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Original Paper

Paraná state's strategic areas for biodiversity conservation and restoration include the majority of threatened plant species in the most degraded phytogeographic units

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Abstract
Designing strategic areas for biodiversity protection should help prevent species extinction. However, these delimitations are rarely evaluated for their effectiveness. To determine whether the original design of the Strategic Areas for the Conservation and Restoration of Biodiversity in Paraná (AECR) adequately protected the species and identify the species most likely to become extinct in the region, we analyzed occurrence records for threatened flora in the state's most degraded phytogeographic regions (Araucaria Forest, Cerrado, and grassland). We developed a list of threatened species for Paraná using herbarium records. We also compiled a threatened species occurrence list for the region by filtering through the herbarium records. Based on the main concepts defining threat status and gap species, we identified the species at an elevated risk of extinction in the study region. A total of 644 threatened species were detected in the regions studied, 86% of which have been recorded within the AECR, and 30% can be characterized as gap species. The species distribution polygons accounted for 98% of species within the AECR and 4% as gap species. A total of 54 species (8.38% of the total) are at a higher risk of extinction.
Key words: gap species, landscape ecology, Paraná flora, public policy, strategic areas for biodiversity conservation in Paraná.

Resumo
A concepção de áreas estratégicas para a proteção da biodiversidade deve ajudar a prevenir a extinção das espécies, porém, estas áreas raramente são avaliadas quanto à sua eficácia. Analisamos os registros de ocorrência de espécies ameaçadas da flora nas regiões fitogeográficas mais degradadas do Paraná (Floresta de Araucária, Cerrado e Campos) com o objetivo de determinar se o desenho original das Áreas Estratégicas para a Conservação e Restauração da Biodiversidade no Paraná (AECR) protegia adequadamente as espécies, bem como identificar as espécies com maior probabilidade de extinção na região. Compilamos uma lista de ocorrência de espécies ameaçadas para região por meio de filtragens nos registros de herbário. Comparamos registros individuais e polígonos de distribuição de espécies para determinar a relação entre as ocorrências de espécies e as AECR. Com base nos principais conceitos para determinação dos status de ameaça e de espécies lacunas, foram apontadas as espécies mais fragilizadas na região. Identificamos a presença de 644 espécies ameaçadas nas unidades fitogeográficas em estudo, das quais 86% possuem registro dentro das AECR e 30% podem ser caracterizadas como lacunas. Ao utilizar polígonos de distribuição verificamos variação, computando 98% dentro das AECR e apenas 4% como lacunas. Determinamos que 8.38% (54 spp) podem ser caracterizadas como as mais fragilizadas da região.
Palavras-chave: espécies lacunas, ecologia da paisagem, flora paranaense, políticas públicas, áreas estratégicas para conservação da biodiversidade no Paraná.

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Introduction

Brazil harbors the highest richness of plant species in the world (Forzza *et al.* 2012; BFG 2015). The country is home to at least 46,097 identified plant species, 43% of which are endemic, with many found in the country's most biodiverse biome, the Atlantic Forest (Costa & Peralta 2015; Maia *et al*. 2015; Menezes *et al*. 2015; Prado *et al*. 2015; BFG 2015). However, this formidable biodiversity is at risk. There are more than 50,000 plant species estimated to be threatened globally (RBG Kew 2016), half lack detailed distribution data (Pelletier *et al.* 2018), and only 10% are assessed for the global IUCN Red List (Bachman *et al.* 2019). It is of concern that 22% of plant species are under threat of extinction, with the majority of them located in tropical regions (Brummitt *et al.* 2015); this is because most habitat loss occurs in tropical and subtropical grasslands, cerrados, mangroves, and rainforests (Almond *et al.* 2020). Brazil's official national list, for example, cites 2,133 threatened plant species (MMA 2014).

The main factors leading to species extinction are habitat loss and fragmentation derived from mining and infrastructure development, plus impacts from overexploitation, species invasion, and climate change (Martinelli & Moraes 2013). Among them, habitat loss and fragmentation stand out since an estimated 2.87 billion hectares of natural areas have been modified for human use worldwide (Strassburg *et al.* 2020). Although much of the world's remaining conserved natural areas are found in Brazil (Lawrence & Vandecar 2015), habitat loss has been ongoing in the country for decades. This process particularly affects the Atlantic Forest Phytogeographical Domain, the most impacted natural region of Brazil by human activities, with the remaining natural areas of Atlantic Forest comprising only 16.6% of its original area (IBGE 2020) and still under deforestation pressure. Paraná, in southern Brazil, has one of the most worrying examples of natural area losses in this biome, in which only 11.8% of the original forest cover remains (SOS Mata Atlântica & INPE 2019).

