reciprocals (values for inverse comparison) (Adapted from Saaty and Vargas [82]).

The criteria weights were obtained by calculating the eigenvectors of the paired comparison matrix [77]. Thus, each criterion assumed a weight based on its importance compared to the others [83] (Table 4).

Table 4. Weights used in multicriteria decision making.

Criterion	**Description**	**Weight***
Criterion 1	Ecological Niche para *U. subquadripara*	0.714
Criterion 2	Ecological Niche para *E. crassipes*	0.143
Criterion 3	Ecological Niche para *S. minima*	0.143

* Eigenvectors resulting from the paired comparison matrix.

The calculation of the consistency ratio (CR) was carried out to measure the consistency of the judgments and avoid inconsistencies in the definition of the values of the paired comparison matrix [77,81,83].

The consistency ratio is obtained as described in equations 2 and 3 [83]. RC values < 0.1 indicate that the pairwise comparison was properly performed [81].

$$CI = \frac{(\lambda_{max.} - n)}{(n - 1)} \qquad (2)$$

$$CR = CI \times RI \qquad\qquad (3)$$

Where: CI: Consistency index; λmax.: maximum eigenvalue of the paired comparison matrix; n: array order; CR: consistency ratio (default value); and; RI: Resultant Average Consistency Index.

The consistency ratio calculated in this study was equal to 0; therefore, the judgments are considered consistent.

After the analytical hierarchy and consistency analysis process, the model maps of the species were classified (Table 2), multiplied with the established weighting (Table 4), and integrated into the raster calculator of ArcGIS® Software version 10.5.

2.6. Global Lakes and Wetlands Database (GLWD)

To compare regions considered highly suitable with the existence of bodies of water for the establishment of species, we present a map with the global database of lakes and wetlands (GLWD). Data used include level 1 (lakes with surface area ≥50 km2 and reservoirs with storage capacity ≥0.5 km3) and level 2 (lakes, reservoirs, and rivers with surface area ≥0.1 km2) [84].

3. Results

3.1. Invasive Exotic Species (Urochloa subquadripara)

The global distribution of *U. subquadripara* generated 276 points of occurrence in 30 countries, with Australia (48.20%), Brazil (14.35%), and Taiwan (11.53%) being the regions with the most reports (Figure 2a). Approximately 28.74% of the world area was considered very suitable for the occurrence of the species (EI>30); 5.28% moderately adequate (30 ≤EI ≤ 100); and 65.98% inadequate (EI=0). The model predicts high climate suitability in tropical regions and does not predict suitability in temperate regions such as European and American countries (Figure 2b).
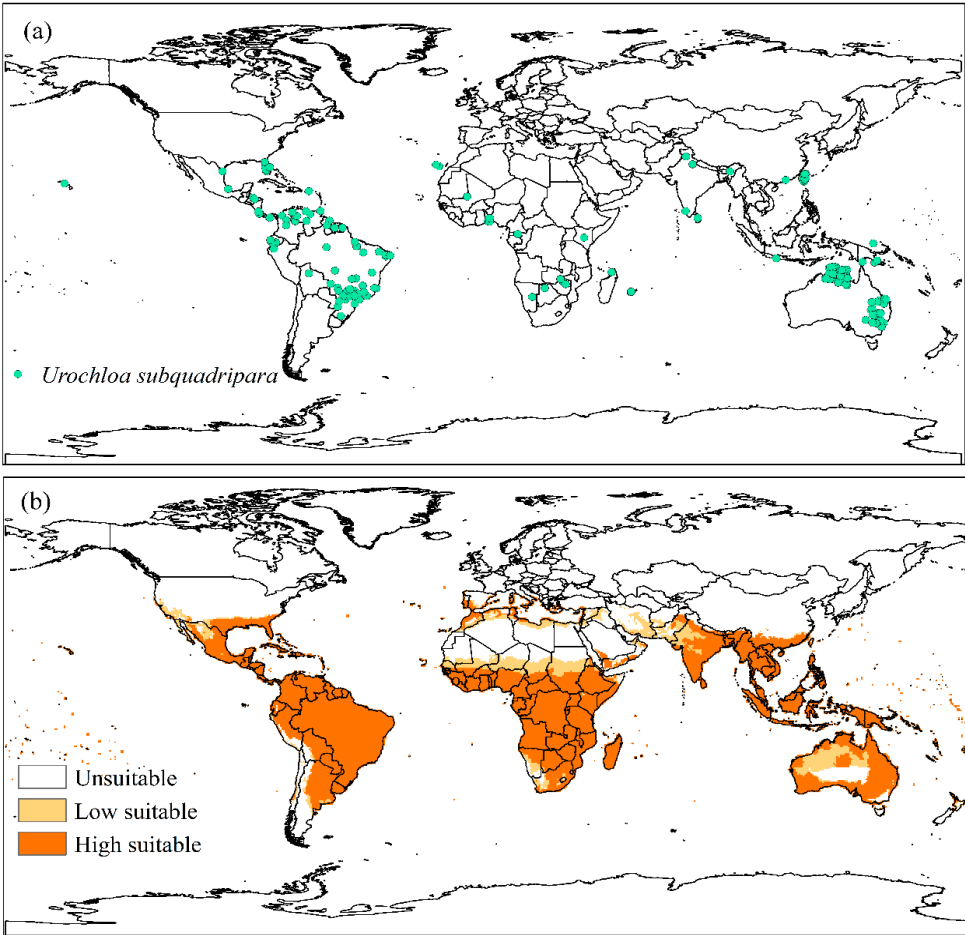
Figure 2. (a) Known global distribution of *Urochloa subquadripara* plants and (b) Ecoclimatic Index (EI) for *U. subquadripara*, modeled using CLIMEX. Unsuitable areas in white (EI = 0), low suitable in light orange (0 <EI <30), and high suitable in orange (30 ≤EI ≤ 100).

