Assessing the extinction risk of tree species in the subtropical Atlantic Forest using multiple IUCN criteria

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Abstract The Atlantic Forest is one of the most threatened tropical forests in the world. Many species have declined and become isolated because of pervasive forest loss and degradation. Here we assess the current population status of Atlantic Forest tree species from Santa Catarina state in southern Brazil to inform conservation policies and future management and protection. We used a novel methodology to generate automated conservation assessments from forest surveys and herbaria data, based on IUCN criteria A, B, C and D. We assessed more than 500 tree species whose populations are considered threatened. Population size reduction (i.e. IUCN criterion A) was the main indicator of threat, followed by restricted geographical range (criterion B). We observed population reductions of over 50% over three generations in more than 60% of the assessments. We recommend including taxonomically verified herbaria data to improve the accuracy of conservation assessments. The results obtained here can be used to identify important and potential regions for creating protected areas and implementing forest restoration programmes.

Keywords Atlantic Forest, forest surveys, herbaria data, IUCN, population decline, Red List, regional assessment, tropical forest

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Introduction

The Atlantic Forest is a biodiversity hotspot supporting more than 5,000 tree species, of which 45% are endemic (Lima et al., 2020b). This biogeographical domain once stretched for 1.5 million km along the Brazilian coast but is now reduced to one-third of its original cover and is divided into small, isolated and heavily disturbed patches (Rosa et al., 2021). Most of the remaining Atlantic Forest is secondary forest (Ribeiro et al., 2009), and only 20% is protected (Presidency of the Republic of Brazil, 2000). Given its vulnerability, it is important to restore the fragmented landscape of the Atlantic Forest (Ribeiro et al., 2009) and conserve its biodiversity (Rodrigues et al., 2006).

The IUCN publishes standardized guidelines for conservation assessments that allow species to be classified according to their risk of extinction and offer relevant information for decision-makers and conservation practitioners (IUCN, 2022). Most Atlantic Forest tree species have not been assessed in the past because a paucity of data has restricted the application of IUCN criteria (Martins et al., 2017). The first comprehensive assessment of all arborescent Atlantic Forest species indicated that 66% of populations and 84% of endemic tree species are threatened (Lima et al., 2024).

Whilst global conservation assessments are based on the known distribution of specific taxa worldwide, the scale of human impacts on biodiversity (e.g. land-use change) is primarily regional (Pimm et al., 2001). Furthermore, most support for species protection is provided at an institutional, regional or national level. These factors underline the importance of regional conservation assessments and local Red Lists. The current list of threatened tree species for Santa Catarina state, southern Brazil (CONSEMA, 2014), was not based on the IUCN criteria and categories (Elias et al., 2019) and needs updating. More recent data are available from the FlorestaSC project (Vibrans et al., 2010, 2020) and other forest surveys (Lima et al., 2015). In addition, the herbaria collections of Santa Catarina have been digitized and integrated into the Global Biodiversity Information Facility database (Gasper et al., 2020), including data from surveys conducted since the 1950s (Reitz, 1965).

Here we compile a comprehensive dataset of all forest survey and herbaria data for Santa Catarina state, comprising over 200,000 measured trees and 12,000 cleaned herbaria records. We use these data to assess the conservation status and update the Red List of tree species using IUCN guidelines. We also evaluate the advantages of using taxonomically verified herbaria data in species

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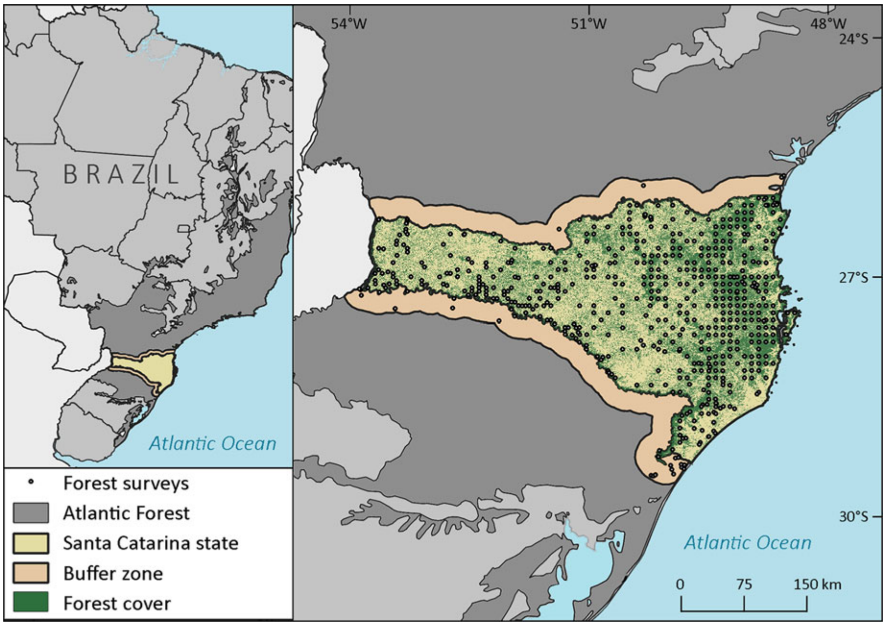