The state is home to three phytogeographic units with particularly high levels of ecological degradation: Atlantic forest with *Araucaria* (mixed ombrophilous forest - MOF; according to IBGE's 2012 vegetation system), cerrado (savanna), and grassland (subtropical grassland of southern Brazil), units described in IBGE (2012). This habitat degradation is reflected in measures of conservation status, with only 0.8% of the state's MOF remnants retaining good conservation status (Castella & Britez 2004). Indeed, MOF is the most threatened ecosystem in Brazil (Carlucci *et al*. 2011). The grassland, which occupied about 15% of Paraná's land area (Maack 2012), currently covers only 0.1% of its original extent (Fundação SOS Mata Atlântica & INPE 2019). Finally, the cerrado (savannas), which originally covered approximately 1% of Paraná's territory (Maack 2012; Parolin *et al.* 2015), has been decimated in many areas (Guerreiro *et al*. 2011), covering only 0.24% of the state by 2012, with only 48% of these remaining fragments included in state and federal Protected Areas (PAs) (Moro 2012).

The Global Strategy for Plant Conservation (GSPC) of 2016 defined objectives and targets to mitigate the continuous loss of plant species, with actions including expansion and dissemination of biodiversity knowledge - including education on the importance of flora conservation - and measures for ecosystem restoration (CBD 2016). In Paraná, conservation actions under the GSPC framework have included the Network of Biological Collections of Paraná - Taxonline (Marinoni & Peixoto 2010), which disseminates biological information through national online databases (Flora do Brasil 2020, continuously updated; SpeciesLink 2020). In addition, the Paraná flora has been analyzed, at least partially, from the perspective of the extinction risk of its species, resulting in species cited on regional (state list) and national red lists (SEMA 1995; Brasil 2014; CNCFlora 2020).

Finally, we mention a set of legal instruments and public policies based on broad scientific evidence, which has resulted in the elaboration of Strategic Areas for Biodiversity Conservation and Restoration in Paraná (*Áreas Estratégicas para a Conservação e Restauração da Biodiversidade no Paraná* - AECR), territories that aim to reduce environmental degradation and subsidize actions for conservation. Consequently, a focus on ecological planning, surveillance, and environmental protection was implemented for biodiversity conservation of the AECR at the municipal, state, and national levels (IAT 2020; MMA 2007). AECR have been designated based on methodologies developed to identify areas of ecological importance, which are generally the most fragile (IAT 2020; MMA 2020). The first configuration of the AECR was established by the Joint Resolution SEMA/IAP 05 of September 29, 2009 (Paraná 2009) and included the legal determinations for various protected territories in Paraná. These protected lands encompass priority conservation areas, sustainable use, and the distribution of biodiversity benefits, as determined by Ordinance No. 9 of January 23, 2007 (MMA 2007). They also include state and national PAs, protected adjacent areas (buffer zones) of PAs with full protection (MMA 2020), indigenous lands (MMA 2020), and ecological corridors that allow the percolation of the landscape (IAT 2020). Therefore, this study considers the initial configuration of AECR, since this includes the areas of most significant ecological importance in the state.

Given the high risk of biodiversity loss, especially in the most degraded phytophysiognomies of Paraná, as well as ongoing initiatives for flora conservation, we aimed to analyze the presence of threatened species within the phytogeographic limits of the MOF, cerrado, and grassland, and the extent to which these presence records overlap with AECR. The questions guiding this study are: i) do the AECR adequately protect most of the threatened species of the MOF, cerrado, and grassland in Paraná by containing a large number of occurrence records? ii) Which species would be at an elevated risk of extinction in these phytogeographic units?

Materials and Methods

The study area in Paraná encompasses the ecological boundaries of the MOF (Araucaria forest), grassland (natural grassland of southern Brazil), cerrado (savannas), and their related ecological tension areas (IBGE 2012). In this study, the first configuration of the AECR was used, which divides the areas into two groups - conservation and restoration priority areas - as determined by SEMA/IAP Joint Resolution 05 of September 29, 2009 (Paraná 2009) (Fig. 1).

We did not consider updates to the AECR configuration since it has been expanded across the territory to cover as many remains as possible so that inspections can be more rigorous. However, the first version of landscape planning and ecological corridors is still valid, followed, and recommended by the environmental agency (SOS Mata Atlantica & INPE 2019; IAT 2020). Additionally, the extended boundaries include areas where it is not feasible to determine degradation risks on a large scale because they contain remnants of native vegetation at medium and advanced stages of ecological succession. Moreover, these remnants are located on private properties (IAT 2020), where conservation guarantees are not plentiful, mainly because Paraná is one of the states with the largest deforested area of the Atlantic Forest biome in recent years (SOS Mata Atlantica & INPE 2019). Such private remnants have protection levels that vary according to individual characteristics and mainly follow the Native Vegetation Protection Law of Brazil (Law No. 12,651 of May 25, 2012) and the Atlantic Forest Law (Law No. 11,428 of December 22, 2006). Therefore, these areas are under higher long-term risks of extinction and degradation than those contained in the initial configuration of the AECR, which are under a more robust legal protection framework.

The method used comprised four stages: a) compilation of a list of threatened plant species in Paraná; b) construction of a database containing all records of threatened species collected in the state that are deposited in herbaria with digital collections; c) identification of specimen records of threatened species in the AECR phytogeographic regions of interest, and d) data analysis and identification of the species at a high risk of extinction.

