Acta Botanica Brasilica, 2022, 36: e2021abb0021
doi: 10.1590/0102-33062021abb0021

Original article

Tree species of the *Araucaria* Mixed Forest: which, how many and how threatened are they?

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Received: January 21, 2021
Accepted: August 31, 2021

ABSTRACT

Although the *Araucaria* Mixed Forest has long been recognized for their woods and ecosystem services, we still lack basic information on what tree species occur there. Habitat loss and overexploitation have led several tree species of this forest into an extinction process. Therefore, it is urgent to compile what are the tree species of this forest type, identify if these species are threatened and which were not assessed for their threat category. We aimed to answer: (1) How many tree species occur in the *Araucaria* Mixed Forest? 2) How many of these species are under a threat category? (3) Does the number of threatened species per state/province mirror the species richness of the state/province through the *Araucaria* Mixed Forest distribution? We found 1,213 tree species for the forest type. The states of São Paulo, Minas Gerais and Rio de Janeiro presented the highest species richness. The number of assessed species reflected the total number of species per state/province. Of the species listed, 5.3 % were classified as threatened and 72.8 % have not been assessed. We provided the most comprehensive tree species list to date for the *Araucaria* Mixed Forest and unveiled the conservation status of its tree flora.

Keywords: *Araucaria angustifolia*, arboreal species, Atlantic Forest, ecoregion, extinction risk, species list, species pool, subtropical forest, threatened species, tree flora

Introduction

The *Araucaria* Mixed Forest is the main original forest type in southern Brazil, also occurring in southeastern Brazil and northeastern Argentina. Although it is widely recognized as an Atlantic Forest type, it can be distinguished from other Atlantic forest types by the prominence of ancient lineages of vascular plants that composed the forests of the Gondwana since the Early Cretaceous (Carlucci *et al.* 2021). The *Araucaria* Mixed Forest originally covered 20 million ha in southern and southeastern Brazil (Campanili & Schaffer 2010) and has been reduced to 12.6 % by 2005 (Ribeiro *et al.* 2009). In southern Brazil, the *Araucaria* Mixed Forest originally covered 40 % of the state of Paraná, 31 % of the state of Santa Catarina and 25 % of the state of Rio Grande

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do Sul, while in southeastern Brazil, it covered 3 % of the state of São Paulo and 1 % of the states of Rio de Janeiro and Minas Gerais (Mattos 1994). It is characterized by the presence of the conifer *Araucaria angustifolia*, commonly known as Paraná-pine or Brazilian-pine (Campanili & Schaffer 2010). *Araucaria angustifolia* is a magnificent tree that is eminent for its presence, emerging beyond the crowns of other tree species (Rambo 1958). *Araucaria angustifolia* and some other species, such as *Ocotea porosa* and *Cedrela fissilis*, have been targets for their highly profitable woods, which have maintained intense anthropogenic pressure upon *Araucaria* Mixed Forest remnants even in present days (Capobianco 2001; Koch & Correa 2002; Carlucci *et al.* 2021). Even though *Araucaria* Mixed Forest tree flora has been repeatedly surveyed along time, these surveys are usually limited to specific sites, states (*e.g.,* Vibrans *et al.* 2013), or are based on compilations of phytosociological and floristic surveys (*e.g.,* Jarenkow & Budke 2009; Scheer & Blum 2011), thereby not covering all the species that really occur in the forest type as a whole. Therefore, as surprising as it may sound, we still miss an integrated list of tree species for the whole *Araucaria* Mixed Forest.

The Brazilian flora has been declining mainly due to habitat loss and fragmentation, driven by land use change for agricultural and livestock activities (Martinelli & Moraes 2013). This issue is not restricted to Brazil, as ca. 40 % of all species of known vascular plants of the world are under some degree of extinction risk (Nic Lughadha *et al.* 2020). To address the challenges posed by threats to plant diversity, the Convention of Biological Diversity adopted the Global Strategy for Plant Conservation (GSPC), which consists of 16 goals that stimulate and direct the efforts of the countries involved in the conservation of plant species (CBD 2010). Among them, GSPC targets 1 and 2 involve the knowledge growth about the worldwide flora and the assessment of their conservation status, respectively. Different instruments are available to conserve species, including red lists, which describe the threat status of species using international criteria (Martinelli & Moraes 2013).

