Universidade de Brasília

Instituto de Ciências Biológicas

Programa de Pós-graduação em Ecologia

Prevendo os impactos das mudanças climáticas na distribuição das espécies de plantas de vereda das áreas úmidas do Cerrado brasileiro

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SUMÁRIO

Resumo

A crise climática em curso está reconfigurando ecossistemas globalmente, com as áreas úmidas entre as mais vulneráveis devido à sua sensibilidade às mudanças hidrológicas e ao aumento da temperatura. As veredas, áreas úmidas exclusivas do Cerrado brasileiro, desempenham um papel crítico na biodiversidade e nos serviços ecossistêmicos, mas enfrentam crescentes ameaças provenientes de mudanças no uso da terra e no clima. Apesar de sua importância ecológica, a resposta das espécies de vereda às mudanças climáticas ainda é pouco compreendida. Este estudo avaliou as mudanças potenciais na distribuição de 24 espécies-chave de plantas de vereda sob dois cenários climáticos (SSP2-4.5 e SSP5-8.5) para o período de 2061-2080. Utilizando 19 variáveis bioclimáticas do WorldClim e o modelo MPI-ESM1-2-HR, foram gerados Modelos de Distribuição de Espécies (SDMs) com nove algoritmos do pacote 'biomod2' no R. A avaliação dos modelos foi realizada por meio das métricas de sensibilidade e especificidade da Curva ROC e da estatística True Skill Statistic (TSS). Os resultados indicaram alta confiabilidade dos modelos, com sensibilidade média de 86,83 ± 10,03 e especificidade média de 87,59 ± 7,45. Treze das 24 espécies apresentaram perda de áreas adequadas, com o nordeste do Cerrado projetado para as maiores perdas, e expansões observadas na fronteira sul com a Mata Atlântica. A espécie *Desmoscelis villosa* teve as maiores perdas, enquanto *Xyris tortula* demonstrou ganhos. A sobreposição das áreas adequadas diminuiu nos dois cenários, sugerindo deslocamentos e fragmentação. Este estudo destaca que as mudanças climáticas podem remodelar a distribuição das espécies de vereda, resultando em perdas de áreas adequadas. Esse estudo reforça a necessidade de incorporar projeções climáticas na formulação de políticas públicas e estratégias de gestão ambiental, promovendo ações que integrem conservação da biodiversidade, planejamento do uso da terra e ampliação de áreas protegidas.

Palavras-chave: áreas úmidas, Cerrado, modelagem de distribuição de espécies, mudanças climáticas, savana brasileira, veredas.

Abstract

The ongoing climate crisis is reshaping ecosystems globally, with wetlands among the most vulnerable due to their sensitivity to hydrological changes and temperature rise. *Veredas*, unique wetlands of the Brazilian Cerrado, play a critical role in biodiversity and ecosystem services, yet face increasing threats from land-use changes and climate variability. Despite their ecological importance, the response of *vereda* species to climate change remains poorly understood. This study assessed potential shifts in the distribution of 24 key *vereda* plant species under two climate scenarios (SSP2-4.5 and SSP5-8.5) for the period 2061-2080. Using 19 bioclimatic variables from WorldClim and the MPI-ESM1-2-HR model, Species Distribution Models (SDMs) were generated with nine algorithms from the 'biomod2' R package. Model evaluation was conducted using sensitivity and specificity metrics derived from the ROC curve and the True Skill Statistic (TSS). Results indicated high model reliability, with an average sensitivity of 86.83 ± 10.03 and average specificity of 87.59 ± 7.45. Thirteen out of the 24 species showed loss of suitable areas, with the northeastern Cerrado projected to experience the greatest losses, and expansions observed along the southern border with the Atlantic Forest. The species *Desmoscelis villosa* exhibited the greatest losses, while *Xyris tortula* demonstrated gains. The overlap of suitable areas decreased in both climatic scenarios, suggesting range shifts and fragmentation. This study highlights that climate change can reshape the distribution of *vereda* species, leading to losses of suitable areas. It reinforces the need to incorporate climate projections into public policy development and environmental management strategies, promoting actions that integrate biodiversity conservation, land-use planning, and the expansion of protected areas.

Key words: Brazilian savanna, Cerrado, climate change, species distribution modelling, *veredas*, wetlands.

INTRODUÇÃO GERAL

Mudanças no clima e no uso da terra ameaçam a integridade dos ecossistemas em todo o mundo (IPCC, 2023). Essas alterações afetam a distribuição e abundância de espécies vegetais, influenciando a composição florística e as interações ecológicas em diferentes regiões (Pecl *et al*., 2017; Mano *et al*., 2023). Tais impactos são particularmente críticos para ecossistemas que dependem fortemente dos ciclos hidrológicos, como as áreas úmidas (Xiong *et al*., 2023).

Presentes em todas as regiões do planeta, exceto na Antártica, as áreas úmidas são caracterizadas pela presença de lençóis freáticos próximos ou acima da superfície do solo, de forma sazonal ou permanente durante o ano (Salimi *et al*., 2021). Apesar de representarem apenas de 5 a 8% da superfície terrestre (Mitsch & Gosselink, 2015), essas áreas oferecem inúmeros serviços ecossistêmicos essenciais, como regulação do clima local, armazenamento de carbono e água, refúgio para fauna, recarga de lençóis freáticos e provisionamento de condições para subsistência e bem-estar humano (Assessment, 2005; Junk *et al*., 2014). Atualmente, o valor monetário estimado por esses serviços é de US$ 47 trilhões/ano (Davidson *et al*., 2019).

Aumentos na temperatura têm ocasionado perdas de habitat (Xi *et al*., 2021), além de alterar padrões de distribuição de plantas nativas (Ferreira *et al*., 2022) e promover a invasão por espécies exóticas (Lopes *et al*., 2023). Tais mudanças climáticas também impactam os ciclos hidrológicos, comprometendo a estrutura e a função dos ecossistemas (Mitsch and Gosselink, 2015), alterando taxas de emissão de metano (Cui *et al*., 2024), facilitando o estabelecimento de espécies exóticas invasoras (Lázaro-Lobo and Ervin, 2021) e agravando a perda de conectividade hidrológica (Meng *et al*., 2020).