To compile the list of all threatened plant species in Paraná (stage 1), the official national list of threatened plant species (MMA 2014) was considered at the national level, supplemented by the list of threatened species evaluated from 2014 to 2020 by the National Centre for Plant Conservation (CNCFlora 2020). Both national approaches categorize threatened species as vulnerable (VU), endangered (EN), and critically endangered (CR), following the IUCN criteria (2016). We also used the red list of the flora of Paraná to encompass a regional approach (SEMA 1995). Because the criteria for this list differ from national ones, they are not equivalent, and the threat statuses are classified as rare, vulnerable, and endangered and treated differently.

All species' scientific names were revised and updated using the Plantminer online tool, following the taxonomic nomenclature available in Flora do Brasil 2020 (continuously updated) (Carvalho *et al.* 2010). The Tropicos database (<https://www.tropicos.org/>) was used to find synonyms among species names not included in the list, which were then updated based on the list of Flora do Brasil database (<http://floradobrasil.jbrj.gov.br>). Taxonomic updates of the Paraná list of threatened species resulted in some species being classified as synonyms of non-threatened species. Such species were excluded from the present analysis.

In the second stage, a database of all records of threatened species collected in the studied phytogeographic regions of Paraná was prepared using data accessed in February 2020 from speciesLink (<http://splink.cria.org.br>) and REFLORA (<http://reflora.jbrj.gov.br>) databases. These databases were combined into one containing the following fields: family name, genus name, specific epithet, authors name, the herbarium of origin, catalog number, collector's number, collector's name, collection year, state, municipality, locality, longitude, and latitude. The spellings of scientific names were updated as in the first stage. The team's experts analyzed the list of species records to identify species with possible misidentifications due to range and taxonomic disagreements, and species that are unlikely to occur in the region were excluded. The database was then reviewed in Excel spreadsheets and the GIS ArcGIS v10.6.1 to find any typos and spelling errors in the names of municipalities and localization errors in geographic coordinate data. Then, non-threatened species were excluded from the database by comparison with the list of threatened species created in the first stage, using the functions PROCV, SE, INDEX, and CORRESP available in Excel.

Occurrence data were refined by excluding low-reliability information on geographic coordinates in R v3.6.1 (R Core Team 2019) using codes we developed and others available in the R CoordinateCleaner package (Zizka 2019). Each record was verified for incomplete coordinates, including ones georeferenced as the centroid of the country or states, recorded as outside the continent, or coordinates very close to cities or research institutions (< 1 km).

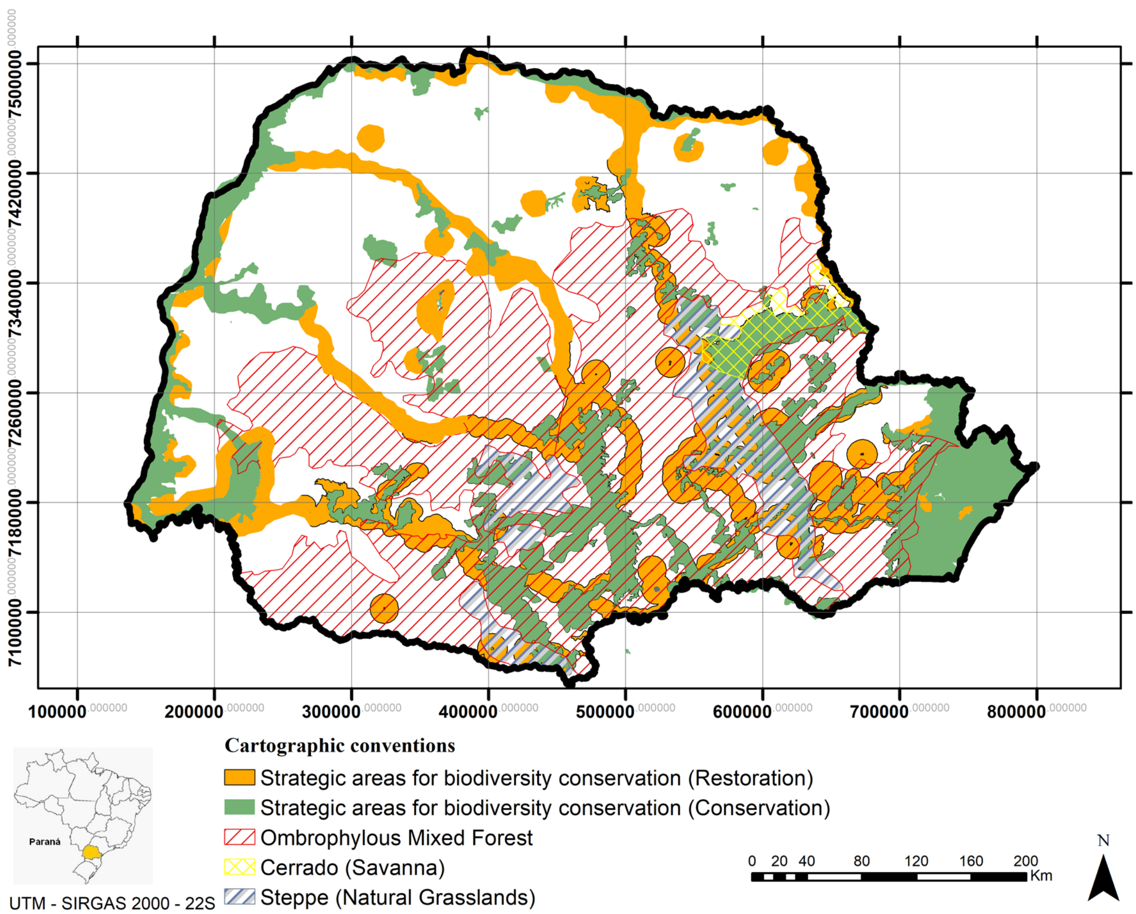

Figure 1 – Study area encompassing the most threatened phytogeographic units of Paraná and the first configuration of the strategic areas for the conservation and restoration of biodiversity in Paraná (Áreas Estratégicas para Conservação e Restauração da Biodiversidade no Paraná - AECR).