In Brazil, the National Center for Flora Conservation (CNCFlora) is responsible for advances on research and conservation of the flora, adopting the standards and procedures for risk assessment analysis recommended by the International Union for the Conservation of Nature (Martinelli & Moraes 2013). So far, 46,223 species have been described for Brazil, with 6,046 of them assessed under an extinction degree. Of these, 2,953 have been categorized as threatened (Critically Endangered = CR; Endangered = EN; Vulnerable = VU), but only 530 are included in National Action Plans with the goal of conserving and recovering species (CNCFlora 2020). To our knowledge, no project similar to the Red List of the Brazilian Flora exists for Argentina.

To elaborate conservation plans that are comprehensive and will ensure species persistence, we need information on which species occur in a region and how threatened they are (Margules & Pressey 2000). Considering the high degree of degradation of the *Araucaria* Mixed Forest, it is urgent to know which are the tree species that occur in this forest type, how many of them are threatened and how they are distributed across Brazilian states and northeastern Argentina. In this study, we aimed to answer: (1) How many tree species occur in the *Araucaria* Mixed Forest? 2) How many of these species are under a threat category? (3) Does the number of threatened species per state/province mirror the species richness of the state/province through the *Araucaria* Mixed Forest distribution in Brazil and northeastern Argentina? Regarding the third question, we expected that the number of species threatened in a state/province would reflect (in proportional terms) the total number of species recorded for that state/province.

Materials and methods

Study area

The *Araucaria* Mixed Forest spreads from 18° S to 31.5° S, mainly on elevations between 500 and 1800 m, in southern and southeastern Brazil and in the Argentinean province of Misiones (Hueck 1953). The plant species occurring in this forest type form dense groups, established under conditions of high precipitation, 1,300-3000 mm.year^{-1}, mean temperatures of 20°C-21°C during the summer and 10°C-11°C during the winter (Klein 1960). Besides the conifers *A. angustifolia* and *Podocarpus lambertii* Klotzsch ex Endl. and several species of arborescent ferns (*e.g.,* Dicksoniaceae), the *Araucaria* Mixed Forest is rich in numerous angiosperm families, especially Myrtaceae, Lauraceae and Fabaceae (Scheer & Blum 2011).

Taxonomic data compilation

We compiled information on angiosperm, gymnosperms and fern species occurring in the *Araucaria* Mixed Forest from online databases (Oliveira-Filho 2017; Flora do Brasil 2020 2020) and specialized literature (Sobral *et al.* 2006; Stehmann *et al.* 2009; Vibrans *et al.* 2013) to build a comprehensive tree species list for the *Araucaria* Mixed Forest. For this, we considered a broad definition of tree species, encompassing both arboreal and arborescent species, which included, besides trees, arborescent cacti, palms, and ferns growing taller than 3 m without climbing other plants (Oliveira-Filho 2017).

We applied the following filters to the Flora do Brasil 2020 (2020) database in order to restrain the species search: “Group: Angiosperms”; “Life form: Tree”; “Vegetation: Mixed Ombrophilous Forest”; “Search: Species”; “Search Options: List only accepted names”. Given that palms are classified as herbs in Flora do Brasil 2020 (2020), we made an additional search regarding the Arecaceae family. We also

made searches for gymnosperms and ferns, always using the same following filters irrespective of the taxon: "Vegetation: Mixed Ombrophilous Forest"; "Search: Species:"; "Search Options: List only accepted names".

