



Temperature and precipitation influence the distribution of different Cyperaceae life forms: The role of protected areas in the Amazon for conservation

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ABSTRACT

Climate change is the main cause of global biodiversity loss and changes in the structure of ecological communities. Species distribution models are an efficient tool for predicting suitable areas for species and their vulnerability to climate change. In this study, we evaluated the impact of precipitation and temperature (factors of climate change) on 12 species of the Cyperaceae family, classified into three groups: aquatic, amphibian, and terrestrial. Our results provide a comprehensive overview of habitat projections for aquatic, amphibian and terrestrial Cyperaceae species in the Amazon biome under current and future scenarios. We highlight significant range losses projected for species such as *Scleria amazonica* and *Cyperus lacustris* in the future. The relationship between climate and its influence on species distribution is critical, emphasizing the urgent need to conserve biodiversity in the face of climate change. In the models, protected areas were essential refuges for species under threat, highlighting their crucial role in preventing biodiversity loss. Variables such as temperature and seasonality (rainfall variability) strongly influenced the distribution patterns of Cyperaceae species. Seasonal fluctuations such as extreme droughts can influence water availability and the growth dynamics of hydrophytic plants. Amphibian species adapt to temperature fluctuations and changes in precipitation, while terrestrial plants prefer warmer and rainy regions. Our results emphasize the importance of conservation strategies for Amazonian species. We have also shown that protected areas play an essential role in conserving biodiversity and protecting Cyperaceae species from future changes.

1. Introduction

The Amazon exhibits unique hydrological characteristics compared to other regions of the world and harbors the majority of accessible water resources (Ríos-Villamizar et al., 2011). However, this region is undergoing significant changes in land use and land cover due to urbanization and deforestation (Tritsch and Le Tourneau, 2016), that can result in emissions of greenhouse gases to the atmosphere and drive of climate change. These changes impact ecosystems in several regions of the Amazon, especially aquatic environments (Monteiro-Júnior et al., 2015). Changes in the environment cause the removal of riparian

vegetation, leading to increased sediment deposition in rivers and streams and increased nutrient fluxes in these degraded environments (Couceiro et al., 2007). Other consequences are observed in the water quality of the impacted environments, with lower pH and dissolved oxygen, and higher conductivity, temperature and total dissolved solids (Ríos-Villamizar et al., 2011).

Several species can exhibit low tolerance to environmental changes, primarily due to their biological characteristics, such as natural abundance and habitat selection for population establishment (Henle et al., 2004). These species include plants that occupy both terrestrial and aquatic niches, such as the Cyperaceae Juss. This family stands out

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because is one of the three largest plant families among the monocots, comprising about 95 genera and 5690 species, is cosmopolitan, highly frequent in tropical regions, and inhabits almost all terrestrial and aquatic habitats (Maciel-Silva et al., 2019; Govaerts, 2020; Larridon, 2022). Species of this family live in wetlands such as swamps, bogs, ponds, and riverbanks (Gil and Bove, 2004; Simpson, 2006), also in terrestrial places and even occurring in desert environments (Leck and Schütz, 2005). Cyperaceae species play a crucial role in maintaining the balance of ecosystems by controlling eutrophication, sedimentation, and water purification. They are also suitable as ornamental plants and create aquarium microhabitats (Piedade et al., 2005). Cyperaceae species can be the most important plants in temporary aquatic ecosystems, typical of the Amazon region that become dry during the dry season and flooded during the rainy season (Maltchik and Pedro, 2001). This is because this group presents great vegetative diversity, with species adapted to arid and wet soils; some are considered purely terrestrial species, others are considered purely aquatic (with life cycle entirely in water), and some species called amphibian are in this transition zone (Nilsen and Orcutt, 1996).

Recent studies indicate that many herbs are under increasing threat due to climate change and environmental degradation, especially in regions such as the Amazon, where aquatic and terrestrial habitats are particularly vulnerable (Sentinella et al., 2020). Some species have already been classified as threatened due to habitat destruction and changes in water regimes (Carvalho et al., 2023). In addition, species with restricted niches, such as many aquatic Cyperaceae, are highly susceptible to extreme climate variations, which can intensify processes such as eutrophication and the loss of essential habitats (Floury et al., 2021). The increasing frequency of extreme climate events, such as prolonged droughts and intense floods, aggravates the extinction risk of these species, reinforcing the importance of investigating and conserving these groups, especially in protected areas, which often represent the last refuges for threatened biodiversity (Broennimann et al., 2007; Veríssimo et al., 2011).

Another point to consider is that the Amazon region is a center of endemism and landscape changes such as converting forest areas to pasture, agriculture, paved roads, mining, and recurrent forest fires threaten these species (Solar et al., 2016). Despite its importance, few human and financial resources are directed to investigate such relationships in the Amazon (Whittaker et al., 2005; Carvalho et al., 2023). Therefore, open-access datasets associated with Species Distribution Models (SDMs) are valuable resources for investigating species distribution patterns and identifying priority areas for conservation across this biome. SDMs estimate the probability of occurrence of a species based on suitable habitats for its population (Guisan and Zimmermann, 2000; Guisan and Thuiller, 2005; Peterson et al., 2011), identify potential threats to biodiversity loss, fill knowledge gaps on species distribution (Wallacean gaps), and define biodiversity conservation areas (Giannini et al., 2012; Velazco et al., 2019) in terrestrial and aquatic ecosystems (Perez-Sweeney et al., 2003).

Therefore, the SDM maps help in species management (Araújo et al., 2011; Nóbrega and De Marco, 2011) by providing valuable information about patterns and distributions of important unsampled groups (Cayuela et al., 2009), and can be used to evaluate the effectiveness of current protected area networks (Rodrigues et al., 2003; Loucks et al., 2008). Recently, these protected areas have played an important and effective role in conserving populations of species threatened or potentially affected by human activities (Veríssimo et al., 2011). However, other studies have shown that these protected areas can be either ineffective or insufficient for biodiversity conservation (Scott et al., 2001), which increases the importance of evaluating these areas. SDMs are also used to predict possible changes in distribution ranges based on climate change scenarios (Pearson, 2006; Broennimann et al., 2007; Park et al., 2022). These models of future distribution summarize information on distribution patterns and predictions of their suitability for different habitats (Barrows et al., 2010; Sinclair et al., 2010). They are

therefore important tool for climate change-based biology (Zhang et al., 2011) and for conservation prioritization based in future scenarios (Floury et al., 2021).

Given this scenario, we aimed to assess the impacts of climate change on different life forms of the Cyperaceae family (aquatic, amphibian, and terrestrial) in the Amazon biome using SDMs. We hypothesize that (1) the increase in frequency and intensity of extreme climatic events such as prolonged droughts and/or extreme floods will cause severe changes in the Amazonian environments, negatively affecting the composition and distribution of aquatic species of Cyperaceae; (2) terrestrial and amphibian species of Cyperaceae will be more tolerant to drought and able to survive longer periods, thus, they will respond positively to the effects of climate change, dominating the plant communities in aquatic environments affected by droughts; however, the distribution of terrestrial and amphibian species of Cyperaceae will be negatively affected by extreme flooding; finally, (3) protected areas will be crucial for the conservation and protection of Cyperaceae species, as species outside these areas will suffer more than species within protected areas as climate change progresses.