For collection records lacking geographical coordinates, the locality field on the database was then used to insert an approximate coordinate of the occurrence, using the centroid of the corresponding locality (for example, the centroid of Pas and other well-known places). This process always checked whether records included any information concerning PAs or other localities with known coordinates (PAs, reference points). Data that could not be reliably georeferenced and records of the same species with identical coordinates were excluded from the database.

In the third stage, data collection records of threatened species in the phytogeographic regions of interest and the AECR were verified. The occurrence record database was reviewed in ArcGIS v10.6.1 using the SIRGAS 2000 datum for all records. The shapefiles for the phytogeographic regions of interest (IBGE 2012) and the AECR (IAT 2020) were used at this stage.

The records of phytogeographic units of interest and then in the AECR were selected using the "selection by locality" tool, checking points within areas or at intersections; in the case of species distribution polygons, we checked when they made intersections with the AECR. Subsequently, an analysis was conducted to determine the percentage of occurrence records and polygons in these regions.

As mentioned, the proportion of species incidence in the AECR was also verified using species distribution polygons following Ribeiro *et al.* (2018) to verify variations between the different forms of analysis, bringing a broader view to the results. The polygons were generated using species records and following the method used by CNCFlora to verify the extent of species occurrence (EOO) (IUCN 2012a,b). Thus, the generated polygons reflected the EOO of each species within Paraná. These polygons were generated by programming in R, connecting the outermost records (points) of occurrence of each species. This allowed us to compare the number of species polygons that intersect with the EOOs and the percentage overlap with the results of the analysis of individual occurrence records.

AECR regions were divided into two main groups: i) strategic conservation areas of native vegetation of ecological interest and with physical or biological attributes indicating environmental fragility and a high priority level for biodiversity conservation in Paraná; ii) priority areas for restoration, which are essential for maintaining the physical stability of the environment and biological flow, comprised of ecological corridors stretching five kilometers from the riverbanks of certain rivers. The first group includes the priority conservation areas, as well as zones designated for sustainable use and shared benefits of biodiversity (MMA 2020); state and national PAs and their buffer zones (MMA 2020); and indigenous lands (MMA 2020). The second group is comprised of the following ecological corridors: ocean coast, Ribeira valley, countryside, and connections with PAs (IAT 2020).

Thus, three approaches were employed at the fourth stage to identify the species at a high risk of extinction in the study area, considering the following aspects: habitat loss and degree of degradation of the remnants as the primary threats to the existence of a species (Saunders *et al*. 1991; Fahrig 2003; Martinelli & Moraes 2013); quantitative and distribution data of species (Mace *et al*. 2005); and gap species, *i.e.*, those whose occurrence does not coincide with the perimeters of protected areas, which are at a higher risk of extinction (Rodrigues *et al.* 2003). We defined gap species as those occurring exclusively outside the strategic conservation areas (AECR sector with the greatest protection potential). This choice is based on the higher risk of extinction, environmental degradation, and anthropogenic pressure outside conservation areas, even within strategic areas for restoration.

The first approach used these three criteria to identify gap species at the highest risk of extinction. Therefore, the selection was limited to gap species classified as CR, the highest species threat status at the national level, considering the method by polygons and registers.

The second set of high-risk species was defined as those classified as CR at the national level and EN at the state level, with only one collection record or species distribution polygons in strategic conservation areas. Although this set does not include gap species, the scarcity of their records makes it unfeasible to establish the species' EOO, crucial for evaluating their distribution, which may be limited to a single population, given that only one record is available for each species (Loyola *et al*. 2014).

Finally, all gap species with EOO distribution polygons containing at least three collection records were classified hierarchically based on extinction risk, considering the method by polygons and registers. This was done by classifying species by threat status (with greater threat status implying higher risk), EOO size (the smaller the EOO, the higher the risk), and the year of the most recent collection (the older the collection, the higher the risk). Spreadsheets with compiled records, species and shapefiles of phytogeographic regions, strategic areas and species hotspots are available as supplementary data at: <https://figshare.com/articles/dataset/PARAN_STATE_S_STRATEGIC_AREAS_FOR_BIODIVERSITY_CONSERVATION_AND_RESTORATION_INCLUDE_THE_MAJORITY_OF_THREATENED_PLANT_SPECIES_IN_THE_MOST_DEGRADED_PHYTOGEOGRAPHIC_UNITS_/21067414/1> (DOI: https://doi.org/10.6084/m9.figshare.21067414.v1).