Devido à complexidade e às características específicas das áreas úmidas em diversas regiões do mundo, os esforços de mitigação e restauração dessas áreas devem ser planejados em uma escala regional (Erwin, 2009). No entanto, ainda existem lacunas significativas no conhecimento sobre como as áreas úmidas respondem às mudanças climáticas, especialmente no que diz respeito ao seu papel como fontes ou sumidouros de gases de efeito estufa e à identificação dos fatores climáticos que influenciam essa mudança de função (Salimi *et al*., 2021). No contexto brasileiro, estudos têm apontado uma perda substancial da extensão das áreas úmidas, particularmente na Bacia Amazônica e no Pantanal, em decorrência das mudanças climáticas (Hardouin *et al*., 2024).

O Cerrado, uma savana neotropical e *hotspot* de biodiversidade (Myers *et al*., 2000), apresenta grande importância para as áreas úmidas do Brasil por abrigar oito das doze bacias hidrográficas do país (Lima & Silva, 2007; Strassburg *et al*., 2017). As planícies alagáveis do Pantanal e as bacias hidrográficas importantes como Paraguai, São Francisco e Tocantins-Araguaia dependem fortemente da vazão que flui do Cerrado para existirem (Lima & Silva, 2007). Nas áreas úmidas do Cerrado, encontram-se zonas de turfeiras que podem armazenar estoques de carbono até nove vezes superiores aos dos solos minerais presentes nas áreas de solos bem drenados do bioma (Beer *et al*., 2024). Nesse contexto, a conservação do Cerrado é chave para a manutenção da estabilidade climática e da biodiversidade em grande escala (Junk *et al*., 2014; Rodrigues *et al*., 2022).

Apesar dessa importância, estima-se que 50% da vegetação nativa do Cerrado já foi perdida devido às atividades antrópicas (Alencar *et al*., 2020). A situação é particularmente crítica para as áreas úmidas, muitas das quais ainda não foram adequadamente mapeadas (Durigan *et al*., 2022). A falta de proteção legal reflete a negligência das legislações ambientais e dos planejamentos políticos em relação a essas áreas, o que inclui a implementação incompleta de políticas de conservação, apesar da existência de instrumentos como a Lei de Proteção da Vegetação Nativa Brasileira (Lei Nº 12.651/12) e a adesão do Brasil à Convenção de Ramsar, que reconhece a importância de proteger as áreas úmidas, mas cujas diretrizes ainda carecem de uma aplicação mais eficaz (Junk *et al*., 2014; Rosolen *et al*., 2015), especialmente para a savana brasileira.

Expostas e sem a devida proteção, as áreas úmidas brasileiras se encontram em risco de colapso (Grasel *et al*., 2018). As atividades de monocultura, pastagem e mineração, nas últimas décadas, contribuíram para redução do escoamento dos rios e abaixamento dos níveis de água subterrânea no Cerrado (Rodrigues *et al*., 2022; Silva *et al*., 2022). Estima-se uma redução de 10% na água reciclada para a atmosfera anualmente no Cerrado na última década (Rodrigues *et al*., 2022).

Os efeitos sobre a hidrologia, solo e vegetação das áreas úmidas se tornam ainda mais relevantes frente às tendências futuras de aumento das temperaturas e diminuição da umidade para todas as regiões do Cerrado (Hofmann *et al*., 2021).Tais alterações comprometem a adequabilidade de hábitat das espécies típicas de áreas úmidas, que abrigam uma importante diversidade de flora característica (Junk *et al*., 2014; Silva *et al*., 2018).

Um dos tipos vegetacionais típicos do Cerrado são as veredas, que são ecossistemas úmidos que ocorrem em meio à uma matriz de savana bem drenada (Silva *et al*., 2018). As veredas apresentam uma composição florística única, com altos valores de riqueza e diversidade de espécies, além de elevada diversidade beta. Essas características resultam da variação na textura e fertilidade dos solos, que influencia significativamente a composição de espécies entre diferentes áreas (Bijos *et al*., 2023). O alagamento do solo atua como um filtro que impede o estabelecimento de espécies não adaptadas, especialmente árvores (Ribeiro *et al*., 2021).

No Brasil, os estudos que focam em áreas úmidas estão concentrados nas espécies arbóreas, principalmente da Amazônia e no Pantanal (Wittmann *et al*., 2017;

Chiminazzo *et al*., 2021; Silva-Souza *et al*., 2023). Essa situação contrasta com a realidade do Cerrado, onde há predominância de formações de savana e de campo compostas por arbustos e herbáceas em detrimento de árvores a uma proporção de 7:1 (Zappi *et al*., 2015). Nesse cenário, entender a ecologia das espécies não-arbóreas e das áreas úmidas do Cerrado e suas respostas às crescentes mudanças no clima e no uso da terra são fundamentais. Assim, o objetivo dessa pesquisa foi avaliar a perda ou ganho de áreas adequadas para 24 espécies herbáceas-arbustivas amplamente distribuídas em veredas do Cerrado frente a cenários de mudanças climáticas para o período de 2061-2080.

A seguir, os resultados estão apresentados no formato de manuscrito submetido ao periódico *Annals of Botany*, conforme regulamento do PPGECL/UnB (Art. 31- c).

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Predicting climate change impacts on *vereda* wetland plant species distribution in the Brazilian Cerrado

INTRODUCTION

In light of the ongoing climate crisis, ecosystems worldwide are experiencing significant changes in functioning and biodiversity (Pecl *et al*., 2017; Xiong *et al*., 2023). These changes affect the distribution and abundance of plant species, influencing floristic composition and ecological interactions across multiple regions (Pecl *et al*., 2017; Mano *et al*., 2023). Wetlands are particularly vulnerable to climate change, as hydrological alterations and rising temperatures profoundly affect their physical properties and ecosystem functions (Salimi *et al*., 2021). Although they represent only 5 to 8% of the Earth's surface (Mitsch and Gosselink, 2015), wetlands provide a range of essential ecosystem services, such as local climate regulation, carbon and water storage, refuge for wildlife, groundwater recharge, and the provision of conditions for human subsistence and well-being (Assessment, 2005; Junk *et al*., 2014). Despite their vital role in providing ecosystem services, an estimated 21% of global wetlands have been lost since 1700 (Fluet-Chouinard *et al*., 2023).