FIG. 1 Distribution of forest cover in Santa Catarina state, southern Brazil, and locations of forest surveys in the state and in a 25 km buffer zone along its borders with neighbouring Brazilian states. (Readers of the printed journal are referred to the online article for a colour version of this figure.)

assessments. We followed the current literature on conservation status (Stévart et al., 2019; Lima et al., 2024) by quantifying extinction risk using multiple IUCN criteria (IUCN, 2012): the decline in a species' population size (IUCN criterion A) across a time series of forest cover; the species' geographical range (criterion B); and small and declining populations (criteria C and D).

Study area

The state of Santa Catarina, southern Brazil, encompasses an area of 95,356 km², located at 26°–29°S and 48–53°W, with altitudes of 0–1,753 m (Fig. 1). The vegetation types are tropical and subtropical moist broadleaf forests (Alto Paraná forests, Araucaria moist forests and Serra do Mar coastal forests) and mangroves (Restingas; Dinerstein et al., 2017). The state has two climate types, classified as humid subtropical with hot summer (Cfa) and humid subtropical with temperate summer (Cfb) under the Köppen system (Alvares et al., 2013). Mean annual temperature is 10–22 °C and precipitation is 1,100–2,900 mm (Pandolfo et al., 2002). The tree flora of Santa Catarina state is threatened by human impacts, including illegal selective logging, clear-cutting, fire, understorey mowing, and understorey cattle grazing and trampling (Vibrans et al., 2020).

Methods

Trees of Santa Catarina

The definition of a tree varies but often stipulates a free-standing trunk that reaches minimum values of height and/or diameter at breast height. We compiled a list of qualifying tree species based on records of all plants that occur in Santa Catarina taken from the Global Biodiversity Information Facility, cross-referenced with Flora e Funga do Brasil (The Brazil Flora Group et al., 2022) to check for any taxonomical modifications and to establish the growth form for each species. We limited our selection to those species that could occur as a tree, excluding those that only occurred as a shrub in the study area. We checked the preliminary list of 972 tree species and removed any that were erroneously assigned to Santa Catarina by Flora e Funga do Brasil, those that did not occur as a tree in Santa Catarina (Vibrans et al., 2020) and species with dubious identification. The final list comprised 577 tree species for Santa Catarina state.

Forest surveys

We obtained forest survey data for Santa Catarina state, and a 25 km buffer along its boundaries with the neighbouring states of Paraná and Rio Grande do Sul (Fig. 1), from the Neotropical Tree Communities database of information for neotropical domains in eastern South America (TreeCo; Lima et al., 2020a). We obtained further data from Lima et al. (2020a) including species abundance records, growth form (shrubs, treelets and trees), ecological group (pioneer, early secondary, late secondary and climax), generation length (IUCN, 2022) and mean proportion of mature individuals in the population known to be capable of reproduction (sensu IUCN, 2022). We used Flora e Funga do Brasil (The Brazil Flora Group et al., 2022) to check the species nomenclature in the dataset and to remove cultivated, naturalized and exotic species. The resultant

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dataset comprised 265 ha of sampled forests, 544 plots, 502 species and 206,207 individually measured trees.

Herbaria data

We applied the workflow and software described by Lima et al. (2023) to obtain and clean herbaria data. We obtained data from the Global Biodiversity Information Facility (2021) and *species*Link (Canhos et al., 2022), then standardized, edited and validated the herbaria collection codes, locality, geographical coordinates and taxon names. We conducted multiple validation steps to ensure data quality, flagging the following issues: outlier occurrences, coordinates not matching the assigned country/state, occurrences in the sea, duplicate records, and erroneous or unreliable species identification. We then removed these invalid records, resulting in a final herbaria dataset comprising 12,318 records of 555 tree species.