The ecological niche model for *U. subquadripara* was validated using the native region (African continent) [7], considering that the species has high adaptation to the climatic conditions of that area. Furthermore, South America was chosen for validation because *U. subquadripara* is found as an invader of hydroelectric reservoirs in Brazil [7,12,85], in environments natural in Argentina [86], and as pasture in Ecuador [87] and Venezuela [88,89]. In the validation regions, about 98.6% of the points reported are in areas considered very suitable and 1.4% with moderate suitability; thus, there is a high correlation between the occurrence of the species and the generated model (Figure 3).
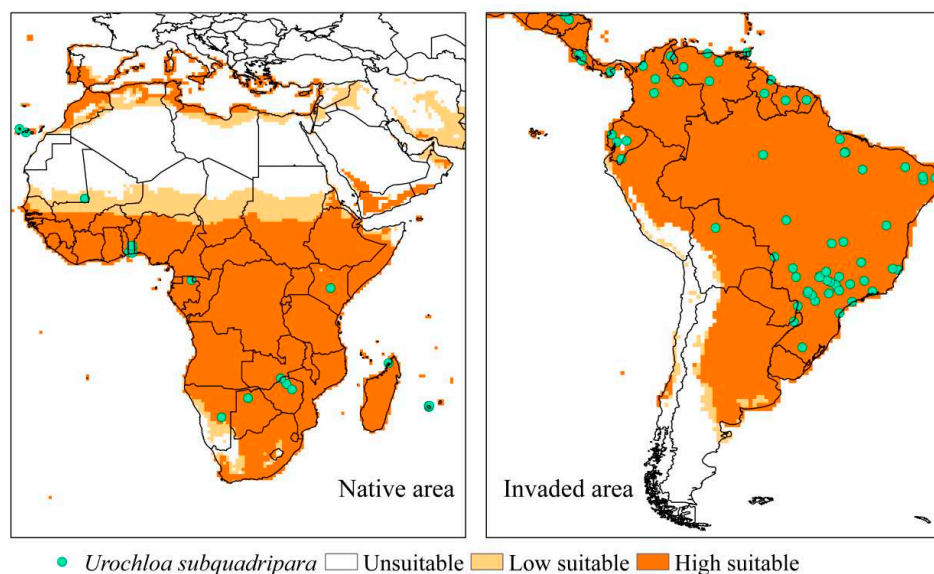

Native area   Invaded area

● *Urochloa subquadripara* ☐ Unsuitable ☐ Low suitable ■ High suitable

Figure 3. Current distribution of *Urochloa subquadripara* in validation regions, native (African continent) and invaded area (South America), based on the Ecoclimatic Index (EI). Unsuitable areas in white (EI = 0), low suitable in light orange (0 <EI <30), and high suitable in orange (30 ≤EI ≤ 100).

3.2. Native Species

3.2.1. *Eichhornia crassipes*

Distribution data for *Eichhornia crassipes* generated 2970 occurrence points, distributed in 110 countries. The countries with the highest occurrences of the species are the United States of America (35.6%), Mexico (12.7%), Australia (5.8%), and India (4.1%) (Figure 4a).