In Brazil, understanding the extent of wetland loss poses a challenge due to the lack of consistent mapping and protection rules by government agencies (Durigan *et al*., 2022). These ecosystems are distributed across diverse biomes within the country, including the Amazon Rainforest, the Atlantic Forest, Pantanal, and Cerrado (Junk *et al*., 2014). In the Cerrado, wetlands occur in distinct formations such as *veredas* (Brazilian savanna palm swamps), wet shrubby grasslands, and wet grasslands (Ribeiro and Walter, 2008).

Veredas are characterized by a continuous herbaceous layer and the presence of the palm tree *Mauritia flexuosa* L. (Ribeiro and Walter, 2008). They are particularly notable for their high diversity and exclusivity of species, making them a unique component of the Cerrado ecosystem (Silva *et al*., 2018; Bijos *et al*., 2023). Wetlands in the Cerrado are shaped by unique hydrological dynamics, where soil waterlogging acts as a natural filter, limiting the establishment of non-adapted species, particularly trees, and favoring vegetation adapted to these conditions (Silva *et al*., 2017; Ribeiro *et al*., 2021). They play an important role in providing important ecosystem services such as groundwater recharge, organic carbon stock, microclimate regulation and cultural services (Assessment, 2005; Junk *et al*., 2014). It is estimated that the peatland areas in the *veredas* of Cerrado may store carbon stocks up to nine times greater than those of the mineral soils found in well-drained areas of the biome (Beer *et al*., 2024). However, over the past decades, *veredas* akin to the Cerrado as a whole, have encountered escalating threats from monoculture, pasture, and mining activities, resulting in diminished river runoff and declining groundwater levels (Rodrigues *et al*., 2022; Silva *et al*., 2022). Projections indicate that ongoing deforestation rates will result in a significant reduction in water flow in over 90% of the Cerrado watersheds (Salmona *et al*., 2023).

Studies suggest that the climate of the Cerrado is becoming both drier and hotter (Hofmann *et al*., 2021), threatening to disrupt the hydrological processes that sustain these ecosystems. Such changes in climate may compromise the habitat suitability of species typical of the Cerrado wetland areas (Junk *et al.*, 2014; Silva *et al.*, 2018). Herbaceous plants, which rely heavily on these conditions, are particularly at risk of losing suitable habitats under changing climates (Xavier *et al.*, 2019). In this context, the conservation of the Cerrado is key to maintaining climate stability and biodiversity on a large scale (Junk *et al.*, 2014; Rodrigues *et al.*, 2022).

Due to the complexity of wetlands, there are still significant gaps in understanding their response to climate change, particularly regarding their role as a source or sink of greenhouse gases, as a reservoir for typical species, and the climatic factors influencing this dynamic (Salimi *et al.*, 2021). Species distribution modelling (SDM) combines environmental factors with species occurrence records to predict habitat suitability and estimate the potential distribution of species (Elith and Leathwick, 2009). SDMs are widely used approach to evaluate the potential impacts of climate change on the suitable habitats for species distribution (Araújo and New, 2007; Wiens *et al.*, 2009; Booth, 2018). Studies in other regions highlight significant declines in habitat suitability for native wetland species under future climate scenarios. For example, projections for the Amazon Basin suggest reduced habitats for native species, contrasting with the expansion of invasive exotic grasses (Mano *et al.*, 2023). Similarly, modelling in Asia predicts a contraction in the distribution of at least three native wetland species (Dang *et al.*, 2021). In Cerrado, most existing studies focus on the distribution of tree species, often of commercial value, under climate change scenarios (Siqueira and Peterson, 2003; Collevatti *et al.*, 2011; Maciel *et al.*, 2021). This focus overlooks the predominance of shrubs and herbaceous plants in the Brazilian savanna (Zappi *et al.*, 2015).

To address this gap, this study assesses how the distribution of 24 key *vereda* species—mostly herbaceous plants—might shift under two climate change scenarios SSP2-4.5 and SSP5-8.5 projected for 2061–2080. By focusing on this understudied group, our findings will provide new insights into the potential impacts of climate change on the unique biodiversity of *veredas*. Based on similar studies in other wetlands (Dang *et al*., 2021; Mano *et al*., 2023; Vento *et al*., 2024), we hypothesize that most species will experience a reduction in suitable areas.

MATERIALS AND METHODS

Study area

Cerrado is the largest neotropical savanna and a biodiversity hotspost (Myers *et al*., 2000). It covers a great portion of the elevated central parts of Brazil (Klink and Machado, 2005). This Brazilian biome comprises forest, grassland, and savanna formations (Ribeiro and Walter, 2008). According to Koppën, the climate is mainly tropical seasonal (Aw), with two well-defined seasons throughout the year: a rainy season and a dry season.

Veredas are a wet vegetation type in the Cerrado (Fig. 1), occupying hydromorphic soils, gleys, and organic turfs (Bijos *et al*., 2023; Beer *et al*., 2024). They are subdivided into three distinct floristic zones along a moisture gradient: edge, middle, and bottom (Eiten, 1994). The edge has well-drained soils and transitional vegetation linked to the adjacent Cerrado *sensu stricto*, while the middle features seasonally waterlogged soils with typical wetland vegetation. The bottom zone is characterized by permanently saturated soils, an herbaceous-shrub layer, and *Mauritia flexuosa* (buriti) stands (Resende *et al*., 2013; Bijos *et al*., 2023). Its most frequent plant families are Poaceae, Cyperaceae, Xyridaceae, Melastomataceae, Eriocaulaceae and Asteraceae (Resende *et al*., 2013; Bijos *et al*., 2023).

Occurrence data

The selection of species for this study was based on the species list from the floristic survey conducted by Bijos *et al*. (2023), which provides the most comprehensive floristic analysis of *veredas* to date. From this list, we identified 26 species that occurred in more than half of the 21 sampled sites, located across six Brazilian states, within the geographic range of 10° to 17° S and 43° to 52° W. These species were retained for modeling as they are considered typical of *vereda* ecosystems or good indicators of wetland areas. However, *Echinolaena inflexa* (Poir.) Chase and *Chamaecrista desvauxii* (Collad.) Killip have been excluded due to their prevalence in dry Cerrado, rendering them unsuitable as indicators of wetland environments (Silva *et al.*, 2018). Consequently, the final list comprised 24 species (Supplementary Data Table S1).