Forest cover

We divided the state of Santa Catarina into 5,738 grid cells measuring 5 × 5 km and removed those situated in highland grasslands to avoid overestimating habitat availability for tree species. We overlapped the final grid of 4,359 cells with land-cover maps at 30 m spatial resolution from MapBiomas (Souza et al., 2020), a highly detailed reconstruction of land-use change in Brazil. We extracted pixels defined by MapBiomas as 'Forest Formation' (areas > 0.5 ha with trees reaching a minimum height of 5 m and with the tree canopy varying for different types of forest formation) from each grid cell, summed the number of those pixels and multiplied this value by their area. We divided this product by 10,000 m^2 to obtain the forested area in hectares in each grid cell and calculated the area of forest across Santa Catarina state. We repeated this procedure for the years 1985–2019 from the MapBiomas time series.

Mapping tree density

To estimate the population sizes and reductions in numbers of Santa Catarina tree species, we predicted tree density distribution across the state using a regression model informed by the forest survey data. We used 10 variables: monthly minimum temperature, annual mean temperature, temperature seasonality, precipitation, relative humidity (WorldClim, 2022), mean solar radiation, annual potential radiation (McCune & Keon, 2002), declivity (Farr et al., 2007), an environmental stress factor (Chave et al., 2014) and the Human Influence Index (Venter et al., 2016). We generated 210 models from these variables and selected the best one (best subset selection) using the Bayesian information criterion (Gareth et al., 2014). We then used the chosen model, which included monthly minimum temperature and temperature seasonality, to predict tree density per ha for each grid cell via universal kriging (Supplementary Material 1, Supplementary Fig. 1, Step 1). We repeated the procedure for the lower and upper values of the 95% CI to account for uncertainty in the estimation.

Species populations and population sizes

We converted the abundance of each species into relative abundance RA_i for each forest survey as follows:

$$RA_i = n_i / N$$

where n_i is the number of individuals of different tree species i, and N is the total number of trees in the survey. Following Steege et al. (2015), we constructed an inverse distance weighting model to predict RA_i per species in each grid cell. Next, to estimate the number of individuals per species in each grid cell, we multiplied the predicted relative abundance RA_i by tree density (tress per ha, calculated previously) and the grid cell area (25 km^2 or 2,500 ha; Supplementary Material 1, Supplementary Fig. 1, Step 2). We then corrected these estimates by overlaying them with forest-cover maps from the MapBiomas time series (1985–2019) and summing the results for all cells (Supplementary Material 1, Supplementary Fig. 1, Step 3). The estimated population size of each tree species accounts for changes in forest cover across time and spatial variation of forest tree density linked to environmental factors.

The IUCN (2022) defines a population as the total number of individuals of a taxon throughout its distribution, including mature and other life stages. However, population size is measured only in terms of the proportion of mature individuals, p. Thus, population size sensu IUCN (2022) only accounts for a fraction of the population, and we calculated it as the product of the species population multiplied by p, the latter obtained from Lima et al. (2024) and estimated from assumptions regarding the growth form of species, their ecological group and previous studies that assessed p for some tropical trees.

Red List criteria and categories

We assessed the conservation status of each tree species using multiple criteria, based on IUCN guidelines (IUCN, 2022). As in Stévart et al. (2019) and Lima et al. (2024), our assessment is preliminary as it does not include the revision and justification steps of species-by-species evaluations. However, these assessments provide all of the metrics and analyses necessary for producing final assessments in future evaluations. We based our assessments on the criteria (A) population reduction, (B) geographic range, (C) small and