2. Material and methods

We downloaded species data from the Global Biodiversity Information Facility (GBIF) (www.gbif.org), using “Cyperaceae” and “Brazil” as search terms (GBIF Occurrence Download doi:10.15468/dl.6kg4sm). The nomenclature of all species was updated according to botanical standards using the FLORA E FUNGA DO BRASIL website (<https://floradobrasil.jbrj.gov.br/reflora>), assigning the lowest taxonomic level possible to all individuals.

We downloaded the species coordinates in the R program (R Core Team, 2023) using the function ‘gbif’ from the ‘dismo’ package (Hijmans et al., 2022). With the accumulated data, we searched for inconsistencies (cleaning pipeline; Gomes et al., 2018) with the ‘GeoClean’ function and the ‘speciesgeocodeR’ package version 1.0–4 (Zizka, 2015) in R (version 4.2.3). This function removes geographic records with incorrect references, duplicates, and latitude and longitude equal to zero. Finally, 12 species were selected based on their spatial distribution, and number of occurrences. Four were classified as aquatic: *Scleria amazonica* Camelb., M.T. Strong & Goetgh., *Cyperus lacustris* Schrad. ex Nees, *Eleocharis nana* Kunth, and *Eleocharis obtusetrigona* (Lindl. & Nees) Steud., four as amphibian: *Cyperus schomburgkianus* Nees, *Hypolytrum strictum* Poepp. & Kunth, *Rhynchospora schomburgkiana* (Boeckeler) T. Koyama, and *Scleria pusilla* Pilg., and four as terrestrial: *Bulbostylis amambaeyensis* Barros, *Cyperus reflexus* Vahl, *Rhynchospora albida* (Nees) Boeckeler, *Scleria robusta* Camelb. & Goetgh. Each group occurs in dry, moist, and completely flooded places. The species classification into these three groups was confirmed by Gil ASB experts in the family and author of this work, linked to the Taxonomy Laboratory of the Museu Paraense Emílio Goeldi, also by literature and information available in *Flora e Funga do Brasil* (n.d.) (Ribeiro et al., 2011; Oliveira et al., 2011; Leite et al., 2012). After the entire filtering process, we were left with 728 occurrence points, whose spatial distribution was analyzed to ensure the representativeness of the selected species.

We used the 19 bioclimatic variables available in the WorldClim database that can explain the geographical distribution of the group. We first performed a Principal Component Analysis (PCA) to reduce the dimensionality of the bioclimatic variables and avoid multicollinearity problems (Silva et al., 2014). Multicollinearity can be problematic in model fitting, leading to instability in the models created (De Marco and Nóbrega, 2018). The axes generated by PCA and based on the 19 bioclimatic variables were used as predictors for modeling the potential distribution of species (SDMs).

The models (SDMs) were created using a resolution of 5 arc-minutes for current models (data from 1970 to 2000) and future scenarios. For the future, we chose the GCM SSP585. The climate models included Australian Community Climate and Earth System Simulator Coupled

Model System (ACCESS-CMS); Centro Euro-Mediterraneo sui Cambiamenti Climatici Earth System Model version 2 (CMCC-ESM2); Hadley Centre Global Environment Model version 3, Global Coupled 31, Low Resolution (HadDEM3-GC31-LL); Institut Pierre-Simon Laplace Climate Model version 6A, Low Resolution (IPSL-CM6A-LR); and Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM2-0). We used the MAXENT algorithm (Maximum Entropy – MXS: Phillips et al., 2017), Random Forest (RF: Liaw and Wiener, 2002), and Support Vector Machine (SVM: Salcedo-Sanz et al., 2014). The pseudo-occurrences were ecologically delineated, randomly distributed, and spatially separated from the presence-only data. The maps were created using ensembles, as they provide precision and robustness to the predictions by combining different approaches (Araújo and New, 2007). We separated the unique presence data into 70 % for testing data and 30 % for training data. We used the 'ENMTML' function from the "ENMTML" package version 1.0.0 (Andrade et al., 2020) in R.

We applied rarefaction to the occurrence points using the command `thin_occ = c(method = 'CELLSIZE')`. This approach ensures that multiple points are not included if they are too close to each other, thus avoiding the introduction of bias into the models due to sparse data.

The SDMs were initially developed for a broad area of South America, allowing relevant environmental variables to be considered in a broader context. These models were then cropped to the region of interest, which is the Amazon. This approach helps ensure that predictions are robust to the environmental variability of the region and minimizes potential biases associated with modeling in a limited geographic area.

To analyze the relationship between the bioclimatic variables and the species distribution (SDMs) we used three Generalized Linear Models (GLMs), one for each group (aquatic, terrestrial, and amphibian). We did one GLM for each group (aquatic, terrestrial and amphibious), because these groups exhibit distinct ecological characteristics and respond differently to environmental factors. By applying a separate GLM to each group, we were able to model these unique responses more accurately, accounting for the variables that influence each group independently. To avoid problems such as overfitting and multicollinearity, we selected four bioclimatic variables from the original 19 for inclusion in the GLMs. We used the variables that contributed most to the formation of the first two axes in the PCA and had low correlation with each other ($r < 0.7$). The variables with correlation coefficients below 0.7 were mean annual temperature (bio_1), temperature seasonality (bio_4), annual precipitation (bio_12), and precipitation seasonality (coefficient of variation - bio_15). The distribution family used in the GLMs was "binomial" as our data are 0 and 1 (Wu, 2005). We used the Area Under the Curve (AUC) to test the predictive performance of the models (Swets, 1988; Pearson et al., 2006; Li et al., 2012; Zhang et al., 2012). To delineate the accessible area of species, we used a mask of the Amazon biome (MASK) (Peterson et al., 2011).

To test the effectiveness of the protected areas, we created maps using QGIS software and data from Instituto Brasileiro de Geografia e Estatística (IBGE) with the date SIRGAS 2000. We also used available shapefiles of protected areas (INPE – Terra Brasilis: <https://terrabrasilis.dpi.inpe.br/> accessed on 24 January 2024), grouped them as 'protected areas' using the 'intersection' function of QGIS, and calculated the area of species within these protected areas. Thus, we measured the total area of the biome and then applied a simple three-step rule to obtain the correct percentage value. This process was performed for both current and future scenarios.

3. Results

3.1. Species Distribution Models for aquatic, amphibian, and terrestrial Cyperaceae

We recorded 728 unique occurrences of the 12 species selected for the SDM. Cyperaceae species included *Bulbostylis amambayensis* Barros ($n = 12$ occurrences); *Cyperus lacustris* Schrad. ex Nees ($n = 74$); *Cyperus*

reflexus Vahl ($n = 256$); *Cyperus schomburgkianus* Nees ($n = 150$); *Eleocharis nana* Kunth ($n = 44$); *Eleocharis obtusetrigona* (Lindl. & Nees) Steud. ($n = 51$); *Hypolytrum strictum* Poepp. & Kunth ($n = 25$); *Rhynchospora albida* (Nees) Boeckeler ($n = 24$); *Rhynchospora schomburgkiana* (Boeckeler) T.Koyama ($n = 28$); *Scleria amazonica* Camelb., M.T. Strong ($n = 23$); *Scleria pusilla* Pilg. ($n = 14$); and *Scleria robusta* Camelb. & Goetgh ($n = 27$).