We used this species list to download occurrence records from the SpeciesLink platform (https://specieslink.net/) on November of 2023 and from the Global Biodiversity Information Facility- GBIF (https://www.gbif.org/) on May of 2024 (Supplementary Data Table S2) using the 'rgibf' package (Chamberlain *et al*., 2019) of the R software (version 4.3.0; R Core Team, 2023). The data was processed to eliminate duplicate records and records without geographic coordinates or without confirmed species identity. We used the 'coordinate cleaner' package (Zizka *et al*., 2019) to identify and exclude problematic geographic coordinates, such as records with identical latitude and longitude values, coordinates at zero, or locations situated over oceans. Our curated dataset comprised 11,927 records for all species.

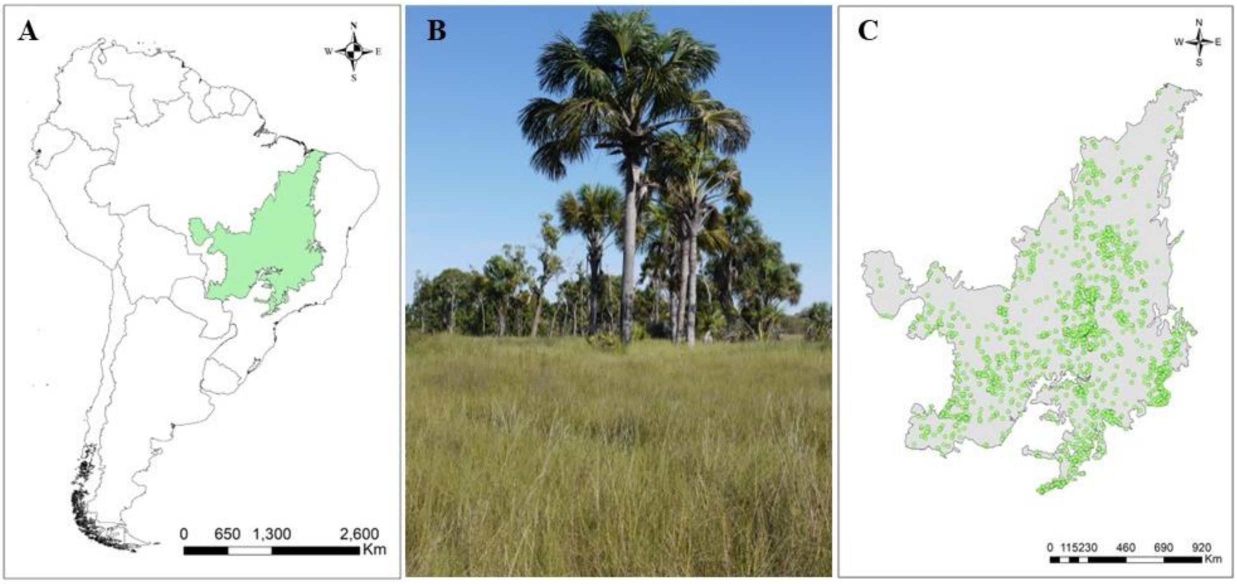

FIG.1. (A) Location of Cerrado in South America. (B) *Vereda* Cerrado vegetation type. (C) Map of the Cerrado showing the distribution of species occurrence points used in this study.

Environmental data

The environmental data was obtained from 19 bioclimatic variables at a resolution of 30 arc-seconds (~1 km²), which was downloaded from the Worldclim plataform (https://www.worldclim.org/). In order to avoid multicollinearity between the environmental variables, we performed a Variance Inflation Factor (VIF) using the 'usdm' package (Naimi *et al*., 2014) in the R program. We first applied the vifcor function to remove those with pairwise correlations above 0.85. We then used the vifstep function to exclude variables with a VIF greater than 3 (Akinwande *et al*., 2015), ensuring the final set of predictors had minimal collinearity.

For the prediction of future scenarios from 2061 to 2080 (hereby referred to as 2070), we employed a General Circulation Model (GCM) known for its strong performance in simulating precipitation in the Cerrado region: MPI-ESM1-2-HR (Ortega *et al*., 2021). This GCM has been effectively applied in previous studies focused on Cerrado (Meireles *et al.*, 2023; Silva *et al.*, 2024). The model is based on the CMIP6 framework proposed by Eyring *et al.* (2016). We analyzed two Shared Socioeconomic Pathways (SSPs) to explore potential climate futures: SSP2-4.5 and SSP5-8.5. SSP2-4.5 represents a scenario where current policies moderately limit emissions, leading to stabilized CO_2 levels and a radiative forcing of 4.5 W m^{-2} by 2100, associated with medium-intensity climate impacts. In contrast, SSP5-8.5 reflects a trajectory of rapid fossil fuel-driven economic growth with minimal mitigation, resulting in higher CO_2 concentrations, radiative forcing of 8.5 W/m^2 by 2100, and severe climate consequences (IPCC, 2022). Notably, SSP5-8.5 is considered to align more closely with the current global emissions trajectory, given the ongoing reliance on fossil fuels and limited mitigation efforts (IPCC, 2022).

Species distribution models (SDMs)

In species distribution modelling, the ensemble species distribution model (SDMs), which combines the results of several simple algorithm models using the committee averaging method, allows more robust decision making by merging multiple models into a single ensemble (Araújo and New, 2007). This method has been successfully applied in numerous ecological studies, demonstrating its effectiveness across a range of contexts (Dang *et al.*, 2021; Fang *et al.*, 2021; Mano *et al.*, 2023; Samal *et al.*, 2023).

To assess current and future SDMs of the 24 species, we used the ensemble forecasting methods available in the R package ‘biomod2’ (Thuiller *et al.*, 2019), including artificial neural networks (ANN; Hopfield, 1982), classification tree analysis (CTA; Breiman *et al.*, 1984), flexible discriminant analysis (FDA; Hastie *et al.*, 1994), generalized additive models (GAM; Hastie and Tibshirani, 1987), generalized boosted models (GBM; Friedman *et al.*, 2000), generalized linear models (GLM; McCullagh and

Nelder, 1989), maximum entropy (MaxEnt; Phillips *et al*., 2006), random forest (RF; Breiman, 2001), and surface-range envelope (SRE; Jiguet *et al*., 2011).