The modeling of the ecological niche of *E. crassipes* is in agreement with the species' current distribution, with most of the points of occurrence inserted in moderately and very suitable places. Compared to the model proposed by Kriticos and Brunel [39], the modeling covers occurrence points in European countries, the United States of America, and Japan, in addition to restricting regions of Africa, where there is no occurrence of the species. About 45.72% of the world area was considered unsuitable (EI=0) climatically for the occurrence of *E. crassipes*; 20.82% moderately adequate (30 ≤EI ≤ 100) and 33.46% very adequate (EI>30) (Figure 4b).
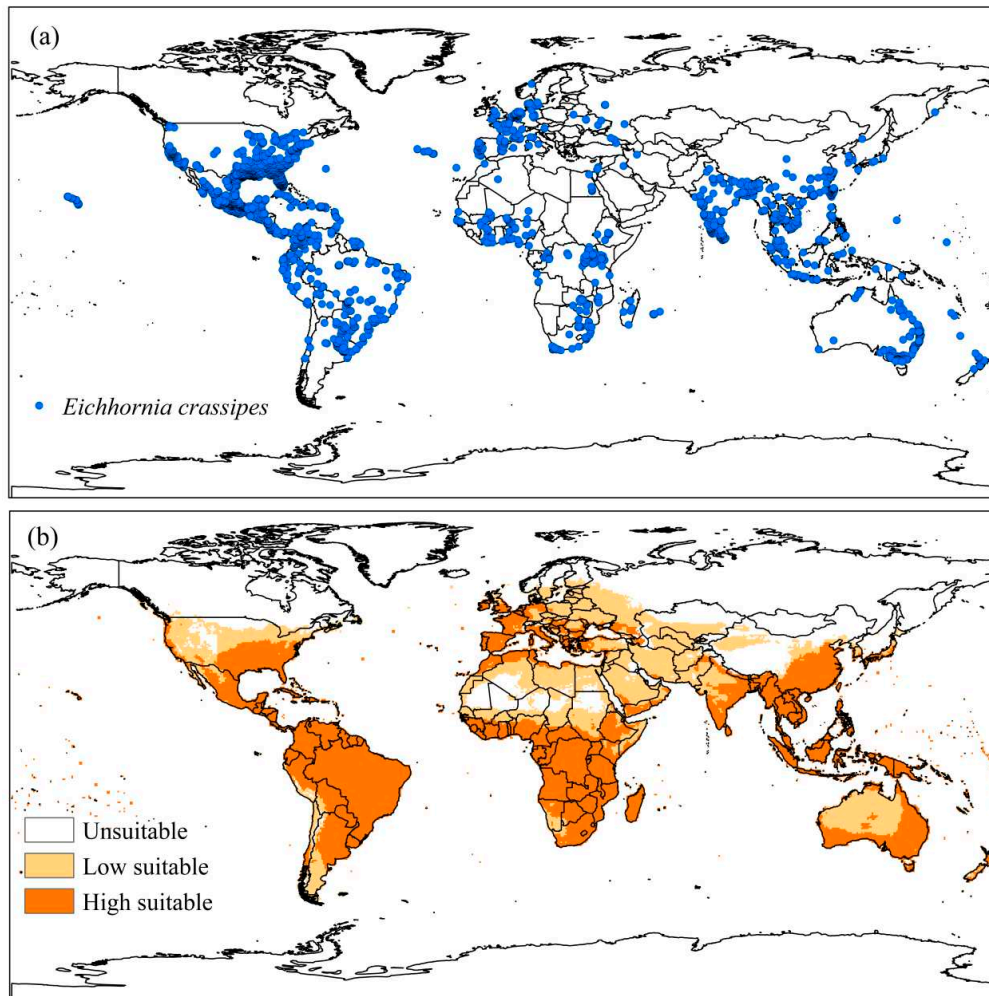
Figure 4. (a) Known global distribution of *Eichhornia crassipes* plants and (b) Ecoclimatic Index (EI) for *E. crassipes*, modeled using CLIMEX. Unsuitable areas in white (EI = 0), low suitable in light orange (0 <EI <30), and high suitable in orange (30 ≤EI ≤ 100).