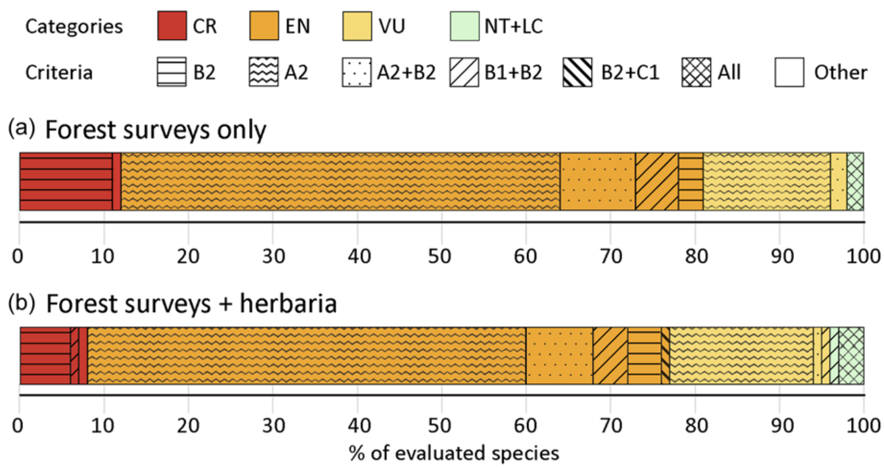

FIG. 2 The per cent of tree species in Santa Catarina state, Brazil, classified under each IUCN category (CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NT, Near Threatened; LC, Least Concern), according to different IUCN criteria (IUCN, 2012). The assessments were based on data from (a) forest surveys only and (b) forest surveys plus herbaria data. Only (sub)criteria assigned to at least 1% of all assessed species are shown; combinations of criteria that represented a smaller percentage of all species are shown as 'other'. The categories Least Concern and Near Threatened were merged as they were assigned to only a small proportion of the evaluated species.

declining populations and (D) very small or restricted populations (IUCN, 2012).

We did not quantify extreme fluctuations in population sizes (criteria B1c, B2c, C2b) because trees are long-lived organisms unlikely to undergo variations in population sizes or distributions 'widely, rapidly and frequently' (IUCN, 2022; Lima et al., 2024; Supplementary Material 1). We adapted all criteria evaluations from the workflow established by Lima et al. (2024); data, scripts and functions are available on GitHub (Lima & Dauby, 2024). We assessed species only under the following IUCN Red List categories: Least Concern, Near Threatened, Vulnerable, Endangered, Critically Endangered and Data Deficient. If there was sufficient information for a taxon to be assessed under two or more IUCN criteria, and if the assigned threat category varied depending on the criteria used, we assigned the higher category of threat overall (IUCN, 2022). We set 2019 as the assessment year for all species because it was the most recent year with available forest cover data from MapBiomas.

The effects of different criteria on species evaluation

Different criteria can impact species assessments in different ways, so we evaluated the results of our analyses using two datasets: one containing only forest survey data and a second containing forest survey data plus herbaria records. We measured differences in criteria, categories and the Red List Index (Butchart et al., 2007) between both datasets (forest survey only, and forest survey plus herbaria). The Red List Index can be used to measure changes in categories over time, between regions or between different sets of species. It is calculated as the proportion of species expected to remain extant in the near future in the absence of additional conservation actions (Butchart et al., 2007). The Index ranges from 0 to 1, where 1 equates to all species classified as Least Concern and 0 equates to all species classified as Extinct.

Regional and local assessments

As a final step, we conducted a species-by-species comparison of threat categories between our local assessments and those from the regional assessments by Lima et al. (2024), looking for any differences and/or similarities. To do this, we created a chord diagram (Supplementary Fig. 2).

Software and packages

We performed all analyses in *R 4.2.1* (R Core Team, 2023). We checked grammar and synonymous terms using the *flora* package (Carvalho, 2023), and cleaned herbaria data using *plantR* (Lima et al., 2023). We handled spatial data using packages *raster* (Hijmans, 2023), *sp* (Pebesma & Bivand, 2005; Bivand et al., 2013) and *rgdal* (Bivand et al., 2023). We performed best subset selection in *leaps* (Miller, 2020) and fitted universal kriging and inverse distance weighting using *gstat* (Pebesma, 2004; Gräler et al., 2016). We evaluated all criteria and categories using *ConR 2.1* (Dauby & Lima, 2023) and measured the Red List Index using *red* (Cardoso, 2017). We obtained protected area maps using *wdpar* (Hanson, 2022; UNEP-WCMC & IUCN, 2023a,b).

Results

We evaluated 502 tree species using forest survey data alone (Supplementary Material 2) and considered 494 (98%) to be threatened under at least one IUCN criterion (Fig. 2a,

TABLE 1 The per cent of tree species in Santa Catarina state, southern Brazil (Fig. 1), assessed as threatened using IUCN criteria A, B, C and D (IUCN, 2012), separately and overall, based on data from forest surveys only and in combination with herbaria data. Median Red List Index values are shown, with 95% CIs.