Since our data consisted of only species presence records, we generated pseudo-absence points (background) following the methodology described by Barbet-Massin *et al*., (2012). For RF, CTA and GBM algorithms, the number of pseudo-absence points matched the number of presence records for each species. For the ANN, FDA, GLM, GAM, MaxEnt and SRE algorithms, 1000 pseudo-absence points were generated. To optimize model accuracy, through the cross-validation method, the data were randomly selected between 70% training (assessing model accuracy) and 30% testing (model fitting) (Huberty, 1994). This procedure was repeated 10 times for each species and each climate scenario.

The final model was generated based on the mean true skill statistic (TSS) values from 10 repetitions. TSS values range from -1 to 1, with values close to 1 indicating that the algorithm is capable of good predictive power (Allouche *et al*., 2006). We applied the criterion that algorithms with a TSS value ≥0.4 were included in the consensus map (Mano *et al*., 2023).

In addition, we assessed the performance of the consensus model using the receiver operating characteristic (ROC) curve, calculating the mean and standard deviation across the 10 repetitions for each species and climatic scenario. The reliability of the consensus maps generated based on ROC values were categorized in 4 groups according to sensitivity and specificity values proposed by Ochoa-Ochoa *et al*. (2016): poor (sensitivity ≤50 or SD ≥ 50, specificity ≤50 or SD ≥ 40), medium (sensitivity ≥50 with SD ≤ 45, specificity ≥50 with SD ≤ 45), good (sensitivity ≥70 with SD ≤ 30, specificity ≥50 with SD ≤ 35) and optimum (sensitivity ≥90 with SD ≤ 30, specificity ≥80 with SD ≤ 10)

We created binary maps for the extent of the Cerrado biome representing suitable and unsuitable areas for current and future conditions using ArcGIS (version 10.8). We used the reclassify function and the 30% threshold for species presence. We did this procedure for each of the 24 species separately and then we used the plus function to make a single map representing areas in which most of the species could occur. The areas of gain and loss were quantified by counting the respective pixels, and the results were incorporated into the equation proposed by Lopes *et al*. (2021), in which:

1) $$\text{SA\%} = \left(\frac{\text{number of pixels in a suitable area for the species}}{\text{total number of pixels}}\right) \text{ x } 100$$

2) $$\Delta\ \text{SA\%} = \text{SA future} - \text{SA current}$$

RESULTS

Climatic variables influencing *vereda* species distribution include mean diurnal range - Bio 2, isothermality - Bio 3, temperature seasonality - Bio 4, mean temperature of wettest quarter (Bio 8), annual precipitation - Bio 12, precipitation of wettest month - Bio 13, precipitation seasonality - Bio 15, precipitation of warmest quarter - Bio 18 and precipitation of coldest quarter - Bio 19 were selected by VIF analysis to be used in the models. However, not all variables were selected for every scenario (Supplementary Data Table S3). Mean sensitivity was 86.83 (± 10.03) and mean specificity was 87.59 (± 7.45), which indicates good reliability. Among the evaluated models, 13 (18.06%) were classified as optimal, while 59 (81.94%) were classified as good (Supplementary Data Table S4).

The ANN and SRE algorithms exhibited the poorest performance among the nine tested algorithms and were excluded from most models due to low TSS values and failed runs. In contrast, the RF algorithm demonstrated the best performance, being excluded from only two models due to high standard deviation (TSS with SD > 0.15).

From the 24 species, 13 showed loss of suitable areas in at least one of the climatic scenarios (Supplementary Data Table S5) and six in both scenarios SSP2 and SSP5. The overlap of the 24 species climatically suitable areas decreased by 1.46% in SSP2 and by 0.45% in SSP5 (Table 1; Supplementary Data Table S6 and S7). Notably, the northeastern Cerrado, at its border with the Caatinga biome, is projected to experience the greatest loss of suitable areas (Fig. 2). Conversely, the largest expansions of suitable areas are projected along the southern border of São Paulo state and the northern region of Paraná, where the Cerrado transitions into the Atlantic Forest.

Desmoscelis villosa was the species that showed the greatest loss of suitable areas in both scenarios (-25.86% in SSP2 and -25.98% in SSP5) (Fig. 3). *Rhynchospora emaciata* decreased its suitable areas by 29.21% in SSP2 and 4.01% in SSP5. *Ludwigia nervosa* (-14.99% in SSP2; -7.93% in SSP5)*, Rhynchospora consanguinea* (-10.11% in SSP5) and *Rhynchospora rugosa* (-11.96% in SSP2; -12% in SSP5) also showed important decrease in suitable areas. In contrast, *Xyris tortula* showed the biggest gain of suitable areas in SSP5 (19.20%), followed by *Paspalum dedeccae* (14.71% in SSP2) and *Hyptis linarioides* (13.52% in SSP5). *Rhynchospora globosa* gained suitable areas in both SSP2 and SSP5 (16.45% and 15.94%, respectively)(Supplementary data Fig. S1).

TABLE 1. Percentage of suitable areas for different species groupings (N) under the current climate and two future scenarios (SSP 245 and SSP 585) for 2070. Gain and loss of suitable areas are also presented. N = Number of species in each grouping.