South America is the region of origin of *Eichhornia crassipes*, so it was one of the areas chosen for validation, along with invaded areas (United States of America and Mexico). The invaded areas were defined due to the high occurrence of the species; in addition, *E. crassipes* is problematic in at least thirteen states of the United States of America [90], being considered a critical invasive macrophyte in Florida [91]. About 94.8% of the occurrence points in the validation regions are found in very suitable areas, 4.7% in regions with moderate adequacy, and 0.5% in inadequate regions, demonstrating high reliability in the final model (Figure 5).
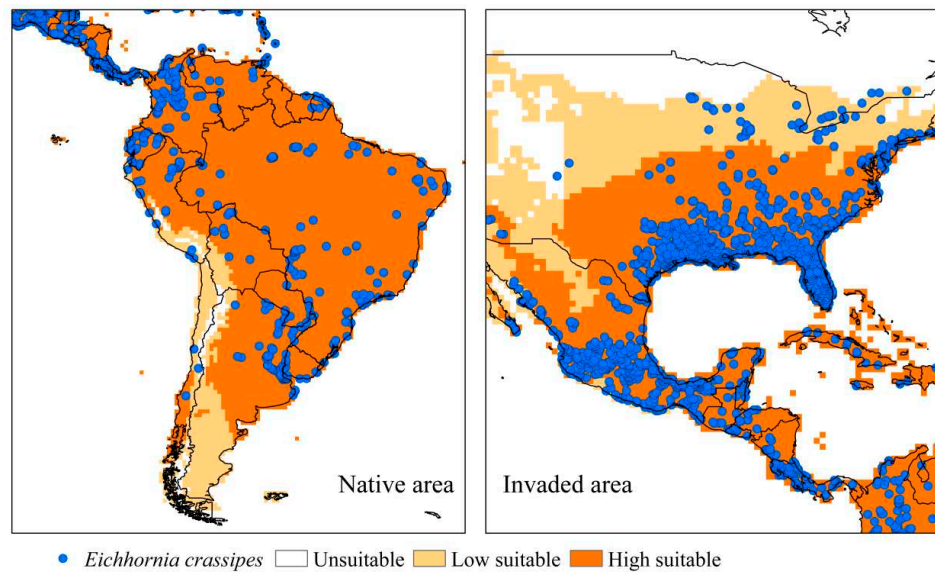
Figure 5. Current distribution of *Eichhornia crassipes* in validation regions, native area (South America), and invaded area (United States of America and Mexico), based on the Ecoclimatic Index (EI). Unsuitable areas in white (EI = 0), low suitable in light orange (0 <EI <30), and high suitable in orange (30 ≤EI ≤ 100).

3.2.2. *Salvinia minima*

The occurrence data of *S. minima* generated 534 points, distributed in African (0.56%), American (94.95%), Asian (2.62%), and European (1.87%) continents in 34 countries (Figure 6a).

Approximately 60.00; 14,19, and 25.81% of the world area were considered inadequate, moderately adequate, and very adequate for establishing *S. minima*, respectively (Figure 6b). Around 98.7% of the occurrence points of *S. minima* are in regions considered very suitable (EI>30), and 1.3% in moderately suitable places (0>EI>30). The occurrence of the species in inappropriate regions was not observed (EI=0).