Results

The first stage of the study resulted in a list of 2,574 species in Paraná identified as threatened at the national and state levels. Subsequent analyses were thus conducted on a total of 673,455 records from botanical collections made in the state, of which 242,028 are from the REFLORA database (<http://reflora.jbrj.gov.br>), and 431,427 are from INCT (speciesLink) (<http://splink.cria.org.br>), deposited in 178 herbaria of 155 institutions.

Limiting the analysis to threatened species from the MOF, grassland, and cerrado regions resulted in a total of 5,422 collection records of 644 species belonging to 376 genera and 110 families (Tab. S1, available on supplementary material <https://doi.org/10.6084/m9.figshare.23902029.v1). These records represent 25% of all officially threatened species in Paraná (SEMA 1995; MMA 2014; CNCFlora 2020).

Most of the collection records of threatened species are in MOF (64% of records and 90% of species), followed by grassland (16% and 37%, respectively), cerrado (12% and 29%, respectively), and areas of ecological tension (7% and 26%, respectively). These figures are consistent with the proportion that the three ecosystems represent in the state.

Of the two groups that comprise the AECR (Paraná 2009), more records (43%) are in the strategic conservation areas than in the strategic restoration areas (26%), with 31% of records located outside the strategic areas (Fig. 2).

The AECR contains 86% of the 644 threatened species, with 51% (326 species) occurring exclusively in these areas and 14% (89 species) only outside.

The AECR region for conservation contains 69% (444 spp) of all threatened species occurrence records from these three habitats, with 19% (122 spp) occurring exclusively in these areas. The region for restoration contains 67% (433 spp) of this occurrence data, with 17% (107 spp) found exclusively in such areas. Meanwhile, 30% (196 spp) are gap species records, defined as species that occur entirely outside the strategic conservation areas.

The minimum threshold for delimiting the minimum convex polygons (three observations) was reached by 420 threatened species. Among these species, 98% (410 spp) have polygons that pass through AECR, 2% (10 spp) have polygons exclusively outside the AECR, while 4% (16 spp) are gap species (species that occur entirely outside the strategic conservation areas).

For the fourth stage, three approaches were used to identify the species at an elevated risk of extinction in the study region. We considered the most extreme aspects that accentuate the threats of extinction: records that show gap species with the highest threat status at the national level (Tab. 1); records with the highest threat status at the national and state level and that are not gaps but have only one collection point in strategic areas for conservation, that is, with evidence of minimal populations (Tab. 2); all the records that show gap species, considering the highest threat status at national and state level, ranked by the year of last collection (Tab. 3). In all tables, we considered the methods of records and species distribution polygons. The tables show drastic scenarios that increase the risks for the species under study. The absolute hierarchy of the most fragile species cannot be established with certainty, but the 54 species shown in the tables deserve closer examination to determine whether urgent conservation actions need to be taken, as they represent a special group of fragility in Paraná. There are 53 species at a higher risk of extinction in the phytogeographic units of the study area. The families that stand out in this list are Orchidaceae (13.20%), Asteraceae (7.54%), Malpighiaceae (5.66%), Malvaceae (5.66%), and Poaceae (5.66%).

Discussion

A first glance at the general structure of the results shows that the number of records of threatened species was proportional to the extent of each phytogeographic unit. Regarding the proportions of families and the percentage of species evaluated by family, there are similarities between our study and the national-wide Brazilian list of threatened plant species (Martinelli & Moraes 2013), which also found Orchidaceae, Asteraceae, Fabaceae, and Myrtaceae as the most threatened families. However, the previous study's list did not include Acanthaceae and Euphorbiaceae. Therefore, the collection records generally followed the proportion of families of threatened species on the national list (Martinelli & Moraes 2013), even after including species from the state list (SEMA 1995).

We found that AECR contributes to the protection of most of the threatened species in the MOF, cerrado, and grassland regions of Paraná, with a large percentage of these species records occurring within the boundaries of AECR. Target 7 of GSPC states that 75% of threatened plant species must be preserved *in situ* (CBD 2016). This proportion was close to that reached in the phytogeographic units of Paraná in the present study, as 69% of the species are located in areas with some legal protection (strategic conservation areas).

Overall, the data indicate that the general principles of landscape ecology considered in the AECR design result in the latter enclosing most of the threatened species. Since their first configuration, the AECR have followed the fundamental principles emphasized by Kremen *et al.* (1998): delimiting areas with representative extensions of the existing habitat types; defining corridors connecting natural habitats that are broad enough to promote the movement of animals; protecting mosaics of habitats and transition zones. Aspects like the percolation of