N	**Percentage (%)**			**ΔSA**	
	Current	SSP 245	SSP 585	Δ SSP245	Δ SSP585
0	13.82	17.34	18.46	3.52	4.64
4	32.35	29.66	26.29	-2.68	-6.06
8	19.99	16.23	17.08	-3.76	-2.92
12	8.93	9.87	11.30	0.94	2.37
16	5.64	7.75	7.37	2.11	1.73
20	6.23	7.58	6.92	1.35	0.69
24	13.04	11.58	12.59	-1.46	-0.45

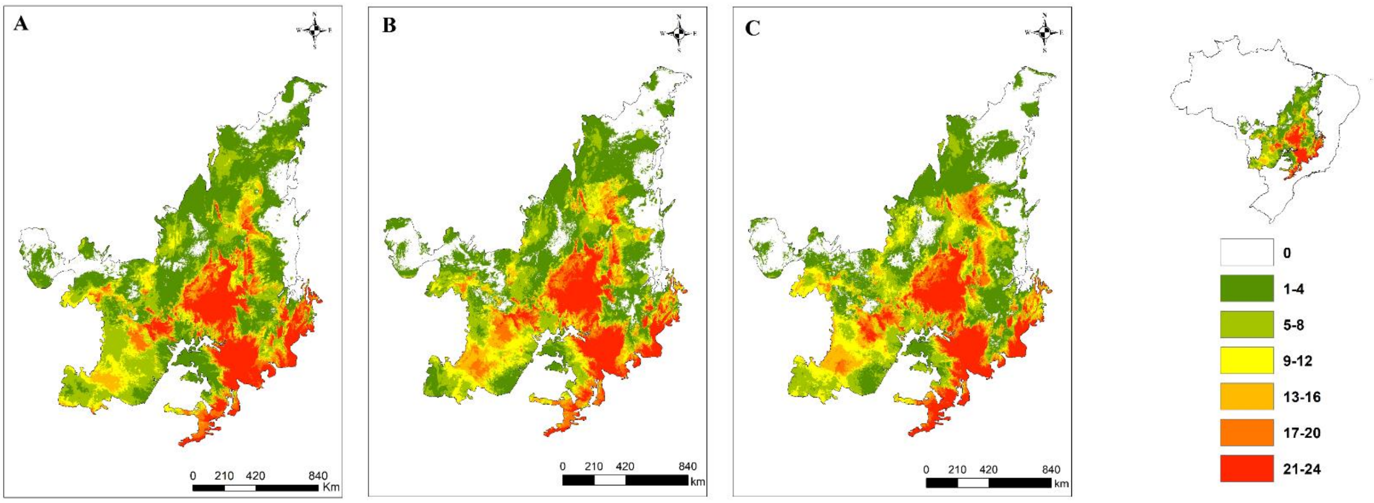

FIG. 2. Projections of climatically suitable areas for the 24 *vereda* species studies. (A) Current climate, (B) SSP245 scenario, (C) SSP585 scenario.

DISCUSSION

In the future, species from Cerrado wetlands are projected to undergo shifts in their distribution, with over half of the 24 *vereda* species projected to lose suitable areas by 2070. The greatest loss of suitable areas is anticipated to occur in the northeastern Cerrado, at its border with the Caatinga biome, likely driven by intensifying desertification processes associated with rising temperatures (Marengo *et al*., 2017; Vieira *et al*., 2021). In the northwestern Cerrado, particularly in the state of Mato Grosso, habitat losses are also projected, although some localized gains may occur near the transition zone with the Amazon rainforest. This pattern can be attributed to the process of "savannization", driven by the replacement of native vegetation with pastures and annual crops, compounded by the combined effects of deforestation and climate change (Sales *et al*., 2020). The projected increase in the length of the dry season and intensification of temperature extremes due to climate change are expected to reduce forest resilience and promote the transition to savanna-like ecosystems (Bottino *et al*., 2024). Deforestation exacerbates heat stress by reducing forest canopy cover, altering local microclimates, and increasing surface temperatures (Alves de Oliveira *et al*., 2021). These environmental