South America and North American regions were defined for model validation. About 79.5% of the occurrence points are located in the United States of America or Mexico; in addition, *S. minima* are present in fourteen states of the United States of America [92], colonizing natural habitats in Florida [93], Texas and Louisiana [94], so this region was chosen for validation. Approximately 98.9% of the points in the areas are inserted in very suitable regions, and 1.1% have moderate climatic suitability (Figure 7).
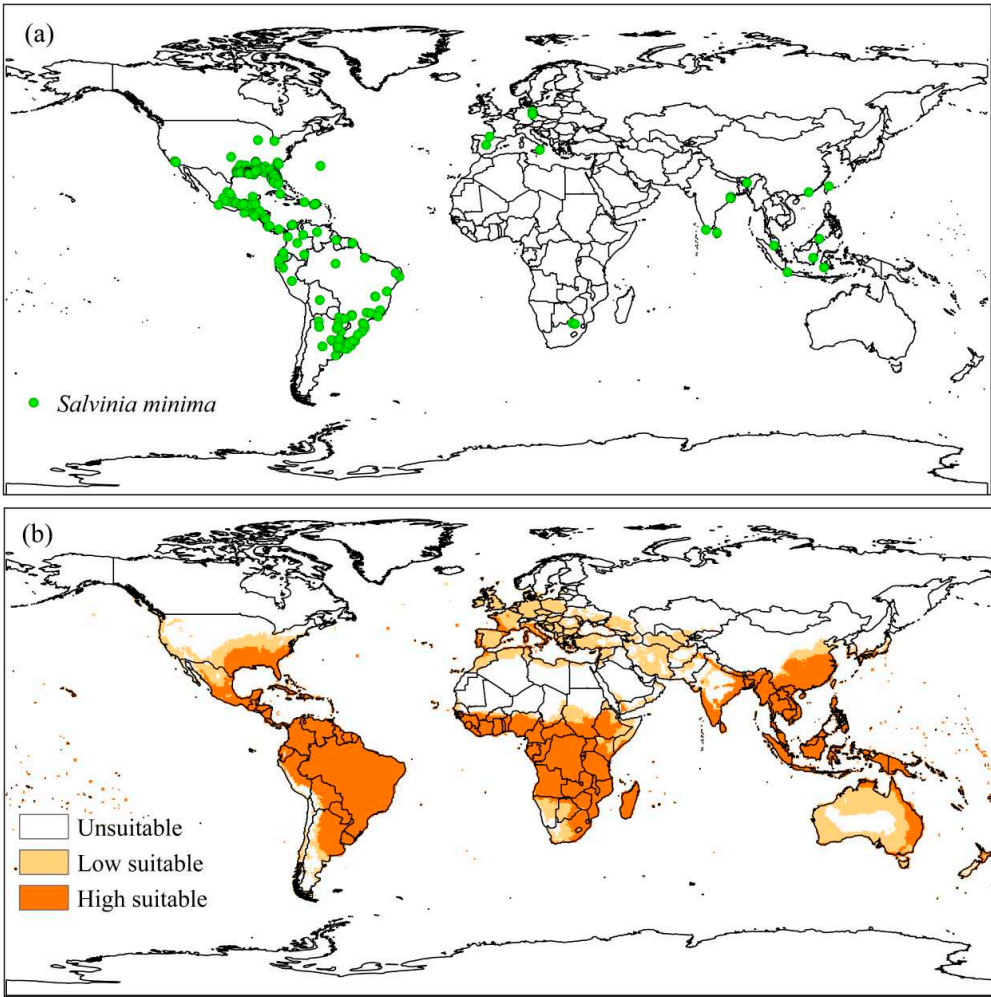
Figure 6. (a) Known global distribution of *Salvinia minima* plants and (b) Ecoclimatic Index (EI) for *S. minima*, modeled using CLIMEX. Unsuitable areas in white (EI = 0), low suitable in light orange (0 <EI <30), and high suitable in orange (30 ≤EI ≤ 100).
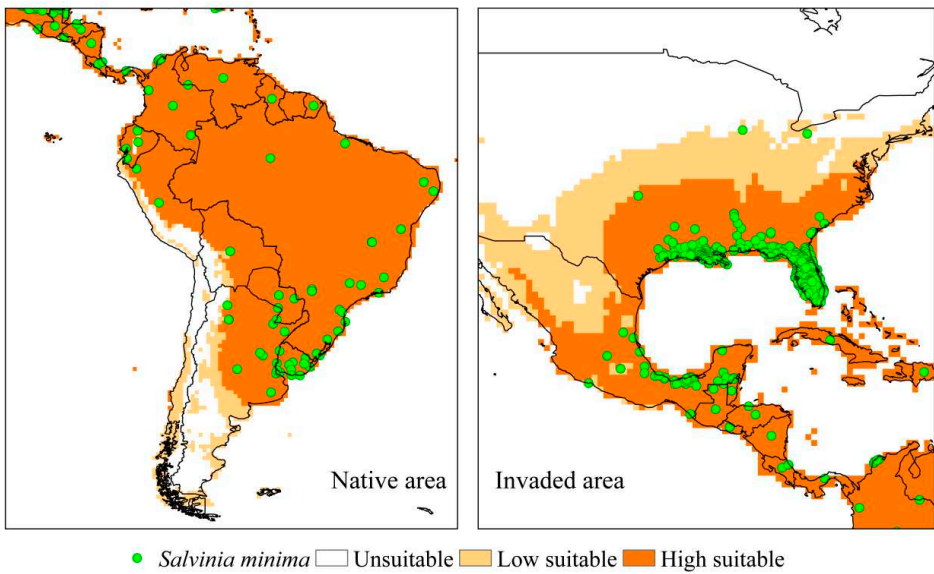

Figure 7. Current distribution of *Salvinia minima* in validation regions, native area (South America), and invaded area (United States of America and Mexico), based on the Ecoclimatic Index (EI). Unsuitable areas in white (EI = 0), low suitable in light orange (0 <EI <30), and high suitable in orange (30 ≤EI ≤ 100).

3.3. Co-Occurrence of Urochloa subquadripara with Native Species

Combining the modeling of *U. subquadripara*, *E. crassipes*, and *S. minima* from the multicriteria decision-making generated a raster whose pixel values ranged from 0 to 1, where 0 are areas considered unsuitable for the occurrence of *U. subquadripara* and 1 very suitable areas (Figure 8a).

The suitability of *U. subquadripara* remains limited in northern temperate regions of the US, China, Canada, and Russia, but there was an increase in suitability compared to modeling alone (Figure 8a). The global database of lakes and wetlands shows a prevalence of lakes in the northern hemisphere; however, due to low temperatures, they are subject to freezing (Figure 8b).