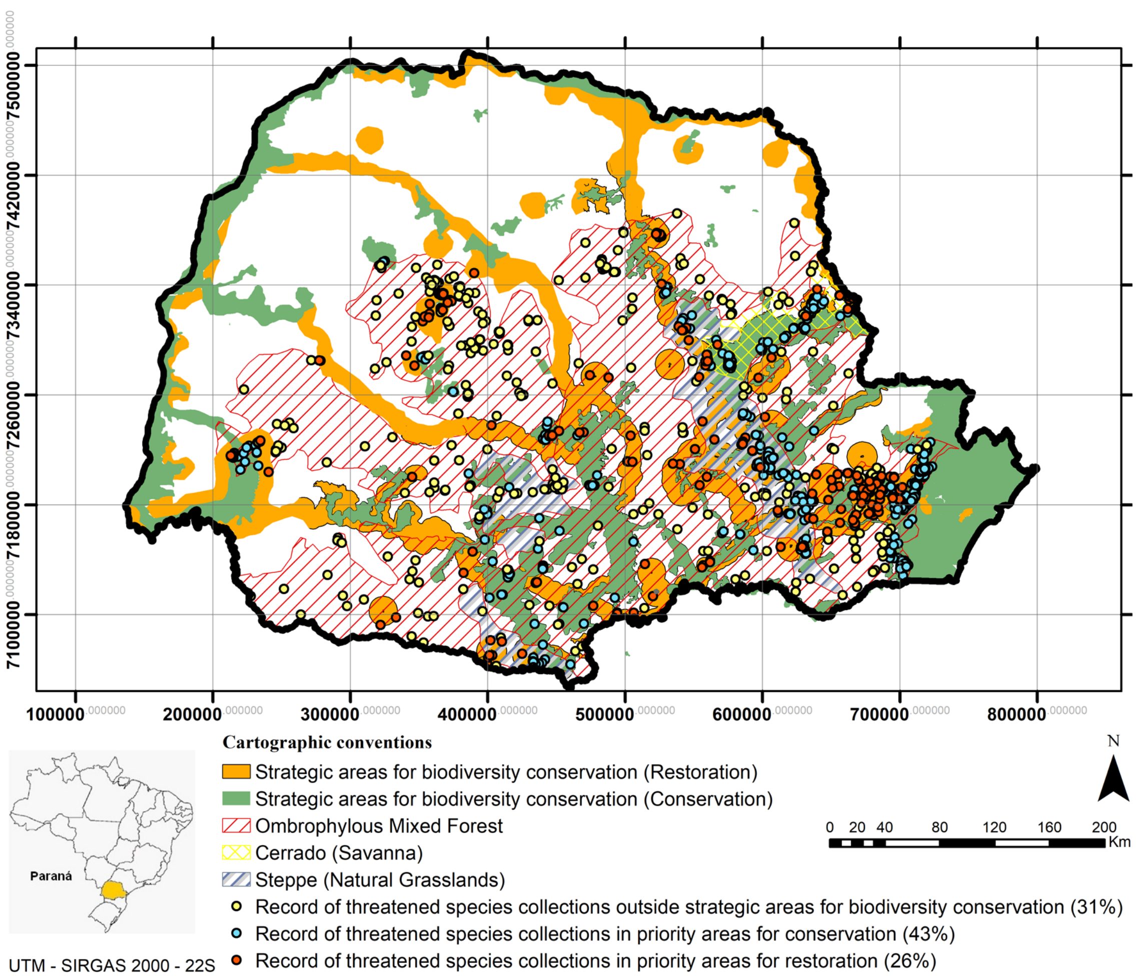

Figure 2 – Distribution of records of threatened plant species in Brazil inside and outside the strategic areas for the conservation and restoration of biodiversity in Paraná (Áreas Estratégicas para Conservação e Restauração da Biodiversidade no Paraná - AECR).

Table 1 – List of gap species critically endangered at the country level occurring in the most degraded phytogeographic units of Parana (mixed ombrophilous forest, cerrado, grassland), according to Brazil's national list (MMA 2014).

Scientific Name	Family
Acianthera adiri (Brade) Pridgeon & M.W.Chase	Orchidaceae
Alstroemeria malmeana Kraenzl.	Alstroemeriaceae
Banisteriopsis pseudojanusia (Nied.) B.Gates	Malpighiaceae
Bipinnula biplumata (L.f.) Rchb.f.	Orchidaceae
Bromidium ramboi (Parodi) Rúgolo	Poaceae
Cirrhaea loddigesii Lindl.	Orchidaceae
Galium rubidiflorum Dempster	Rubiaceae
Hippeastrum vittatum (L'Hér.) Herb.	Amaryllidaceae
Piper hatschbachii Yunck.	Piperaceae

the landscape were well delineated in the AECR design, which proposed connections throughout Paraná's regions, mitigating the harmful effects of habitat fragmentation and, importantly, forming major corridors between source habitat fragments. This design fits within the 30% natural coverage threshold proposed by Andrén (1994) and Fahrig (2003) as the most common scenario for disturbed landscapes, resulting in decreased biological diversity more strongly correlated with habitat loss than with other degradation factors. This fact was highlighted by Metzger (2010). The authors indicated that Brazilian landscapes with less than 30% of conserved habitat tend to have small and very isolated habitat fragments, leading to forest communities with a very low richness of different taxonomic groups; the effects on grassland and cerrado are more diverse and challenging to generalize.

We can consider that the design of the AECR is successful in protecting most threatened species, especially concerning forest environments where the impacts of fragmentation and isolation are best evidenced. In general, implementing the strategic areas is fundamental for the environmental balance and biodiversity conservation in Paraná. However, they are still far from playing an effective role due to implementation challenges (Muchailh 2007). For example, the natural remnants with the highest level of protection ("Unidades de Conservação de Proteção Integral" - the fully protected category of nature reserves as defined by Brazilian law) encompass only 1.8% of the area with forest cover in the state, with most areas with a more flexible level of protection (of the protection type of sustainable use) and no adequate zoning to avoid genetic isolation and edge effects (Muchailh 2007).