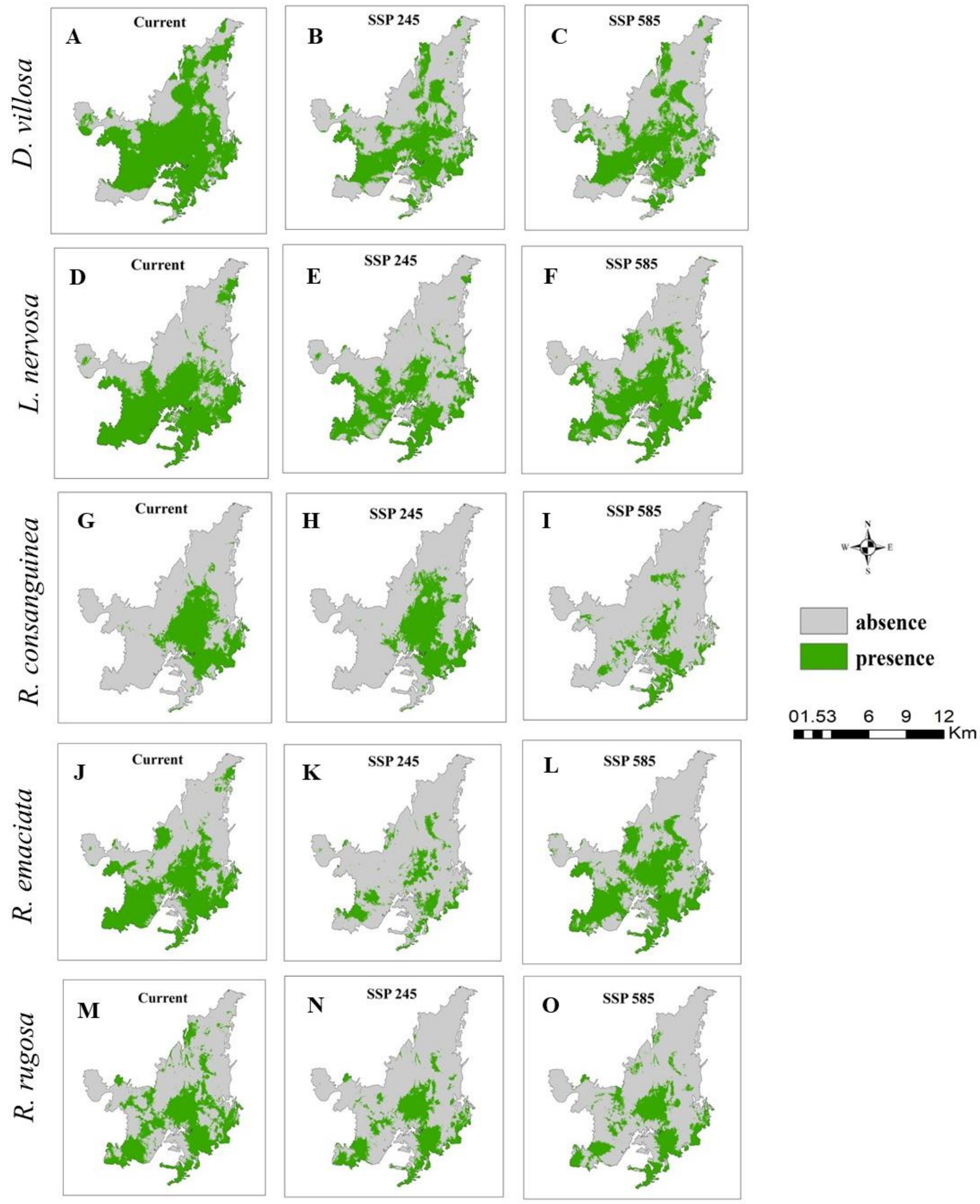

FIG. 3. Projections of climatically suitable areas for Current, SSP245 and SSP585 scenarios for A-C – *Desmocellis villosa*, D-F – *Ludwigia nervosa*, G-I – *Rhynchospora consanguinea*, J-L – *Rhynchospora emaciata* and M-O – *Rhynchospora rugosa.*

changes may accelerate the transition from neotropical forests to open ecosystems in transitional zones, where wetter soils can still sustain Cerrado wetlands vegetation. Moreover, the northern region of the biome is already facing increasing pressures due to land conversion into agro-pastoral systems, a trend expected to intensify in the coming decades (Ferreira *et al*., 2021). In contrast, the largest expansions of suitable areas are projected along the southern border of São Paulo state and the northern region of Paraná, where the Cerrado transitions into the Atlantic Forest. This shift may reflect broader patterns of savannization affecting tropical forests worldwide, as rising temperatures and prolonged dry seasons alter ecosystem structure and function, potentially leading to biome shifts in these transition zones (Sales *et al*., 2020).

Species from the Melastomataceae and Cyperaceae families appear particularly vulnerable to the impacts of climate change. Projections indicate that five species—*Desmoscelis villosa*, *Miconia chamissois*, *Rhynchospora consanguinea*, *Rhynchospora emaciata*, and *Rhynchospora rugosa*—are likely to experience significant reductions in suitable habitats. One possible explanation for these reductions is the influence of global warming on the phenology of these species, as shifts in flowering and fruiting seasons may directly affect their survival and population maintenance by modifying reproductive timing and resource availability (Lima *et al*., 2021). Altered precipitation patterns, increased evaporation rates, and intensified drought events are expected to diminish both the availability and quality of wetland ecosystems, which are critical habitats for many Cyperaceae species (Junk *et al*., 2013). Moreover, disruptions in soil waterlogging and seasonal flooding—key ecological processes that govern the distribution of numerous Melastomataceae and Cyperaceae species—could further hinder the establishment and persistence of these plants (Moreira *et al*., 2019). Furthermore, rising temperatures may exceed the physiological thresholds of some species, particularly those with highly specialized ecological niches, further restricting their capacity to adapt and survive under changing environmental conditions (Wiens *et al*., 2009; Evans *et al*., 2015). This trend was not observed for *Rhynchospora globosa*, which also occurs in dry grasslands (Flora do Brasil, 2025).

Syngonanthus nitens is a widespread species in Brazil (Giulietti *et al*., 2016) and holds significant cultural importance for local communities. It is used to produce handicrafts, generating approximately US$1,800 per year per artisan (Schmidt *et al*., 2007). Our study projects a 2% reduction in suitable areas for S. nitens under SSP2, contrasting with a 1.2% increase under SSP5. These findings diverge from previous projections, which predicted a substantial reduction in suitable climatic areas across South America for *S. nitens*, particularly in central-west and northeast Brazil by 2050, and a more pronounced decline in central and northern Brazil by 2100 (Mendes *et al*., 2024). One possible explanation for these discrepancies lies in the differences between the modelling approaches. While our study is based on species occurrence data and climate variables, Mendes *et al*. (2024) used CLIMEX, a model that simulates species distribution by incorporating ecophysiological constraints, such as temperature and moisture limits. Additionally, the authors analyzed a broader geographic extent, encompassing all of South America, whereas our study focused specifically on the *veredas* of the Cerrado. These methodological differences likely contribute to the variation in projections, underscoring the influence of modelling choices on climate change impact assessments.

Similarly, for *Ludwigia nervosa*, a characteristic wetland species (Bedoya and Madriñán, 2015), also demonstrates varying responses under different climate scenarios. Our study predicts a 14.99% reduction in suitable areas under the intermediate SSP2 scenario and 7.93% under the high-impact SSP5 scenario. These findings reveal a smaller loss compared to previous studies on other species within the same genus, which estimated reductions of up to 55% in suitable areas under the RCP 8.5 scenario (Gillard *et al*., 2017). This contrast underscores the advantage of using the shared socioeconomic pathways (SSPs), which integrate both greenhouse gas emissions and socioeconomic dimensions, offering a more nuanced perspective on climatic variations impacts than the earlier RCP framework (Riahi *et al*., 2017).

The trends observed for *Trachypogon spicatus* further illustrate the importance of incorporating global environmental factors into climate change assessments. Our projection indicates a -5.46% reductions in suitable areas under SSP2 and -3.98% reduction under SSP5. These losses align with findings from other regions; for instance, in a South African park, the distribution of *T. spicatus* was shown to be shaped by local temperature and moisture gradients (Jewitt *et al*., 2023). Similarly, in the Cerrado, *T. spicatus* is expected to face habitat reductions, particularly in drier regions. In *veredas*, *T. spicatus* is among the most abundant species (Bijos *et al*., 2023). This highlights the interplay between large-scale climate shifts and local environmental conditions, emphasizing the need for tailored conservation strategies that address both scales.

Xyris tortula, *Paspalum dedeccae*, and *Hyptis linarioides* were species that gained a significant amount of suitable habitat areas. Particularly for X. tortula and P. dedeccae, a relatively small number of occurrence records were available (258 and 47, respectively), compared to other species analyzed in this study, which may have influenced the ability of the model to accurately predict both current and future distribution scenarios. This highlights the need for a larger effort in species data collection, especially directed at enhancing the quantity and quality of records per species through continued field collecting, more geographically balanced sampling, and improved access to existing herbarium collections (Feeley and Silman, 2011; Heberling *et al*., 2019). Such actions would provide a more robust foundation for modelling and improve the reliability of future ecological projections.