The aquatic species *S. amazonica*, *C. lacustris*, *E. nana*, and *E. obtusetrigona* showed different suitability patterns in the current model. *C. lacustris* (Fig. 1 – B1) showed the largest suitability area, reaching a maximum score of 1 and occupying 88 % of the area considered suitable for this species. *S. amazonica* (Fig. 1 – A1) showed an extensive transition area and several points with maximum suitability scores, totaling 53 % of the area predicted as suitable by the model. In contrast, *E. nana* and *E. obtusetrigona* occupied the southern part of the Amazon region (Fig. 1 – C1 and D1), with 0.7 of suitability. AUC values of the ensemble for the four aquatic species showed reliable predictions ranging from 0.917 to 0.980. *S. amazonica* and *C. lacustris* had 60 % and 54 % of their suitable area within protected areas of the Amazon in the current model, respectively (Fig. 2 – A1 and B1). *E. nana* and *E. obtusetrigona* had 43 % and 42 % of suitable areas within protected units in the current model, respectively (Fig. 2 – C1 and D1).

In the future model, the four aquatic species showed a considerable loss of accessible areas. *S. amazonica*, *E. nana*, and *E. obtusetrigona* had high suitability values but with a considerable reduction of the available areas (Fig. 1 – A2, C2, D2). *C. lacustris* presented good suitability in the model but its total area accessible will decline by approximately 44 % (Fig. 1 – B2). *S. amazonica* and *E. obtusetrigona* will experience a significant loss of suitable area with a decrease of 43 % each (Fig. 1 – B2, D2). According to the ensemble AUC values, the prediction results were largely reliable and ranged between 0.787 and 0.951 for the four species. *S. amazonica* and *E. obtusetrigona* had 87 % and 76 % of their suitable area within protected areas of the Amazon in the future respectively (Fig. 2 – A2 and D2), while *C. lacustris* and *E. nana* had 70 % and 56 % of suitable areas within protected areas in the future, respectively (Fig. 2 – B2 and C2).

In the current model, the amphibian species *C. schomburgkianus*, *H. strictum*, *R. schomburgkiana*, and *S. pusilla* showed variable suitability areas among them. *R. schomburgkiana* had 68 % of suitable areas, in contrast to *S. pusilla* which had 8 % of suitable areas. *H. strictum* and *R. schomburgkiana* had regional suitability reaching the maximum value of 1 (Fig. 3, CB1 and DC1). *S. pusilla* had only 0.9 suitability in the southern Amazon, a region associated with the deforestation arc. *H. strictum* (Fig. 3 – B1) had higher suitability in the best-preserved areas of the region. *R. schomburgkiana* had the highest percentage of the predicted area (53 %), while *S. pusilla* had an extremely low area predicted by the model (2 %). The AUC values of the ensemble for the four amphibian species indicate a high reliability of the prediction results, ranging between 0.916 and 0.982. Regarding the current suitability of amphibian species within protected areas, *H. strictum* showed the highest percentage of suitability (64 %; Fig. 4 – B1), and *S. pusilla* the lowest (23 %; Fig. 4 – D1).

The predictions for the future also showed a significant loss of accessible areas for amphibian species. *C. schomburgkianus* will suffer the greatest habitat loss, losing 34 % of its total suitable area predicted by the model (Fig. 3 – A2). *R. schomburgkiana* will lose approximately 21 % of its suitable areas and migrate further to northern Amazon areas (Fig. 3 – C2). Conversely, *H. strictum* is the species that lost the least accessible areas and showed only a slight shift to the western part of the Amazon (Fig. 3 – B2). *S. pusilla*, which already had a small accessible area, the future models predict an 8 % increase in accessible areas, suggesting that this species will seek other niches. The AUC values for the four amphibian species were reliable ranging from 0.870 to 0.972. Regarding the future predictions of amphibian species within protected areas, *R. schomburgkiana* showed the highest percentage of suitable areas (68 %; Fig. 4 – C2), and *S. pusilla* the lowest (44 %; Fig. 4 – D2).