Our findings support the functionality of the initial design proposed for the AECR, making it clear that they are an important contribution to achieving GSPC goals. This study was only possible due to the advances in the availability of herbarium data and many advances in plant conservation in Brazil, including studies by Martinelli & Moraes (2013), Loyola *et al*. (2014), BFG (2015), and Martins *et al*. (2017). All these works showed that applying resources in planned actions to conserve threatened plants brings promising results and illuminating perspectives.

Of the species analyzed, 30% (196 spp) are considered gap species in the studied regions. According to Vieira *et al*. (2018), gap species should be the highest priority for conservation actions due to the rapid loss of their habitat. Heywood (2017) also indicated that the conservation of gap species requires measures aimed at unprotected areas. Another interesting finding is that 17% (107 spp) of the species records were exclusively found in strategic restoration areas, which are part of a plan to re-establish natural communities. Although this group of AECR is less effective for conservation because it generally does not have full natural vegetation coverage, the presence of species exclusively found in these areas indicates that actions in these areas can help reduce extinction risks. It is worth pointing out that the lack of records of these species in other areas may be because collection efforts are not as extensive, and it is always recommended to intensify collections to provide further stability to results such as ours.

Table 2 – List of species under the highest threat status at the country and state levels and with only one collection record or species distribution polygons in strategic areas for the conservation of biodiversity in Paraná [*Áreas Estratégicas para a Conservação da Biodiversidade no Paraná* (AECR) - group of strategic conservation areas] in the most degraded phytogeographic units of Paraná (mixed ombrophilous forest, cerrado, and grassland). CR = critically endangered species; EN = endangered species (intermediate threat status in the national list and the highest in the state list); VU = vulnerable species.

Scientific name	Federal threat status	State threat status	Quantity of records or polygons	%
Aldama paranensis (Malme) Magenta & Pirani	CR	VU	1 record	0.02
Alstroemeria malmeana Kraenzl.	CR	-	1 record	0.02
Arthropogon xerachne Ekman	CR	-	1 record	0.02
Banisteriopsis pseudojanusia (Nied.) B.Gates	CR	EN	1 record	0.02
Bipinnula biplumata (L.f.) Rchb.f.	CR	EN	1 record	0.02
Bromidium ramboi (Parodi) Rúgolo	CR	-	1 record	0.02
Butia pubispatha Noblick & Lorenzi	CR	-	1 record	0.02
Butia paraguayensis (Barb.Rodr.) Bailey	-	EN	1 polygon	0.05

Estimates based on species records and indirect estimates based on distribution polygons led to considerable variation in the species deemed to be present in the AECR. For example, 196 spp were classified as gap species using the simple record approach, while only 16 spp were considered gap species using the distribution polygon approach. However, both analyses resulted in high species percentages within the strategic areas. These variations are similar to those reported by Ribeiro *et al.* (2018) when analyzing data from all over Brazil using a similar method. The authors reported 699 spp gap species using occurrence records and 219 spp with the polygon method.

The analysis of the risk level of threatened species [Tabs. S1 (available on supplementary material <https://doi.org/10.6084/m9.figshare.23902029.v1>); 1; 2] aimed to provide helpful information to support studies on species under critical conservation status. Including these threatened species in projects aiming at seedling production, propagation, and restoration is essential for reducing the high risks of regional extinction. Martinelli & Moraes (2013) showed that the families at a higher risk of extinction locally are also among the most threatened species on the national red list.

The high risks facing the species analyzed in the phytogeographic units studied highlight the high demand for restoration in Paraná. Therefore, although the strategic areas for restoration occupy important areas for the species evaluated, the locality factor alone does not guarantee the formation of viable populations. The restoration process, combined with the different methods applied and the species richness considered, are essential for an effective result (Rodrigues *et al*. 2009). Shaw (2019) presented worrying evidence that seedlings' production and use in restoration projects are not at the level needed to meet ecological restoration needs in Paraná. On average, only 20 species are used in restoration projects in the MOF region, few of which are threatened - indeed, only three threatened species are commonly used in restoration projects. In general, only 16% of the species produced in nurseries are categorized as rare or threatened, representing only 10 species (Shaw 2019).

A lack of knowledge about the biology, propagation, and management requirements of individual species makes seedling production for ecological restoration difficult. Consequently, restoration initiatives rarely include lesser-known species or those difficult to obtain and grow, particularly threatened species. Hoffmann *et al*. (2015) tested a methodology for identifying mother trees and seed collection for 71 rare or threatened taxa in the Araucaria Forest. They found that only five species could achieve broad production with adequate genetic diversity. There is a need for in-depth research on the distribution, ecology, and conservation of these threatened species for safe and viable production (Hoffmann *et al*. 2015).

We conclude that 54 species, representing 8.38% of the threatened plant species in the studied

Table 3 – List of gap species (occurring only outside the AECR group of strategic conservation areas) threatened at the country or state levels and present in the most degraded phytogeographic units of Paraná (mixed ombrophilous forest, cerrado, and grassland), threat status, extension of occurrence (EOO), and most recent collection year, in hierarchical order. CR = critically endangered species; EN = endangered species (highest level in the state list); VU = vulnerable species; * = gap species verified by collection records and species distribution polygons.