While the ensemble modelling approach used in this study has been successfully applied to various plant species (Rathore *et al*., 2019; Lopes *et al*., 2021; Mano *et al*., 2023), it is important to acknowledge its inherent limitations. The models do not account for critical factors such as biotic interactions (Araújo and Luoto, 2007), soil properties, and dispersal processes (Classen *et al*., 2015; Urban *et al*., 2016), which are crucial for accurately predicting species distributions. Despite these constraints, the strong predictive performance of the models, as indicated by high TSS and ROC values, suggests that the results provide a reliable baseline for understanding potential changes in species distributions under future climate scenarios.

In this study, we employed an ensemble modelling approach to project potential gains and losses in suitable areas for the 24 *vereda* species. Our findings confirm that climate change could potentially alter the distribution of *vereda* wetland species, a finding consistent with previous studies (Chao *et al*., 2020; Dang *et al*., 2021). Importantly, the projected loss of suitable areas for *vereda* species is particularly concerning, as *veredas* occur as small, wet islands within the dry matrix of the Cerrado. Even relatively small reductions in suitable habitat represent a significant loss, given their critical ecological role as biodiversity hotspots and hydrological regulators within this ecosystem. These impacts must be investigated alongside other factors, such as land use changes and the ineffectiveness of existing protected areas, which significantly contribute to the loss of native species' habitats (Velazco *et al*., 2019). The ecological responses of species will ultimately depend on their capacity to adapt to rapidly changing environmental conditions (Sheldon *et al*., 2019). In this context, integrating climate change models with land-use and environmental protection areas will be essential for informing effective conservation and management strategies. Such approaches can help mitigate the adverse impacts of these transformations on species within the Cerrado. While some species, such as

Rhynchospora globosa, may benefit from global heating, the predominant trend among the species analyzed in this study is a loss of suitable areas, supporting our initial hypothesis. This highlights the urgent need for targeted conservation efforts to safeguard the unique biodiversity of *veredas* in the face of climate and land-use pressures.

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SUPPLEMENTARY DATA

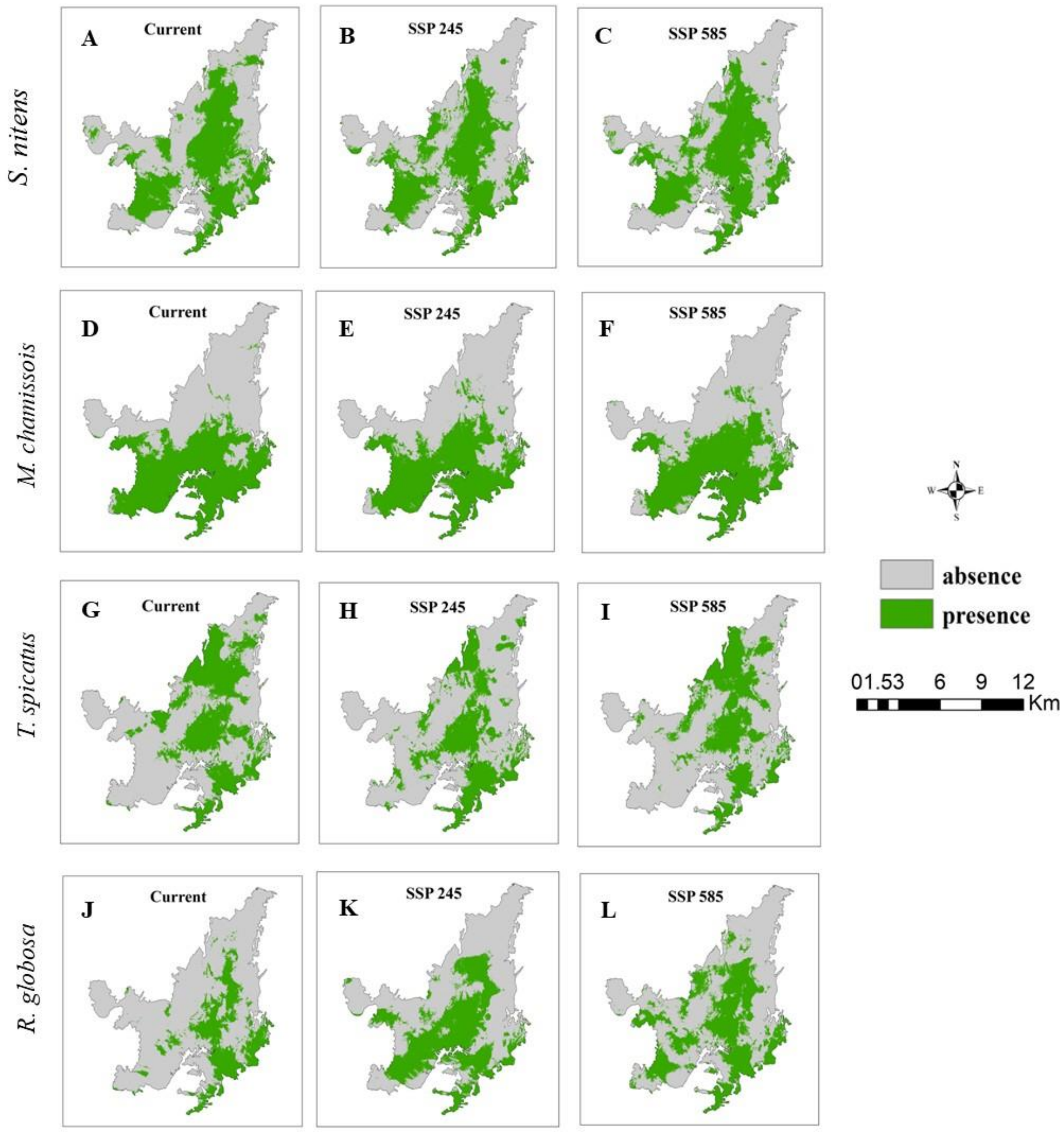

Fig. S1. Projections of climatically suitable areas for current, ssp245 and ssp585 scenarios for A-C – *Syngonanthus nitens*, D-F – *Miconia chamissois*, G-I – *Trachypogon spicatus*, J-L – *Rhynchospora globosa.*

NOTE

Other supplementary data will be made available upon reasonable request.