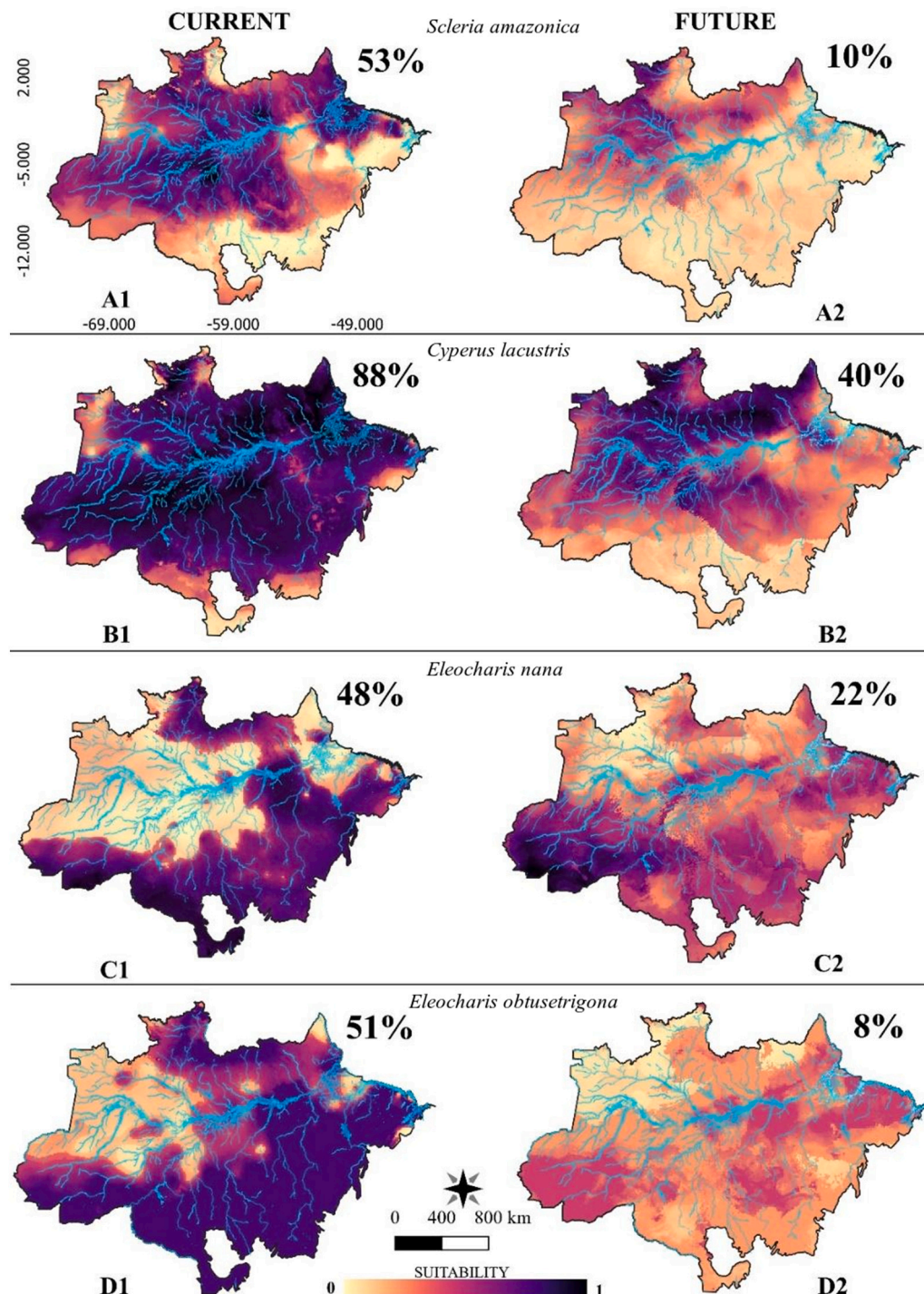


Fig. 1. Suitability model for aquatic Cyperaceae in the Brazilian Amazon. Predictions made by an ensemble of algorithms for the current time and future (2061–2080). Suitability areas range from zero (lighter shades) to one (darker shades). The hydrography of the Brazilian Amazon is shown in blue. A1 and A2 are *S. amazonica* distribution for the current and future, respectively; B1 and B2 are *C. lacustris* distribution for the current and future, respectively; C1 and C2 are *E. nana* distribution for the current and future, respectively; D1 and D2 are *E. obtusetrigona* distribution for the current and future, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Regarding the terrestrial Cyperaceae species in the current predictions, *R. albida* and *S. robusta* showed the suitability of 1; *R. albida* had the largest suitability area predicted by the model (74 %), and *C. reflexus* the lowest (Fig. 5 - C1 and B1, respectively). *B. amambayensis* model presented a low AUC (0.604) (Fig. 5 - B1). The AUC values of the ensemble for the other three terrestrial species were reliable, with values ranging from 0.604 to 0.995. *C. reflexus* suitability areas were 100 %

within areas with high deforestation rates in the Amazon region (Fig. 5 - B1). *S. robusta* had suitable areas associated with regions with lower deforestation rates in the Amazon region (Fig. 5 - D1). Regarding the suitable areas of terrestrial species within protected areas in the current model, we observed that *B. amambayensis* had a high percentage of suitability areas (73 %; Fig. 6 - A1), while *C. reflexus* occupied 35 % of its suitability areas within protected areas (Fig. 6 - B1).

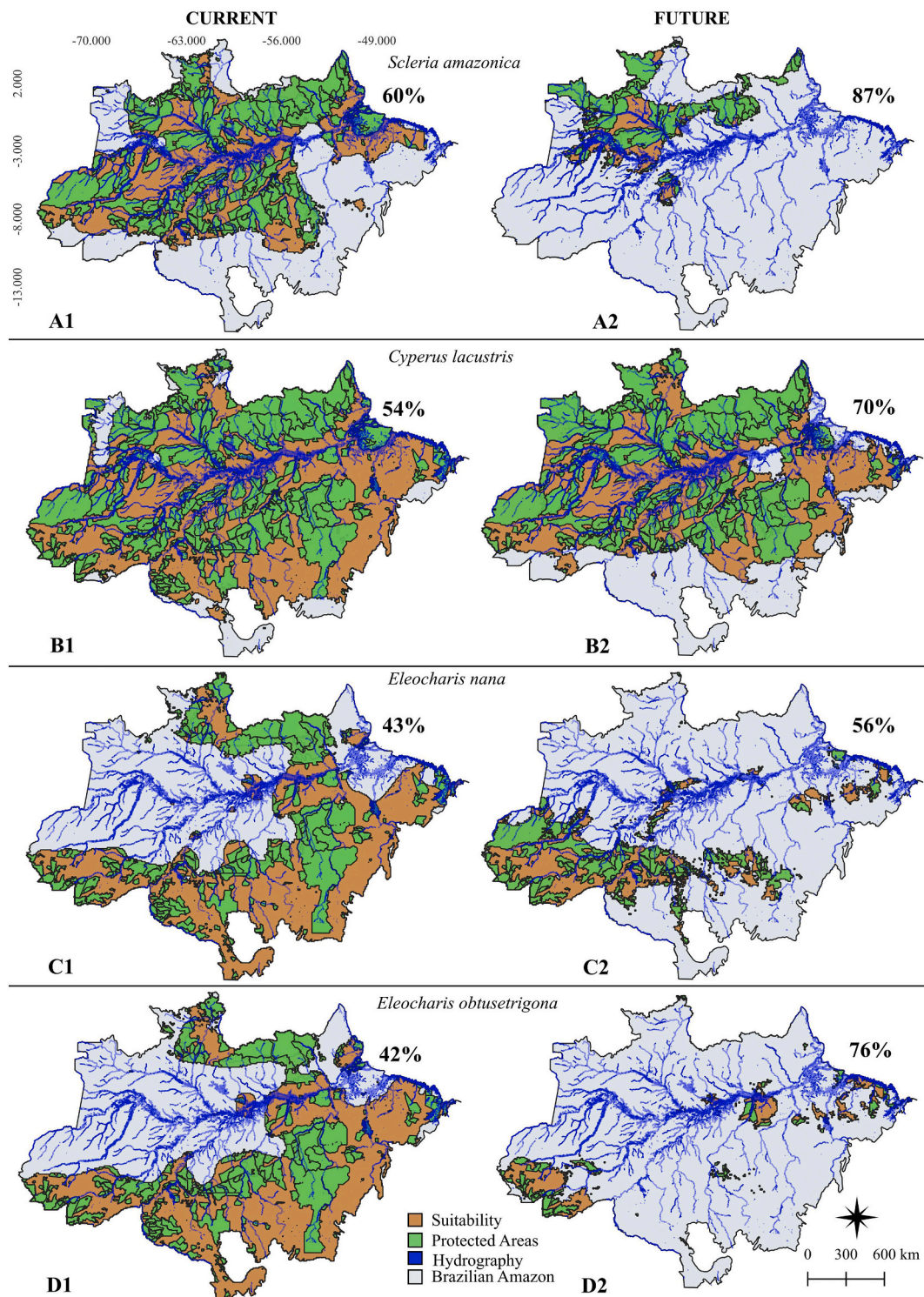


Fig. 2. Relationship between protected areas and aquatic Cyperaceae suitability in the Brazilian Amazon Predictions made by an ensemble of algorithms for the current time and future (2061–2080). Gray represents the Brazilian Amazon region; brown represents suitable areas; green represents the intersection between protected areas and species suitability. The hydrography of the Brazilian Amazon is shown in blue. A1 and A2 are *S. amazonica* distribution for the current and future, respectively; B1 and B2 are *C. lacustris* distribution for the current and future, respectively; C1 and C2 are *E. nana* distribution for the current and future, respectively; D1 and D2 are *E. obtusetrigona* distribution for the current and future, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the future, for terrestrial species, we also observed a significant loss of accessible areas in the Amazon. *R. albida* and *C. reflexus* lost the most accessible habitats, retaining 7 % of suitable areas (Fig. 5 – B2 and C2). *C. reflexus* will occur in areas further in the Amazon's northwestern part and showed an adequacy of 0.3 (Fig. 5 - B2). *B. amambayensis* was

also affected, retaining 10 % of suitable areas within areas with low deforestation rates (Fig. 5 – A2), this species will suffer a loss of 41 % of its current range in the future. In the future, the AUC values of the ensemble for terrestrial species were reliable, ranging from 0.729 to 0.975. Considering future predictions and terrestrial species within