Regions such as Brazil, the African continent, and Asia show high suitability, and desert areas in Africa and Australia remained unsuitable for *U. subquadripara* (Figure 8a). In the southern hemisphere, the greatest risk of biological invasion by macrophytes is about reservoirs and large rivers (Figure 8b).
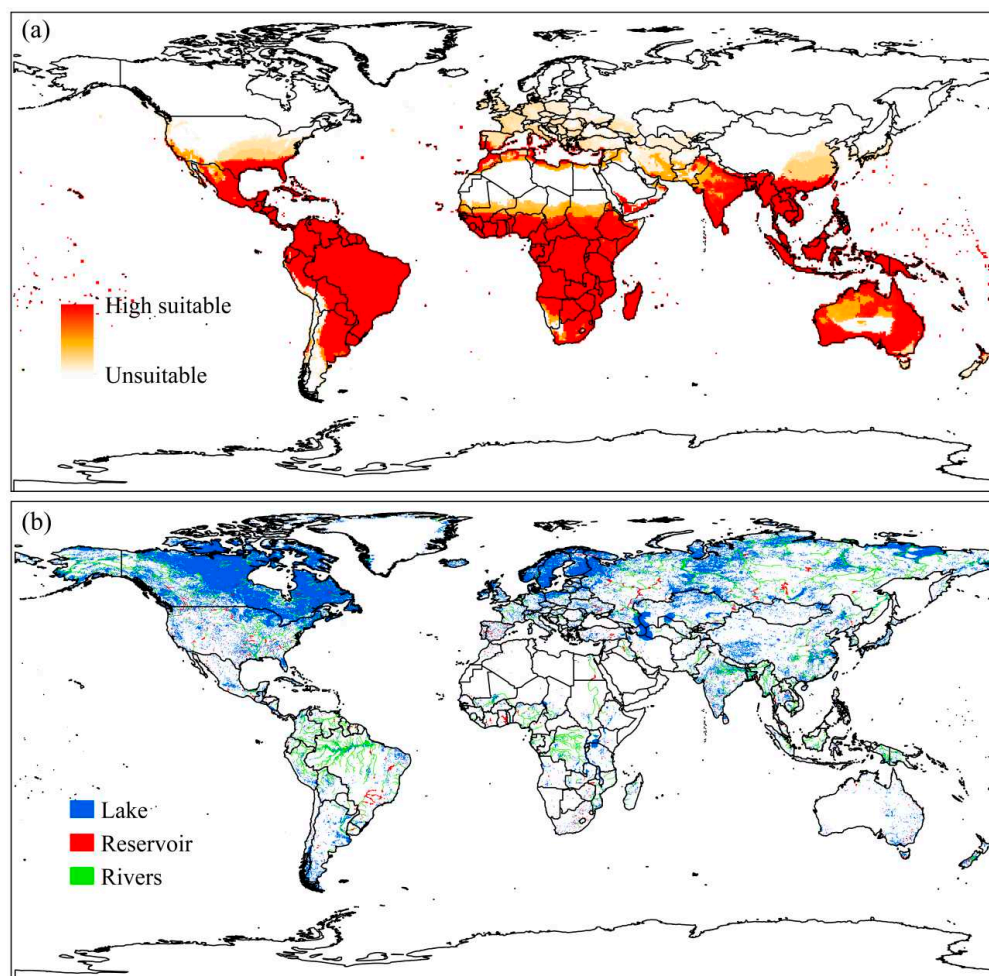

Figure 8. (a) Climate suitability for *Urochloa subquadripara* considering co-occurrence with native species (*Eichhornia crassipes* and *Salvinia minima*), considering Ecoclimatic Indices (EI) modeled using CLIMEX. Inappropriate areas in white (0) and very suitable areas in red (1); (b) global lakes and wetlands database (GLWD), including tier 1 (lakes with surface area ≥50 km2 and reservoirs with storage capacity ≥0.5 km3) and tier 2 (lakes, reservoirs and rivers with surface area ≥0.1.

4. Discussion

4.1. Invasive EXOTIC species (Urochloa subquadripara)

There are about 3457 macrophyte species in the world, and Brazil has the highest number [95]. The distribution of *U. subquadripara* follows the general pattern, with few occurrences in temperate

climates. The species is found in 38.7% of the world's area [95] and is restricted by cold, heat, and drought stress. Distribution limits are compatible with climatic regions, with restrictions observed in arid climates (BWh and BWk); Mediterranean and temperate (Cs and Cw); wet continental (D); and glacial (E) [96].