For NeoTropTree, which is a database on species distribution along the Neotropical region (Oliveira-Filho 2017), we filtered only the tree species that occur in the *Araucaria* Mixed Forest and the states/province where this forest types occurs: Rio Grande do Sul, Santa Catarina, Paraná, São Paulo, Rio de Janeiro, Minas Gerais, and Misiones Province. For Argentina, we carefully considered only the species of the *Araucaria* Mixed Forest occurring in the Misiones Province to avoid the inclusion of species from the *Araucaria araucana* mixed forests, which occur in other provinces of the country, but not in Misiones.

Finally, we merged all the lists into one general list and standardized the botanical nomenclature according to the Flora do Brasil 2020 (2020) database (accessed on January 22nd 2020) by using the "flora" package in the software R version 3.5.2 (R Development Core Team 2019). In this search of the integrated species list in Flora do Brasil 2020 (2020), we obtained information on the distribution of the species across Brazilian states. We also added the occurrences in Misiones Province and additional occurrences in Brazilian states found in the other references.

Threat categories

We obtained the assigned threat category for each species from the standardized species list using "flora" R package, which retrieves threat categories from CNCFlora (2020). The three threat categories are Critically Endangered (CR), Endangered (EN), and Vulnerable (VU). The "non-threatened" categories are Near Threatened (NT), Least Concern (LC), Data Deficient (DD), and Not Evaluated (NE). We considered CNCFlora's threat category for all species, including those occurring in Misiones, as no project similar to the Red List of the Brazilian Flora exists for Argentina, and Misiones represents a minor portion of the original *Araucaria* Mixed Forest distribution.

Data analyses

We assessed the distribution of threatened tree species across states/province. We obtained the total number of species per state/province, the number of species with extinction risk assessment per state/province, and the number of threatened species per state/province. We performed a Pearson correlation analysis to test whether there was an association at the state scale (1) between the number of assessed species and the species richness, (2) between the number of threatened species and the species richness and (3) between the number of assessed species and threatened species. The data presented Gaussian distribution, so that we used parametric analyses. The analyses were performed in R (R Development Core Team 2019).

Results

Our results indicated that 1,213 species (Tab. S1 in supplementary material) and 101 families of trees occur in the *Araucaria* Mixed Forest (Tab. S2 in supplementary material). One of these species is cultivated and five are naturalized (Tab. S1 in supplementary material), thus there are 1,207 native tree species in the *Araucaria* Mixed Forest. Of the 1,213 species, 962 occur in the mixed forests of São Paulo, 893 in Minas Gerais, 869 in Rio de Janeiro, 865 in Paraná, 708 in Santa Catarina, 486 in Rio Grande do Sul, and 307 in the Misiones Province (Fig. 1A). Among these 1,213 species, 64 (5.3%) are currently threatened (Tab. S3 in supplementary material) according to CNCFlora (2020): only one (0.0008%) is CR (*Eugenia rotundicosta*), 32 (2.6%) are EN and 31 (2.5%) are VU. Among non-threatened species, 42 are NT, 218 are LC, six are DD, and 883 (72.8%) have not been assessed (Fig. 1B). The families with the highest number of species were Myrtaceae, Fabaceae, Melastomataceae, Lauraceae, Rubiaceae and Solanaceae (Fig. 1C).

It is interesting to note that, by searching the tree species that occur in the *Araucaria* Mixed Forest using the Flora do Brasil 2020 (2020) database, we found only 395 species for this forest type. However, we noted that some of these species were misleadingly attributed to occur in the *Araucaria* Mixed Forest despite not occurring in the states in which this forest type is distributed. This issue also occurred with data from two other sources (Oliveira-Filho 2017; Stehmann *et al*. 2009). We excluded, from our first integrated list (n = 1,251 species), a total of 38 species that were incorrectly cited for the *Araucaria* Mixed Forest without occurrences for the states of this forest type.