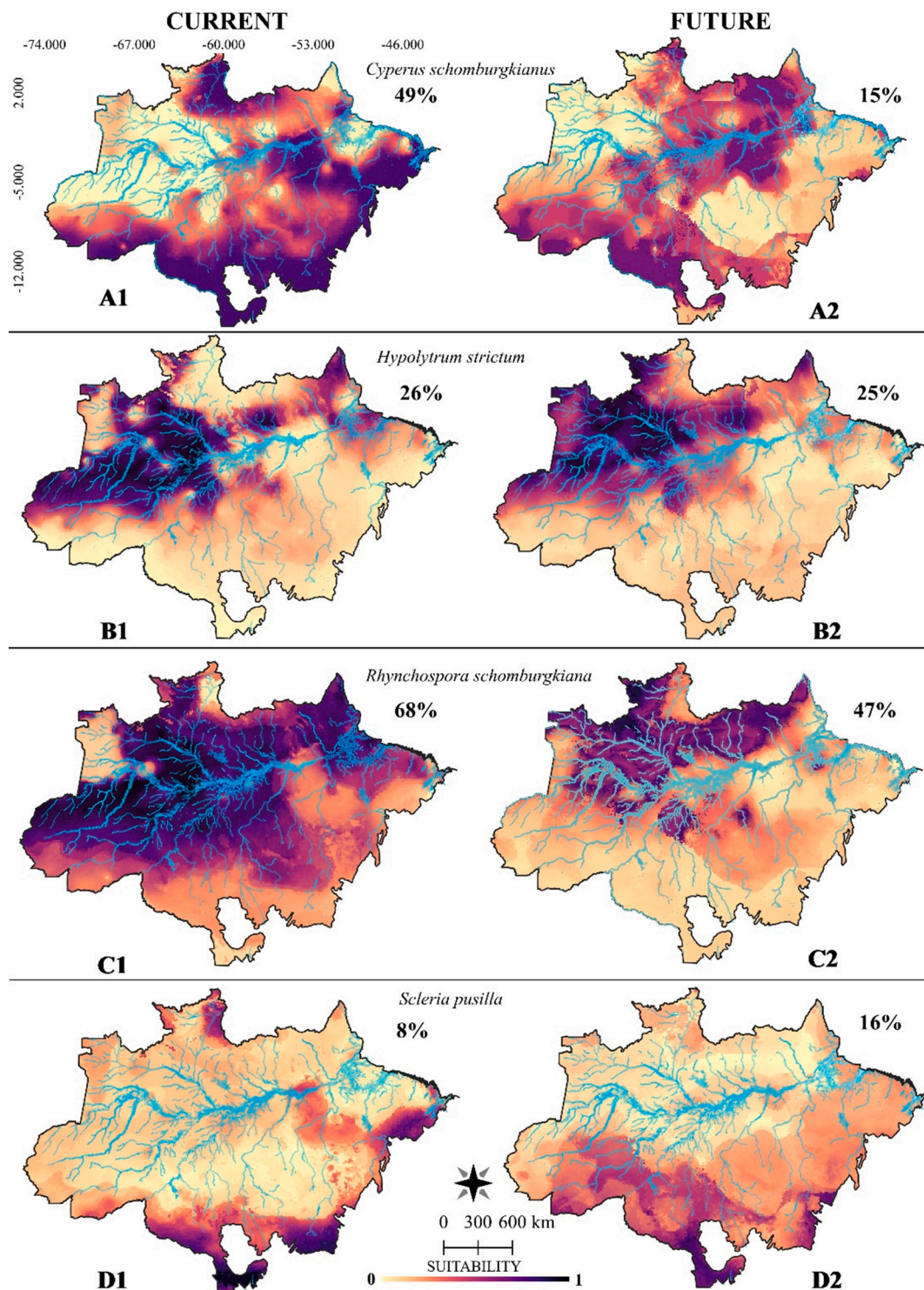


Fig. 3. Suitability model for amphibious Cyperaceae in the Brazilian Amazon. Predictions made by an ensemble of algorithms for the current time and future (2061–2080). Suitability areas range from zero (lighter shades) to one (darker shades). The hydrography of the Brazilian Amazon is shown in blue. A1 and A2 are *C. schomburgkianus* distribution for the current and future, respectively; B1 and B2 are *H. strictum* distribution for the current and future, respectively; C1 and C2 are *R. schomburgkiana* distribution for the current and future, respectively; D1 and D2 are *S. pusilla* distribution for the current and future, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

protected areas, *B. amambayensis* decreased its suitable areas (13 %; Fig. 6 – A2). *R. albidia* presented 70 % of its suitable areas within protected areas of Amazonia, value greater than the current model. *C. reflexus* and *S. robusta* also increased their distribution within protected areas in the future (Fig. 6 - B2 and D2).

3.2. Relationship between the bioclimatic variables and the species distribution (SDMs)

In the current scenario, the annual mean temperature and temperature seasonality (variables related to habitat preferences) were