IUCN criteria	Forest surveys only		Forest surveys plus herbaria data	
	Threatened (%)	Red List Index (95% CI)	Threatened (%)	Red List Index (95% CI)
A	74.5	0.45 (0.45–0.46)	74.5	0.45 (0.45–0.46)
B	31.7	0.37 (0.35–0.39)	26.9	0.39 (0.37–0.41)
C	1.6	0.58 (0.51–0.60)	1.6	0.58 (0.52–0.60)
D	16.5	0.60 (0.60–0.60)	16.5	0.60 (0.60–0.60)
All	98.4	0.41 (0.40–0.42)	96.6	0.43 (0.42–0.43)

Table 1). The most common threat category was Endangered (70%), followed by Vulnerable (17%) and Critically Endangered (11%). Only eight species were classified as not threatened (Near Threatened and Least Concern). After integrating herbaria data, we were able to evaluate 555 tree species (Supplementary Material 3), but there were minimal changes in the results (Table 1). The Red List Index for Santa Catarina was 0.42 (95% CI: 0.41–0.43) when considering only forest survey data and 0.45 (95% CI: 0.44–0.46) after herbaria data were integrated.

We found that the Red List category assigned to each species varied depending on the IUCN criteria used in the assessment (Table 1). For both datasets c. 80% of all tree species were assessed as threatened under criterion A2, which corresponds to population declines above 30% in the last three generations (ranging from 30 to 240 years). Overall, almost 70% of species had an estimated population decline of more than 50% in the last three generations. Only 6% of populations were estimated to have declined by less than 30%, which classifies them as not threatened. Only one species (*Condalia buxifolia*) showed an increase in population size. When considering only the last 25 years, just 22% of all tree species had an estimated population decline of less than 30%.

The main difference between the results from the two datasets (forest surveys only vs forest surveys plus herbaria) related to interpretation of criterion B, geographical range, because the addition of herbaria data affected the distribution parameters of threatened tree species and thus their range (Fig. 2). Criterion B1 (extent of occurrence) was the main criterion for 13% of all conservation assessments and criterion B2 (area of occupancy) was the main criterion for 35% of the assessments based on forest survey data alone. When herbaria data were added, this percentage remained at 13% for criterion B1 and decreased to 30% for criterion B2. At least 20% of all threatened tree species showed a continuing decline in severely fragmented populations.

The IUCN criteria C (small and declining populations) and D (very small or restricted populations) were less relevant to conservation assessments (Fig. 2, Supplementary Materials 2, 3). Only eight species (*Euplassa cantareirae*, *Monteverdia patens*, *Myrceugenia acutiflora*, *Myrcia subacuminata*, *Oreopanax capitatus*, *Rhamnidium elaeocarpum*, *Schinus mole*, *Trichilia silvatica*) had population sizes of <10,000 individuals (criterion C threshold for Vulnerable), and only one, *C. buxifolia*, had a population size of < 1,000 individuals (criterion D threshold for Vulnerable).

We assigned a categorization of Data Deficient to 22 species that were expected to occur as trees in Santa Catarina state but for which the taxonomic delimitation was unclear and the herbarium voucher data were not reliable enough to verify identification (Supplementary Material 4).

Discussion

Species abundance data are essential when estimating population sizes and declines. These data are scarce in Brazil so species assessments often use IUCN criterion B (Martinelli & Moraes, 2013), which is based on geographical range. At most, 35% of Santa Catarina tree species would be categorized as threatened if criterion B was used alone, which is 60% fewer than the proportion reported in this study. The multiple-criteria approach offered a way to look beyond the distributions of species across their geographical range to assess their extinction risk. In a biodiversity hotspot where deforestation has destroyed most of the original habitat (Dean, 1997; Joly et al., 2014), it is crucial to consider trends in population size reduction (criterion A) to accurately assess the conservation status of tree species or other organisms dependent upon the forest ecosystem. When habitat loss is high, neglecting criterion A could result in an inaccurate IUCN categorization. Our findings suggest that tree species face greater threats at the local level than at the regional level, at least within our study area. A comparison with assessments across the Atlantic Forest (Lima et al., 2024) reported that 461 of the 555 tree species evaluated there

(83%) were classified as threatened, which is 15% less than our study's estimate (98%). Nearly all species classified as Least Concern in the Atlantic Forest domain were considered threatened in Santa Catarina, with some even listed as Critically Endangered (Supplementary Material 1, Supplementary Fig. 2).