In total, 330 species (27%) were assessed by CNCFlora following the IUCN guidelines, which, in our compilation, resulted in 21 families that present threatened species (Tab. S2 in supplementary material): Myrtaceae (with 27 species), Lauraceae (7), Fabaceae (5), Proteaceae (3), Arecaceae (2), Meliaceae (2), Rhamnaceae (2), Sapotaceae (2), and Symplocaceae (2); Anacardiaceae, Araucariaceae, Bignoniaceae, Dicksoniaceae, Lecythidaceae, Monimiaceae, Myristicaceae, Podocarpaceae, Quillajaceae, Salicaceae, Sapindaceae and Vochysiaceae presented only one species categorized as threatened each.

The states with the highest numbers of threatened species were Paraná (41), Santa Catarina (36) and São Paulo (30) (Fig. S1 in supplementary material). Two states presented occurrence of the only tree species categorized as CR in the *Araucaria* Mixed Forest, *E. rotundicosta*: Santa Catarina and Rio Grande do Sul (Tab. S1, Fig. S1 in supplementary material). The states with the highest number of non-assessed species were São Paulo (694), Minas Gerais (666), and Rio de Janeiro (653).

The number of assessed species reflected the total number of species found per state/province (r = 0.97, $d.f.$ = 5, P < 0.001; Fig. S2 in supplementary material).

Moreover, the higher the number of assessed species for the threat category, the higher the number of species categorized as threatened (r = 0.79, $d.f.$ = 5, P = 0.032; Fig. S3 in supplementary material). We found no statistical evidence that the number of threatened species reflects species richness per state/province (r = 0.68, $d.f.$ = 5, P = 0.092; Fig. S4). However, taking into account that the number of threatened species reflected the number of assessed species per state, and that the number of assessed species reflected the species richness per state/province, these numbers are likely all correlated. The reason why we found no statistical support for a correlation between the number of threatened species and the species richness per state/province are likely the low degrees of freedom ($d.f.$ = 5), which are constrained by the low number of states/province involved in the analyses (n = 7).

Discussion

Our results indicated that the *Araucaria* Mixed Forest harbors a rich tree flora, reaching 1,213 species in over 100 families. The previous literature information on the tree species richness of this entire forest type was very limited, because available studies were usually based on compilations of local surveys of forest fragments (*e.g.,* Scheer & Blum 2011), so it is difficult to compare our list with the existing literature. The species list we present for the *Araucaria* Mixed Forest is, therefore, the first comprehensive tree species list for the entire forest type. This list is of paramount importance because it provides basic information that can be used in pure botanical and ecological studies, as well as in studies and plans for the conservation and restoration of territories of the *Araucaria* Mixed Forest and its tree species.

Data from the Flora do Brasil 2020 (2020) presents an elevated taxonomic rigor (Flora do Brasil 2020 2020). However, because of this strict taxonomic focus, Flora do Brasil limits the species information to those obtained from herbarium vouchers revised by specialists. Since there is a lack of sampling for many species and often the plant material collected is not deposited in herbaria, there are major distributional knowledge gaps for most species. Moreover, taxonomists may not focus or may not have extensive knowledge on the distribution of species across different vegetation types, so that specific occurrence in the *Araucaria* Mixed Forest may not be attributed for many species. Therefore, despite Flora do Brasil 2020 (2020) being taxonomically accurate, it still does not allow a complete listing of species per forest type. We trust that the tree species list we presented here fills this gap for the *Araucaria* Mixed Forest.

Our results suggested that the number of threatened species per state/province mirrors the species richness of the state/province throughout the *Araucaria* Mixed