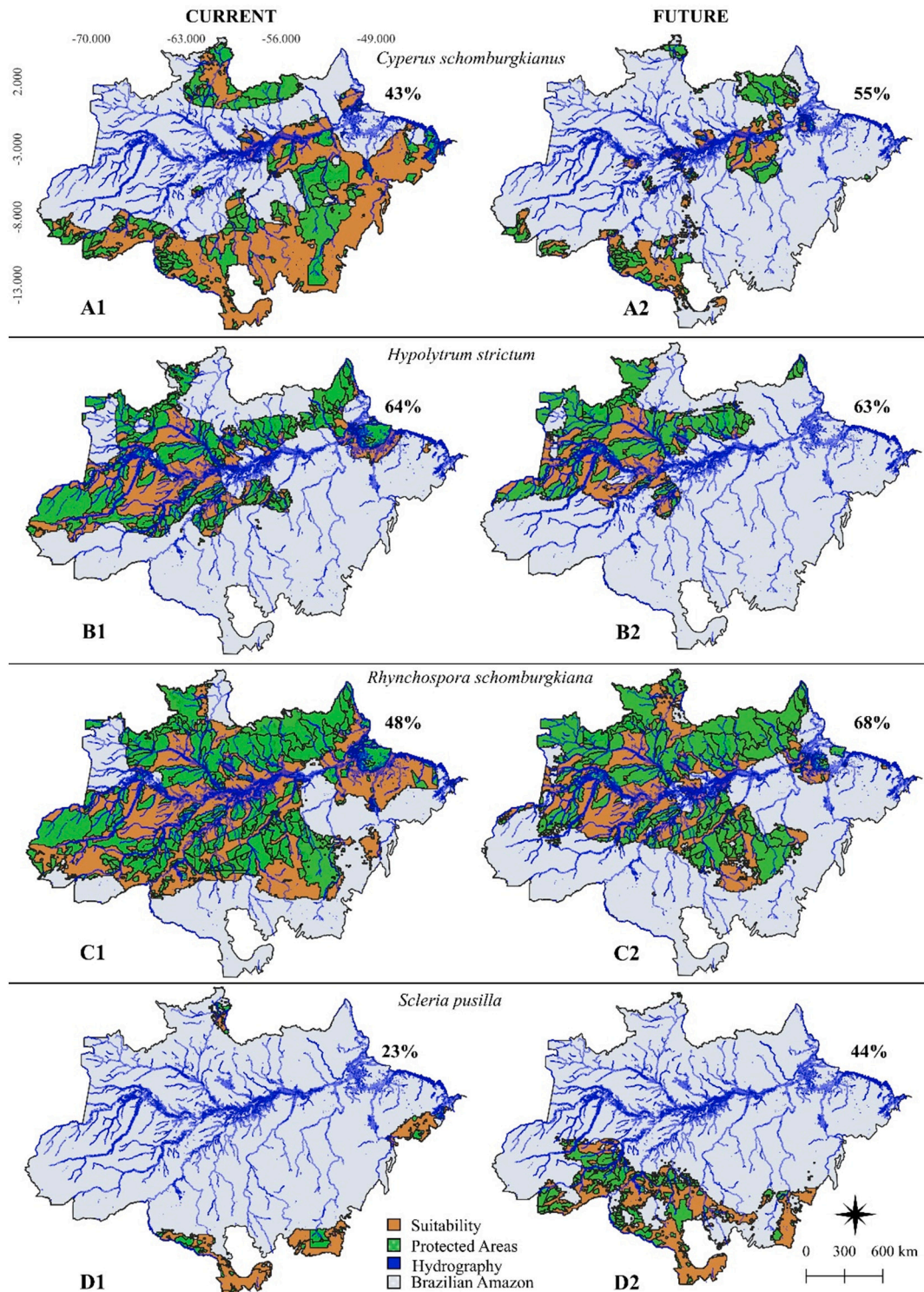


Fig. 4. Relationship between protected areas and amphibian Cyperaceae suitability in the Brazilian Amazon Predictions made by an ensemble of algorithms for the current time and future (2061–2080). Gray represents the Brazilian Amazon region; brown represents suitable areas; green represents the intersection between protected areas and species suitability. The hydrography of the Brazilian Amazon is shown in blue. A1 and A2 are *C. schomburgkianus* distribution for the current and future, respectively; B1 and B2 are *H. strictum* distribution for the current and future, respectively; C1 and C2 are *R. schomburgkiana* distribution for the current and future, respectively; D1 and D2 are *S. pusilla* distribution for the current and future, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

positively associated with the distribution of aquatic species and negatively with the distribution of amphibian species ($p < 0.005$; Table 1). The annual mean temperature was also positively associated with the distribution of terrestrial species, while precipitation seasonality

negatively influenced these species (Table 1).

In the future scenario, the distribution of aquatic species was positively associated with the annual mean temperature and negatively with precipitation seasonality (Table 2). The distribution of amphibian

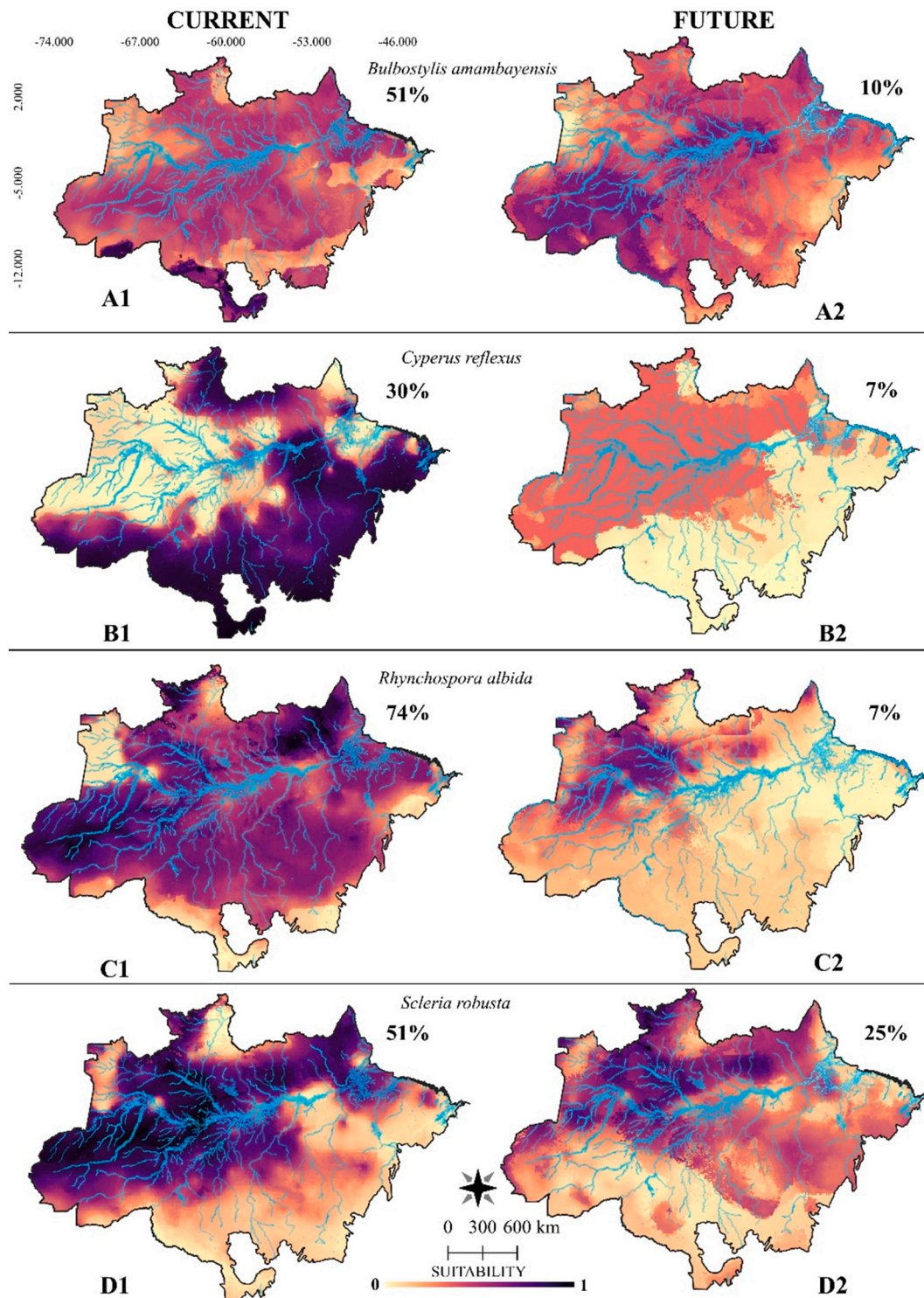


Fig. 5. Suitability model for terrestrial Cyperaceae in the Brazilian Amazon. Predictions made by an ensemble of algorithms for the current time and future (2061–2080). Suitability areas range from zero (lighter shades) to one (darker shades). The hydrography of the Brazilian Amazon is shown in blue. A1 and A2 are *B. amambayensis* distribution for the current and future, respectively; B1 and B2 are *C. reflexus* distribution for the current and future, respectively; C1 and C2 are *R. albida* distribution for the current and future, respectively; D1 and D2 are *S. robusta* distribution for the current and future, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

species was influenced negatively by annual mean temperature and temperature seasonality (Table 2), and positively by precipitation seasonality (Table 2). Annual mean temperature and precipitation seasonality negatively influenced the distribution of terrestrial species (Table 2).