The occurrence of *U. subquadripara* is highly dependent on water availability and quality [97]. However, when compared to other macrophytes, such as Hymenachne pernambucensis, *U. subquadripara* is more resistant to periods of drought [98], which may be related to greater accumulation of biomass, efficiency in the use of N and P [99], and root and stem regrowth [10]. In addition, *U. subquadripara* is also terrestrial, being used as pasture [54]. Therefore, the species does not occur in arid climates but in semi-arid climate regions (BSh). In addition, species of the genus Urochloa have cold stress as the main distribution limiting factor [37].

The regions considered suitable in India and the African continent are classified as tropical savanna climate (Aw), monsoon climate (Am), and equatorial climate (Af), which are also predominant in Brazil. Regions of Argentina with high climatic suitability have humid subtropical climates (Cfa) and oceanic climates (Cfb) [96], similar to regions of Australia, the country with the highest number of occurrences. Sub-Saharan Africa concentrates the largest number of endemic macrophytes [28,95]; therefore, the dissemination of *U. subquadripara*, whose invasion success mechanism consists of a competition, mainly shading of submerged species [97], would pose a risk to these species.

4.2. Native Species

4.2.1. Eichhornia crassipes

The worldwide distribution of *E. crassipes* is the widest of the species studied, occurring in tropical and subtropical regions and extending into Mediterranean and temperate climates. *Eichhornia crassipes* are reported in 57.28% of the world, and only 1.2% of cataloged macrophytes have this vast distribution [95].

The occurrence of the species is limited by cold, heat [39], and drought; however, its distribution shifts to higher latitudes than *U. subquadripara*, colonizing regions with humid continental climate (Dfb and Dfa) [96]. The model proposed by Kriticos and Brunel [39] highlights that, with climate change, the species may colonize higher latitudes due to reduced cold stress and be limited by increased heat stress in Africa, India, Brazil, and Australia. [39]. This pattern is already observed in the current model, mainly about the displacement to the north.

In the current model, occurrences of *E. crassipes* in temporary, permanent, or ephemeral water courses were considered [100]. However, the model by Kriticos and Brunel [39] does not include reports in ephemeral watercourses in the United States of America (Colorado, Connecticut, Illinois, Maryland, Seattle, New England) and casual occurrences in European countries. Whereas under periodic drought conditions, *E. crassipes* present phenotypic plasticity [66]. Progressive drought can reduce the photosynthesis of the species; however, morphological adaptations are strategies of *E. crassipes* that survive both as an emergent macrophyte and as a terrestrial [66,101].

Control strategies after species establishment are difficult and costly. Biological, chemical, and mechanical control methods have been used to reduce the density of *E. crassipes* plants [102]; however, the main measure adopted is the prevention of dissemination, with the creation of laws that prevent the commercialization and distribution of the species [39,103].

4.2.2. Salvinia minima

The distribution of *S. minima* is the narrowest of the studied species, occurring in 14.54% of the world area [95]. The species occurs in tropical (Af, Am, Aw), humid subtropical (Cfa), and oceanic (Cfb) climatic regions [96]. The generated model highly correlates with the *S. minima* distribution data, with no occurrence points inserted in inappropriate regions.

Regions of Europe and China considered suitable have climatic conditions similar to the United States of America and southern South America [96]. Meanwhile, regions of the African continent and

Australia have similar climatic characteristics to Brazil and India [96]. *Salvinia minima* were first identified in South Africa in 2022 at the Hartbeespoort dam, where it already causes damage to recreational activities, fishing, and boat traffic [104]. The presence of the macrophyte is worrying because, according to the model obtained, sub-Saharan Africa is suitable for the occurrence of *S. minima*; thus, laws that require its control have been applied [104].

Salvinia minima are highly prevalent in North America. The species was introduced to the United States through the aquarium trade [105], first identified in St. John's in Florida in 1928 [106], and expanded in the country due to high propagation, with a leaf doubling time of 3.5 days [26]. It is widely found in the coastal region of the country and problematic in the states of Florida and Louisiana, where biological control is carried out with Cyrtobagous salviniae Calder and Sands (Coleoptera: Curculionidae) [92,105].

Despite causing economic and biodiversity damage, *S. minima* have a high potential to be used in phytoremediation due to its rapid growth, adaptation to different climatic conditions, and tolerance to contaminants [68]. The species has already been identified as a phytoremediator of sewage treatment water, reducing the content of total suspended solids [107], heavy metals such as chromium [69,108], lead [109], cadmium, nickel and zinc [110]; and herbicides such as atrazine [111].