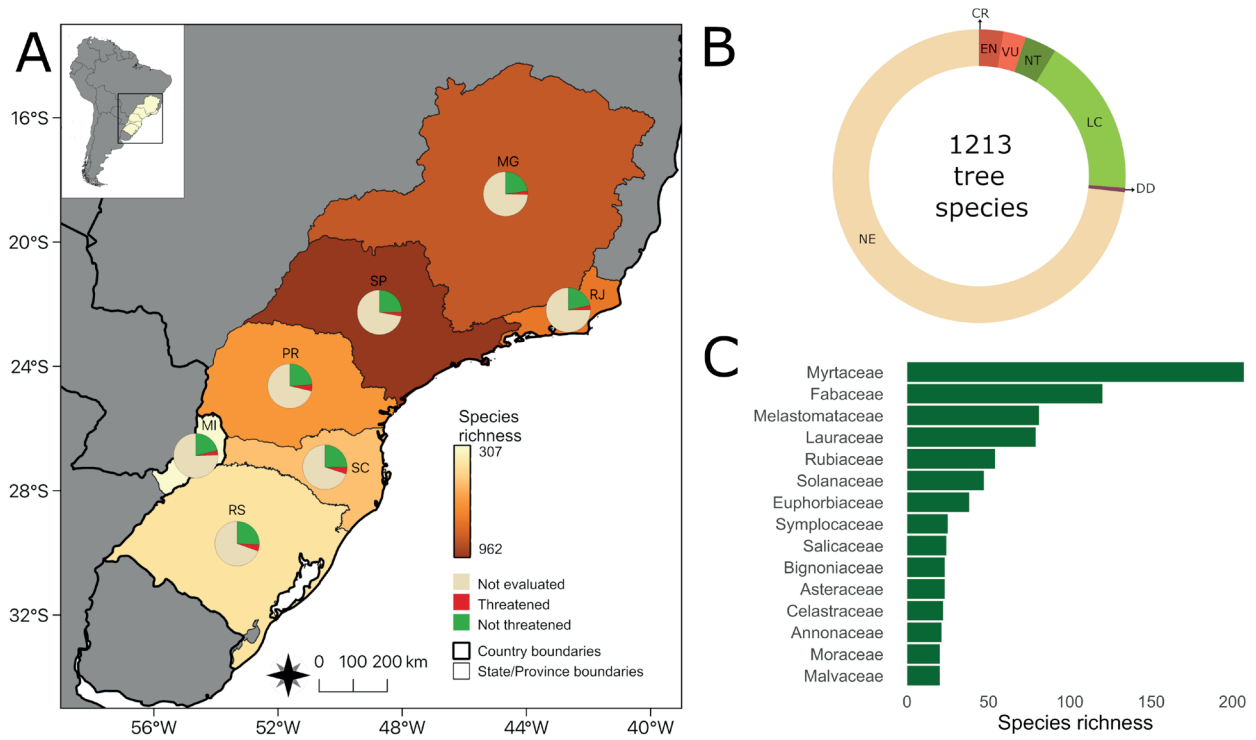

Figure 1. A) Total species richness per state/province and number of species under IUCN Red List categories (according to CNCFlora 2020) throughout the *Araucaria* Mixed Forest. **A**) Colors indicate species richness for S and SE Brazilian states and for the Misiones Province, Argentina. **B**) Number of species per IUCN Red List category in the *Araucaria* Mixed Forest. **C**) Species richness per family in the *Araucaria* Mixed Forest.

Forest distribution. This finding indicates that there is no trend in the number of threatened species towards one or a few states; rather, the number of threatened species is approximately the same proportion of species from the regional pool irrespective of the state. The causes behind this pattern are not clear yet. First, considering that only a minor portion of species were assessed (27 %), we need to accomplish more assessments of species conservation status to learn whether the proportions observed here are really representative of the whole tree flora of this forest type. Second, if the proportions are maintained, the reflection of the number of threatened species relative to the number of species in the state/province pool might be explained as follows: (1) the drivers of extinction risk are evenly distributed throughout the original distribution of the *Araucaria* Mixed Forest; (2) the number of threatened species is merely a random draw of the same proportion of species from the regional pool across states/province. We consider the first explanation is more feasible, because the whole *Araucaria* Mixed Forest range has been subject to the same drivers of deforestation and land use changes throughout the past century (reviewed by Carlucci *et al.* 2021).