4. Discussion

Our results show that the increase in the intensity and frequency of climate events, such as extreme droughts and floods, resulted in the loss of areas suitable for Cyperaceae species. Terrestrial and amphibian species are more resilient to climate change but were negatively affected

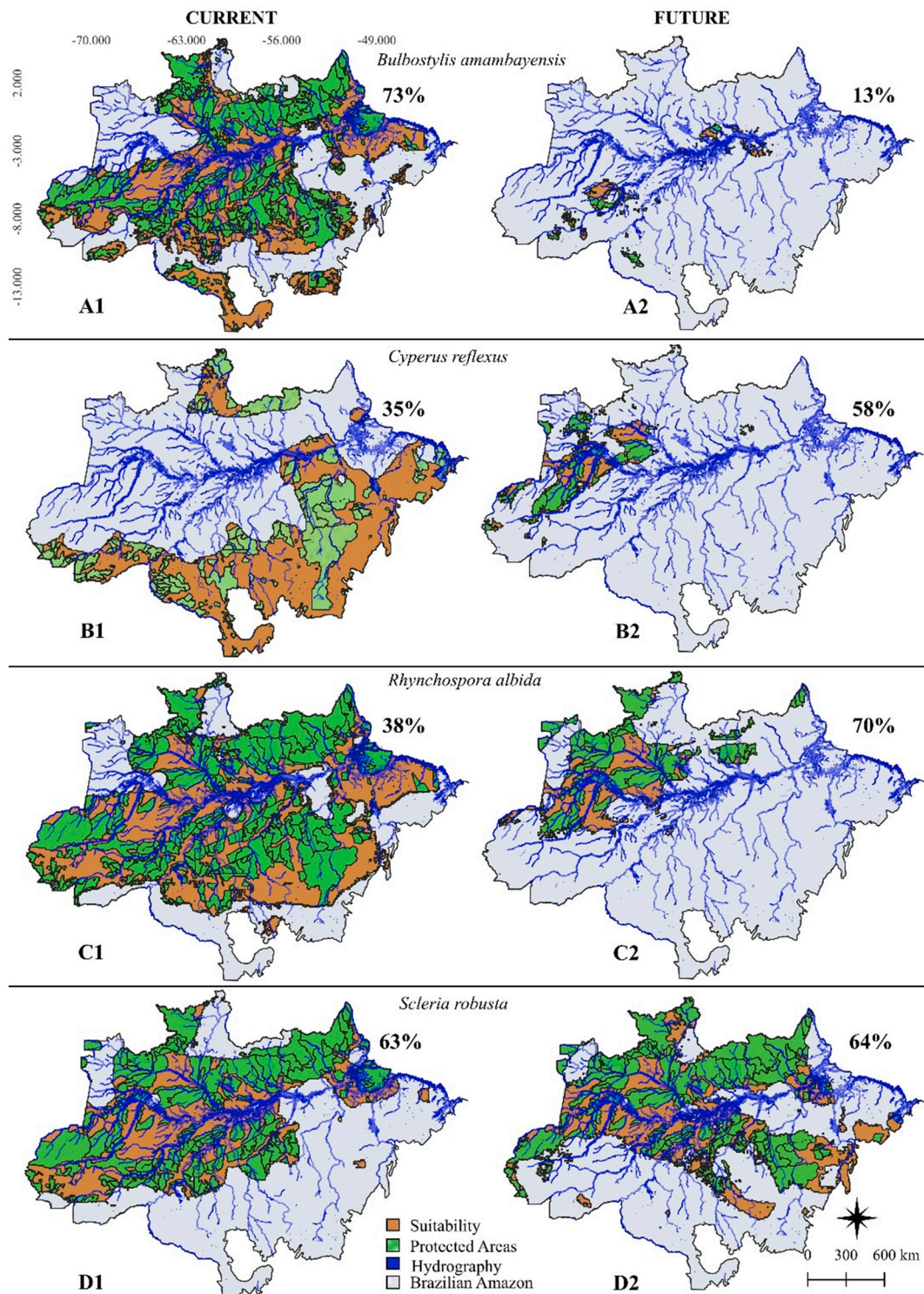


Fig. 6. Relationship between protected areas and terrestrial Cyperaceae suitability in the Brazilian Amazon Predictions made by an ensemble of algorithms for the current time and future (2061–2080). Gray represents the Brazilian Amazon region; brown represents suitable areas; green represents the intersection between protected areas and species suitability. The hydrography of the Brazilian Amazon is shown in blue. A1 and A2 are *B. amambayensis* distribution for the current and future, respectively; B1 and B2 are *C. reflexus* distribution for the current and future, respectively; C1 and C2 are *R. albida* distribution for the current and future, respectively; D1 and D2 are *S. robusta* distribution for the current and future, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by extreme flooding scenarios. Furthermore, protected areas can be a refuge for most species in future projections and will be crucial to conserve these species as climate change increases. Our results provide a comprehensive overview of habitat projections for different species of

aquatic, amphibian, and terrestrial plants in the Amazon biome, in the present and future, considering climate change patterns, this data is essential to understanding populational dynamics in Cyperaceae specific habitats (Tyberghein et al., 2012; Rathore and Sharma, 2023).

Table 1

Shapiro-Wilk test from the GLMs showing the relationship between the bioclimatic variables and the Cyperaceae species distribution (aquatic, amphibian, and terrestrial) for the current. Significant values ($p > 0.005$) are shown in bold.

	Coefficient	Estimate	Std.	Error
Aquatic species	(Intercept)	-2.859	0.621	-4.606
	Annual mean temperature	0.085	0.023	3.705
	Temperature seasonality	0.002	0.001	3.009
	Annual precipitation	0.000	0.000	-0.154
	Precipitation seasonality	-0.002	0.003	-0.581
	Shapiro-Wilk = 0.636; $p < 0.005$			
Amphibian species	(Intercept)	0.648	0.629	1.030
	Annual mean temperature	0.006	0.020	0.305
	Temperature seasonality	-0.003	0.001	-3.439
	Annual precipitation	-0.001	0.000	-6.055
	Precipitation seasonality	-0.002	0.003	-0.812
	Shapiro-Wilk = 0.636; $p < 0.005$			
Terrestrial species	(Intercept)	-0.872	0.264	-3.304
	Annual Mean Temperature	0.034	0.008	4.445
	Temperature Seasonality	0.000	0.000	0.875
	Annual Precipitation	0.000	0.000	-0.276
	Precipitation Seasonality	-0.011	0.002	-6.060
	Shapiro-Wilk = 0.637; $p < 0.005$			

Table 2

Shapiro-Wilk test from the GLMs showing the relationship between the bioclimatic variables and the Cyperaceae species distribution (aquatic, amphibian, and terrestrial) for the future (2061–2080). Significant values ($p > 0.005$) are shown in bold.