4.3. Co-Occurrence of Urochloa subquadripara with Native Species

Species distribution models generated by CLIMEX have limitations because they only consider climatic factors, not considering, for example, biotic interactions [112]. In addition to climate and the occurrence of watercourses, biological invasion by macrophytes depends on the composition of the community, the existence of natural enemies, and correlations with native species [23].

The invasion of *U. subquadripara* is positively correlated with the occurrence of *E. crassipes* and *S. minima* [7]. Furthermore, as it occurs in the epiphytic life form, the presence of native macrophytes such as *E. crassipes* increases the pressure of *U. subquadripara* propagules, favoring local colonization and the invasive expansion [11]. Therefore, considering the co-occurrence between species allows for identifying the potential distribution of the invader, minimizing model limitations.

The result of the co-occurrence of *U. subquadripara* with *E. crassipes* and *S. minima* has tropical and subtropical regions as very suitable areas. However, there is an increase in moderately suitable regions with humid subtropical (Cfa) and oceanic (Cfb) climates in the United States of America, China, and European countries [96]. This occurs because the modeling of both native species identified these locations as climatically suitable, therefore, likely for biological invasion by *U. subquadripara*.

These results align with climate forecasts, which estimate that northern latitudes will have higher warming rates than the rest of the world [113], which causes an increase in lake temperatures and a more extended melting period [114]. In addition, higher precipitation rates may occur [28], which, associated with surface runoff, transports more nutrients to the lakes, favoring the occurrence of emerging macrophytes [115]. Therefore, *U. subquadripara* can move to temperate climates [116].

The northern hemisphere encompasses the most significant number of lakes in the world [84] and the largest number of lakes larger than 10 ha [117]. Thus, the risk of invasion is aggravated because the surface area of the watercourse is positively correlated with the richness of macrophytes [27]. It is predicted that, with climate change, the number of invasive macrophytes in Europe and North America will increase [118], which would suppress native macrophytes, mainly underwater [28].

Brazil, sub-Saharan Africa, and the Asian continent were classified as very suitable. These locations are also subject to climate change; however, the impact on macrophytes' occurrence depends on the lake's depth [28]. Shallow lakes subject to warming [119] and decreases in precipitation [120] can reduce water volume and colonization by invasive macrophytes such as *U. subquadripara*. However, in the southern hemisphere, the concern with the invasion of macrophytes is mainly in hydroelectric reservoirs and large watercourses.

Anthropogenic changes, such as the creation of dams and hydroelectric plants, can interfere with natural geographic barriers and encourage the invasion of exotic species [10]. Generally,

hydroelectric reservoirs are more invaded than natural lakes [121] due to the increase of nutrients in the water, sedimentation, and changes in biotic interactions [122,123]. Macrophytes obstruct the water intake in the reservoirs, reducing efficiency in energy generation and causing economic losses [124]. There are around 391 large hydroelectric plants in Brazil [125]; therefore, the modeling indicates a high risk of invasion since the country is climatically very suitable for *U. subquadripara*, *E. crassipes*, and *S. minima*.

5. Conclusions

Urochloa subquadripara has a high invasive potential; in addition, *E. crassipes* and *S. minima*, considered native, are also considered exotic invasive in other regions and are problematic even in native areas. With climate change favoring the growth and dissemination of floating and emerging macrophytes, the displacement of these species to the northern hemisphere is worrying since it is the region with the most significant number of lakes in the world.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: Global distribution points of *Urochloa subquadripara*, *Eichhornia crassipes* and *Salvinia minima*; Figure S1: Current distribution of *Eichhornia crassipes* plants and Ecoclimatic Index (EI), modeled by Kriticos and Brunel, 2016, using CLIMEX. Unsuitable areas in white (EI = 0), low suitable in light red (0 <EI <30), and high suitable in red (30 <EI <100).

Author Contributions: Tayna Sousa Duque: Conceptualization, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing. Iasmim Marcella Souza: Formal analysis, Investigation, Writing - Original Draft, Writing- Review & Editing. Débora Sampaio Mendes: Formal analysis, Investigation, Writing - Original Draft. Ricardo Siqueira da Silva: Conceptualization, Methodology, Resources, Writing - Review & Editing. Danielle Piuzzana Mucida: Resources, Writing - Original Draft, Writing - Review & Editing, Supervision. Francisca Daniele da Silva: Writing - Review & Editing. Daniel Valadão Silva: Writing - Review & Editing, Resources. José Barbosa dos Santos: Conceptualization, Methodology, Resources, Writing - Original Draft, Writing - Review & Editing.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare that they have no conflict of interest.

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