Scientific name	Federal threat status	State threat status	EOO (km^2)	Ano
Mimosa strobiliflora Burkart	CR	-	1006.56	2008
Acianthera adiri (Brade) Pridgeon & M.W.Chase	CR	EN	8835.33	2000
Astraea cincta (Muell. Arg.) Caruzo & Cordeiro *	EN	EN	0.05	2011
Senecio heteroschizus Baker *	EN	RR	0.18	1969
Janusia occhionii W.R.Anderson *	EN	EN	1.09	1962
Mikania pinnatiloba DC. *	EN	EN	1.28	1971
Pavonia hatschbachii Krapov. *	EN	EN	80.71	1966
Cuphea glaziovii Koehne *	EN	EN	778.18	2017
Aloysia hatschbachii Moldenke	EN	EN	3108.12	2013
Schwenckia curviflora Benth.	EN	EN	3476.61	2015
Bipinnula penicillata (Rchb.f.) Cisternas & Salazar	EN	EN	3678.18	1945
Zephyranthes blumenavia (K.Koch & C.D.Bouché *ex* Carrière) Nic.García & Dutilh	EN	EN	4943.13	2001
Barbosella trilobata Pabst	EN	EN	5481.25	1952
Eugenia myrciariifolia Soares-Silva & Sobral	EN	EN	847.31	1995
Axonopus argentinus Parodi	EN	EN	4255.99	1972
Colletia exserta Klotzsch *ex* Reissek	EN	EN	9832.45	2013
Colletia paradoxa (Spreng.) Escal.	EN	EN	11903.50	2015
Holocheilus hieracioides (D.Don) Cabrera	EN	EN	13639.10	2008
Alstroemeria caryophyllaea Jacq.	EN	EN	37835.9	2010
Escallonia obtusissima A.St.-Hil.	VU	EN	278.37	1989
Octomeria chamaeleptotes Rchb.f.	VU	EN	9980.78	2016
Valeriana reitziana Borsini	VU	EN	24912.7	2013
Froelichia procera (Seub.) Pedersen *	EN	EN	1.09571	1967
Talisia angustifolia Radlk. *	EN	EN	14.3282	1967
Ceratosanthes hilariana Cogn.	EN	EN	118.465	1991
Oxalis sellowii Spreng *	EN	EN	165.703	2014
Cochlospermum regium (Mart. *ex* Schrank) Pilg.	EN	EN	167.963	2013
Hiraea cuneata Griseb.	EN	EN	1124.65	2007
Cuphea hatschbachii Lourteig	EN	EN	1753.03	1968
Pavonia lanata R.E.Fr.	EN	EN	2723.05	1998
Centrosema sagittatum (Humb. & Bonpl. *ex* Willd.) Brandegee	EN	EN	3189.97	2017
Verbena caniuensis Moldenke	EN	EN	4158.83	1969

Scientific name	Federal threat status	State threat status	EOO (km^2)	Ano
Pouteria salicifolia (Spreng.) Radlk.	EN	EN	4180.42	1968
Krapovickasia urticifolia (A.St.-Hil.) Fryxell	EN	EN	5578.54	1966
Trichostigma octandrum (L.) H.Walter	EN	EN	11953.9	2015
Eryngium ekmanii H.Wolff	EN	EN	12017.5	2018
Cattleya cernua (Lindl.) Van den Berg	EN	EN	13314.6	2011
Salvia uliginosa Benth.	EN	EN	17082.4	1971
Glechon ciliata Benth.	EN	EN	17489.7	1989
Ruellia bulbifera Lindau	EN	EN	22720.9	2005
Gomphrena elegans Mart.	EN	EN	23115.8	2014
Escallonia chlorophylla Cham. & Schltdl.	EN	EN	25829.6	1991

regions, are in risk locations, rely on small (often unique) populations, and are therefore severely exposed; these are generally the most worrying species for conservation actions. In addition, they have diverse ecological, economic, and social importance, and there are few studies on them.

A full assessment of the threat status for several of the species analyzed in this study requires an examination of other biomes and phytogeographic units, as well as data beyond the borders of the Paraná. Moreover, the conservation of populations and their genetic diversity at the regional level is also important (Gleason 1917), as are state laws and actions with a significant potential to generate results. Therefore, this and future studies can contribute to state planning and assess ongoing projects to corroborate the promising conservation results of the AECR planning.

Limitations in collection records, both qualitative and quantitative, must also be considered (Meyer *et al.* 2016; ter Steege *et al.* 2011). However, these records serve as verifiable evidence of the presence of species at specific points in space and time. This information is valuable for ecological studies, especially in regions of high diversity where field observations are often scarce and when identifications may be inaccurate (Lughadha *et al*. 2018). Therefore, the present study should be understood as a starting point for further refinements and updates. Further in-depth research depends mainly on expanding floristic inventories, particularly in protected areas (Sobral & Stehmann 2009; Martins *et al*. 2017; Loyola *et al*. 2018; Ribeiro *et al.* 2018).

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