Among all the *Araucaria* Mixed Forest species with extinction risk assessment, 19.4 % are classified as threatened, which represents 5.3 % of the total number of species of this forest type. If this proportion of ca. 20 % of species being threatened is maintained as more species are assessed, this is very concerning. However, the criterion behind the selection of the first set of species assessed by CNCFlora was not random with respect to extinction risk, as species that had been historically included in previous red lists were prioritized (Martinelli & Moraes 2013). We found that 72.8 % of the tree species of the *Araucaria* Mixed Forest have not been assessed yet. Considering the potential bias in the selection of species to start the extinction risk assessment, it is possible that among the non-assessed species the percentage of threatened species is actually lower than the ca. 20 % of threatened-to-assessed species ratio; however, this hypothesis remains to be tested in the future. When there is not enough data on biodiversity, we are under the risk of losing species without having basic information about their biology and function in nature, because knowledge gaps and global anthropogenic changes increase the biodiversity crisis, leading many species to a process of extinction (Hortal *et al.* 2015). Therefore, we urge to increase the velocity in which our plant species are assessed regarding their extinction risk.

In phytogeographical terms, surprisingly, we found that states with the smallest coverage areas of *Araucaria* Mixed Forest – São Paulo, Minas Gerais and Rio de Janeiro – were the ones presenting the highest richness of tree species in this forest type. We attribute these findings to the species-rich forests that surround the *Araucaria* Mixed Forest in these states, i.e. Atlantic rainforests and seasonal forests, which are richer in species at tropical than at subtropical or temperate latitudes (Zwiener *et al.* 2021). Paraná was the only state in the core region of the *Araucaria* Mixed Forest distribution to present more than 850 species and was the fourth place in species richness. Paraná has high coverage of this forest type both historically and currently and also presents a high influence of species-rich tropical forests from the north. Going southward in the *Araucaria* Mixed Forest, in the Misiones Province and the states of Santa Catarina and Rio Grande do Sul, there is a marked reduction in tree species richness, possibly because the subtropical/temperate climate with frequent frosts limit the establishment of tropical species (Oliveira-Filho *et al.* 2015).

The families with higher richness of tree species for the *Araucaria* Mixed Forest were Myrtaceae, Fabaceae, Melastomataceae, and Lauraceae. This finding is similar to that found by Scheer & Blum (2011) analyzing tree communities of *Araucaria* Mixed Forest and other Atlantic forest types in the state of Paraná. From these most speciose families, Myrtaceae, Lauraceae and Fabaceae were also those with the highest number of threatened species in the *Araucaria* Mixed Forest. Interestingly, Melastomataceae, which is a highly speciose family in this forest type and which appears as one of the top-ten families with more species under a threat category in Brazil (Martinelli & Moraes 2013), presented no threatened tree species in the *Araucaria* Mixed Forest. It is noteworthy, however, that only seven out of the 81 Melastomataceae tree species of the forest type have been assessed so far.

We compiled a list of 1,213 tree species occurring in the *Araucaria* Mixed Forest and recorded species richness and number of threatened species of this forest type across Brazilian states and the Misiones Province, Argentina. About one-quarter of the species of the forest type have an extinction risk assessment and about 20 % of the assessed species have been classified as threatened. We have filled the gap of a comprehensive tree species list and unveiled the conservation status of the tree flora of the *Araucaria* Mixed Forest, which is very concerning. We urge future efforts towards the assessment of more species regarding their risk of extinction and towards basic ecological and botanical studies of the tree flora of this severely threatened forest type. We hope that our results are useful for prioritizing species data collection and supporting conservation and restoration actions in the near future.

Acknowledgements

We thank Pablo Viany Prieto, Marina Scalon and two anonymous reviewers for useful comments on earlier versions of this paper; the PPG Botânica UFPR, and the members of the Laboratório de Ecologia Funcional de Comunidades (LABEF), Dep. Botânica, UFPR, for logistic support. This study was funded by Coordenação

de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) - Finance Code 001, through MSc fellowships to AZ, ACPS and GFM and a postdoctoral fellowship to FTB (PNPD 88882.306081/2018-1).

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