Habitat fragmentation

We have shown that populations of at least 20% of all threatened tree species in Santa Catarina state are fragmented. This result was expected based on the severe fragmentation of the Atlantic Forest (Ribeiro et al., 2009), where > 80% of the fragments are smaller than 50 ha, half of the remaining forest area is located close to forest edges, and the distance between fragments is large (Ribeiro et al., 2009). As trees are defined as the main components of a forest, population fragmentation can be considered equivalent to habitat fragmentation (IUCN, 2022). Apart from the short-term impacts (e.g. edge effects), the long-term exposure of forests to habitat fragmentation may restrict gene flow between isolated subpopulations (Couvet, 2002). Dispersal is also hampered by fragmentation, and both recolonization and demographic rescue effects may not be sufficient to stabilize threatened populations, leading to their extinction over time (Tilman et al., 1994).

Caveats regarding the methodology used

We estimated population sizes using abundance data modelled via inverse distance weighting. Different from kriging, inverse distance weighting is a deterministic method. Nevertheless, the method can achieve results like or better than those of kriging (Zarco-Perello & Simões, 2017). However, its estimation power depends on assumptions regarding sampling intensity, which can be difficult to attain for rare species (Steege et al., 2013). Even in Santa Catarina, where the FlorestaSC project has systematically sampled the whole state (Marques & Grelle, 2021), the performance of the inverse distance weighting model may be compromised by some species for which there are few records, resulting in wider CIs in population sizes and possibly unreliable estimates.

Some species were expected to occur in the state but were not found in our datasets (Data Deficient species; Supplementary Material 4). Our preliminary list of trees for Santa Catarina comprised 577 species, but data were only available for 555 species. Various factors can explain this lack of data. Firstly, some of these species are rare and were not found in the forest surveys or are known only by the type specimen. Others are subject to taxonomic uncertainty (Hortal et al., 2015), as species delimitation can be hampered by a paucity of data (e.g. *Ocotea* species); for example, some individual records were based on written descriptions only, without any collection voucher to allow proper taxonomic verification.

The importance of herbaria data

The inclusion of herbaria data resulted in a more accurate assessment of the conservation status of threatened tree species because it improved our estimates of the extent of occurrence and the area of occupancy (Delves et al., 2024). Whilst the majority of species were considered threatened under IUCN criterion A2 (population size reduction), for 64 species the inclusion of herbaria data changed the species category from higher to lower risk. The herbaria data contributed additional occurrence points to the assessments, which also increased the extent of occurrence, area of occupancy, number of locations and number of subpopulations. For example, the median extent of occurrence increased from 4,566 to 11,294 km² for the 64 species and the median area of occupancy increased from 8 km² (equivalent to four occurrence points in a 2 × 2 km grid) to 36 km² (equivalent to nine occurrence points in a 2 × 2 km grid). Validation of the herbaria data also highlighted 53 species that were not recorded in the forest surveys, reinforcing the importance of local collections for species conservation (Delves et al., 2024).

In tropical regions, where funding can be insecure, forest surveys conducted over extended periods are often hampered by poor working conditions, a lack of basic infrastructure and other practical problems (Nuñez et al., 2021; Lima et al., 2022). Adequate forest survey data are hard to obtain, making it difficult to estimate the parameters related to criterion A (population size reduction). Thus, across the tropics, regional collections are crucial to any assessment of spatial threats to biodiversity conservation (Nualart et al., 2017; Rocchetti et al., 2021). Some examples of this can be seen in the Afrotropical (Schatz, 2002) and Palearctic/Indo-Malay realms (Zhang et al., 2015), where rapid assessments of at-risk taxa were performed using herbaria data.

Conclusion

We evaluated the conservation status of Santa Catarina tree flora based on data from both forest surveys and herbaria using the IUCN criteria A, B, C and D. We demonstrate the importance of using forest surveys to estimate population sizes and assess species under IUCN criterion A (population size reduction) in locations where deforestation has been the main driver of habitat loss in the past. We also highlight how a more accurate Red List assessment can be produced by incorporating herbaria data to complement forest surveys, even when the forest surveys are well distributed within a study region. Whilst we have increased the number of species assessed at the state level, the results we obtained are alarming: almost all tree species in the region are potentially threatened and most of them are already restricted to fragmented remnants such as the Alto Paraná and Araucaria forests. The results reported here can be used to identify important and potential regions for the creation of protected areas and the implementation of forest restoration programmes.

Author contributions Study conceptualization: RAFdL, ALdG; data curation: RAFdL, ACV, ALdG; design of methodology: GSG, RAFdL, AKF; data analysis: GSG; writing: GSG; revision: AFK, ACV, ALdG; supervision: RAFdL, ALdG.

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Conflicts of interest None.

Ethical standards This research abided by the *Oryx* guidelines on ethical standards.

Data availability Data are available from the corresponding author upon reasonable request.

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