	Coefficients	Estimate	Std.	Error
Aquatic species	(Intercept)	-3.867	1.299	-2.977
	Annual mean temperature	0.202	0.048	4.201
	Temperature seasonality	0.000	0.000	0.617
	Annual precipitation	0.000	0.000	-0.778
	Precipitation seasonality	-0.022	0.006	-3.426
	Shapiro-Wilk = 0.636; $p < 0.005$			
Amphibian species	(Intercept)	1.369	1.409	0.971
	Annual mean temperature	-1.468	4.690	-3.130
	Temperature seasonality	-4.064	1.959	-2.074
	Annual precipitation	3.955	2.214	0.179
	Precipitation seasonality	4.890	6.291	7.774
	Shapiro-Wilk = 0.636; $p < 0.005$			
Terrestrial species	(Intercept)	-2.566	8.024	-3.198
	Annual mean temperature	1.821	2.332	7.811
	Temperature seasonality	1.264	9.085	1.391
	Annual precipitation	-6.801	1.842	-0.037
	Precipitation seasonality	-2.964	5.056	-5.862
	Shapiro-Wilk = 0.636; $p < 0.005$			

Our results showed that most aquatic, amphibian, and terrestrial species are widespread in the current scenario, however, in future projections these species will lose large suitable areas, examples are *S. amazonica* and *C. lacustris* which have a wide distribution in the present and will face a drastic loss of suitable habitats in the future. These results highlight the challenges for biodiversity conservation in the Amazon, especially considering climate change that is facilitated by increasing deforestation and urbanization (Ometto et al., 2011; Tritsch and Le Tourneau, 2016; Rodríguez and Redondo, 2023; De Oliveira and Mendes-Oliveira, 2024), and also an opportunity to implement conservation measures in this region. These results also reaffirm the importance of maintaining the existing protected areas in the Amazon, as the future projections showed increased species distribution within these protected areas. Furthermore, mitigating measures against climate change should be developed in impacted areas to protect natural habitats and biodiversity as emphasized by other studies with a similar focus (Levis et al., 2024; Sousa et al., 2024).

Habitat loss is one of the greatest threats to biodiversity, regionally and globally (Simpson et al., 2011; Mantyka-Pringle et al., 2012; Vellend et al., 2017; Brooks et al., 2002). For Cyperaceae species, the loss of

accessible areas due to increased temperature and extreme droughts could lead to irreversible changes, diminishing suitable areas for aquatic and amphibian species. This scenario worsens in flooded areas where these species normally occur (Tanaka et al., 2021; Tiandraza et al., 2023). Flooded and humid areas play important roles in the distribution of this group as most Cyperaceae species have a great affinity for these environments (Barrett, 2013).

Protected areas are species refuges, playing key roles in species conservation, including the Cyperaceae studied. These areas are important in buffering the effects of climate change and expanding land use (Watson et al., 2014). This importance has already been reported in protected areas conserving Amazon biodiversity, pointing to the urgent need to maintain these areas (Naughton-Treves et al., 2005; Rayner et al., 2014; Heywood, 2019; Walker et al., 2020). Thus, we emphasize the critical importance of conserving and expanding protected areas for the conservation of Amazonian biodiversity and remaining natural habitats, in the present and especially in the face of ongoing climate change (Fearnside, 1999; Vieira et al., 2008; Rorato et al., 2021; Sousa et al., 2023). This will ensure the persistence of species in a scenario of rapid environmental change and increasing human pressure (Soares-Filho et al., 2010), allowing the survival of species and the health of aquatic, terrestrial, and transitional ecosystems.

Temperature and seasonal variables structured Cyperaceae species in the Brazilian Amazon. The positive relationship between temperature and the distribution of aquatic species indicates the preference of these plants for higher temperatures (Santamaría, 2002; Poff et al., 2002). Temperature directly affects the biology and metabolism of aquatic plants, altering their growth, reproduction, and survival (Alahuhta et al., 2017). In warmer environments, aquatic plants usually present higher metabolic rates, which increases growth and development (Yvon-Durocher et al., 2010; Bornette and Puijalon, 2011; Thiébaud et al., 2021). In contrast, the negative impact of seasonality on the distribution of aquatic species suggests that these plants are less favored in areas with extreme rainfall variability or severe droughts throughout the year (Simpson et al., 2011; Fletcher et al., 2020). Seasonality fluctuations alter water availability in aquatic habitats and directly impact the survival and development of aquatic plants. In areas with strong seasonal variation, aquatic plants usually face prolonged droughts or excessive flooding, which can limit their establishment and growth (Lambers et al., 2019; Piao et al., 2019; Gan et al., 2021).

In the current scenario, amphibian species were negatively influenced by temperature seasonality and annual precipitation. Amphibian species are adapted to environments with greater temperature fluctuations throughout the year and have physiological adaptations that allow their resistance to low temperatures in specific periods and heat in warmer periods (Wetzel and Grace, 2019; Li et al., 2019; Nabi et al., 2021). The combined effects of temperature and precipitation on species distribution provide a comprehensive understanding of Cyperaceae species to these factors. For example, in regions with high seasonality and high precipitation, some species adapt through physiological mechanisms such as water exchange via the roots, and are thus, resistant to extreme droughts or seasonal flooding (Lambers et al., 2019). Further investigations of these specific variables related to amphibian plants can help predict species changes as climate change progresses.

Terrestrial Cyperaceae species were influenced by annual average temperature and seasonal precipitation, which reaffirms the importance of these factors, especially temperature, influencing plant distribution and ecology. The seasonality of precipitation plays a crucial role in water availability and affects the physiology and morphology of plants, especially the root system. Under conditions of low water availability, plants tend to invest more in root growth to reach deeper soil water (Pyankov et al., 2010; Wetzel and Grace, 2019; Gan et al., 2021). Our results showed that terrestrial species will become more common in warmer regions, this pattern is even more pronounced in future models. However, the distribution of the terrestrial species could be negatively influenced by greater seasonal variability that will reduce the accessible

areas for these species and consequently reduce their abundance.

Our results highlight the significant impact of climate change on the distribution of aquatic, amphibian, and terrestrial Cyperaceae species in the Amazon biome. Temperature and seasonal precipitation influenced the distribution, survival, and vulnerability of terrestrial species. As climate change progresses, the projected increase in temperature and precipitation variability will greatly reduce suitable habitats, threatening the diversity of Cyperaceae species in the Amazon. We emphasize the essential role of protected areas in the conservation of these species, as these areas serve as refugia that mitigate the effects of environmental change. Policymakers, scientists, and society should recognize the importance and urgent need to maintain and expand protected areas to preserve the unique biodiversity of the Amazon. Further research on specific environmental variables is essential to developing effective conservation strategies and predicting future distribution patterns due to ongoing climate change, considering plant diversity in general.

CRedit authorship contribution statement

Raimundo Luiz Morais Sousa: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fernando Geraldo de Carvalho:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **André dos Santos Bragança Gil:** Writing – review & editing, Resources, Conceptualization. **Thiago Bernardi Vieira:** Writing – review & editing, Formal analysis. **Thaisa Sala Michelin:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

We declare that there were no conflicts of interest in this submission and that all co-authors are in agreement with the work.

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Data availability

Data will be made available on request.

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