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Article

Floristic data to support conservation in the Amazonian *canga*

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Abstract: *Canga* is an environment of great natural and economic value because it harbours a considerable number of endemic species on a substrate that is rich in iron ore. In the Amazon, this open vegetation type grows on top of isolated outcrops in a dense forest matrix found in the Carajás region, in southeastern Pará. Of these outcrops, the Parque Nacional dos Campos Ferruginosos (PNCF) is the only area of Amazonian *canga* with a strict protection status. Therefore, industrial activity in the region needs to implement mitigation actions to ensure species and habitat conservation. The objective of this study is to complement and review the floristic list of this recently created protected area, enabling us to compare the floristic similarity between it and other 14 Amazonian *canga* outcrops found outside the conservation units of full protection in the region. This data provides a basis to understand the floristic and phylogenetic complementarity of those patches to support conservation action. For this, six field trips were carried out in the Serra da Bocaina and two in the Serra do Tarzan, respectively, in order to increase the sampling efforts in PNCF and to obtain a more comprehensive plant list. Floristic composition was investigated using multivariate analyses (*non-metric multidimensional scaling and unweighted pair group method with arithmetic mean*) and phylogenetic structure across studied areas. We added 159 species to the floristic list of the PNCF and the results of the analyses showed that all 16 areas (n.b. PNCF comprises two of these sites) have an overall floristic similarity of 42%, with the least similar areas at 35% and the most similar at 50%. The different micro-habitats found in each study site highlight the high beta diversity of the Amazonian *canga* sites, making each area unique. Therefore, even if the Parque Nacional dos Campos Ferruginosos does not harbour all the species found in the other Amazonian *canga* sites, it is strategic for the conservation of the vegetation on ferruginous outcrops in the Amazon, protecting its biodiversity, different habitats, and associated ecosystem services.
Keywords: *edaphic endemismo; floristic list; multivariate analyses; Parque Nacional dos Campos Ferruginosos; phylogenetic structure.*

Dados florísticos para apoiar a conservação nas cangas amazônicas

Resumo: Canga é um ambiente de grande valor natural e econômico por abrigar um número considerável de espécies endêmicas sobre substrato rico em minério de ferro. Na Amazônia, esse tipo de vegetação aberta cresce sobre afloramentos isolados em uma matriz de floresta densa encontrada na região de Carajás, no sudeste do Pará. Dentre esses afloramentos, o Parque Nacional dos Campos Ferruginosos (PNCF) é a única área de canga Amazônica que apresenta *o status* de proteção integral permanente. Dessa forma, a atividade industrial presente na região necessita implementar ações de mitigação para assegurar a conservação de espécies e habitats relacionados às cangas. O objetivo deste estudo é complementar e revisar a lista florística dessa área protegida, recentemente criada, permitindo comparar a sua similaridade florística com outros 14 afloramentos de cangas Amazônicas localizados fora de unidades de conservação de proteção integral encontradas na região. Tais dados fornecem subsídio para entender a complementaridade florística e filogenética desses fragmentos para apoiar ações de conservação.

Para isso, foram realizadas seis viagens de coleta à Serra da Bocaina e à Serra do Tarzan, respectivamente, para aumentar o esforço amostral no PNCF e obter uma lista de plantas mais abrangente. A composição florística foi investigada por meio de análises multivariadas (*non-metric multidimensional scaling and unweighted pair group method with arithmetic mean*) e estrutura filogenética nas áreas estudadas. Nós adicionamos 159 espécies na lista florística do PNCF e os resultados das análises demonstraram que todas as 16 áreas (n.b. o PNCF compreende duas dessas áreas) têm uma similaridade florística total de 42%, com áreas menos similares de 35% e as mais similares de 50%. Os micro-habitats encontrados em cada área de estudo evidenciam a alta diversidade beta das áreas de cangas Amazônicas, o que as tornam únicas. Portanto, ainda que o Parque Nacional dos Campos Ferruginosos não abrigue todas as espécies encontradas em outras áreas de cangas Amazônicas, ele é estratégico para a conservação dos afloramentos ferruginosos na Amazônia, protegendo a sua biodiversidade, os diferentes habitats e os serviços ecossistêmicos associados.

Palavras-chave: *análises multivariadas; composição florística; endemismo edáfico; estrutura filogenética; Parque Nacional dos Campos Ferruginosos.*

Introduction

The creation of protected areas is a global strategy to reduce biodiversity loss and to maintain ecosystem services (Soares et al. 2010, Yang et al. 2021), being one of the 2011-2020 Aichi Targets for halting biodiversity loss (CBD 2013). Recent years have seen an increase of the number of protected areas, and currently, 15.4% of the Earth's surface is protected (UNEP-WCMC 2020). In addition to increasing the number of protected areas, it is also fundamental to invest in their management so that they can contribute significantly to curbing biodiversity loss (Laurance et al. 2012, Geldmann et al. 2015, 2019, Yang et al. 2021). Despite a number of programmes and initiatives towards conserving nature having been created in Brazil (Coelho 2018), detailed knowledge of the organisms protected by parks and reserves is still scant (Moreira et al. 2019, 2020, Oliveira et al. 2017), hindering the advance of more targeted prioritization of areas based in species rarity or genetic distinctiveness (Tucker et al. 2012).

The IUCN provides guidelines on how to implement and develop protected areas by presenting them as six categories: I. Strict protection (Ia. Strict Nature Reserve, Ib. Wilderness Area), II. Ecosystem Conservation and Protection (National Parks), III. Conservation of Natural Features (Natural Monument), IV. Conservation through active Management (Habitat/species management area), V. Landscape/Seascape Conservation and Recreation (Protected Landscape/Seascape), VI. Sustainable use of natural resources (Managed resource protected area) (Dudley 2008). In Brazil, protected areas are known as *Unidades de Conservação* (UC) and have specific legislation under the SNUC law (Brasil 2000), being divided into full protection, such as National Parks (IUCN category II) and sustainable use, as National Forests (VI) (Dudley 2008, ICMBIO 2016a). In addition to the Brazil's UC system, there are other categories of protected areas such as the Indigenous and Quilombola (Brazilian afro-descendent community) lands (Brasil 2006) and Legal Reserves, represented by a fraction of land located inside a rural property that must legally maintain the original native vegetation (Brasil 2012). Currently, 26.6% of the Brazilian Amazon is protected by federal UCs (Fundo Amazônia 2023). It is important to note that this percentage is underestimated as it does not consider state and private conservation units, for example the *Reservas Particulares do Patrimônio Natural* (RPPN).

The protected biodiversity within the Amazonian UCs is still poorly known due to the scarcity of faunistic and floristic inventories in the region (Cardoso et al. 2017, Oliveira et al. 2017). The lack of information regarding the Amazon is related in part to the large extension of this biome, mostly covered by rainforest, but that also includes open vegetation, which comprises approximately 5% of the Brazilian Amazon territory (Devecchi et al. 2020).

In contrast to its relatively small range, recent studies carried out in some of these habitats (Mota et al. 2018, Zappi et al. 2019, Andrino et al. 2020, Devecchi et al. 2020, Fonseca-da-Silva et al. 2020) have been pointing that the open vegetation types occupying these small areas in the Amazon are clearly relevant in terms of biodiversity distinctness, forming a scenarium similar to island habitats (Prance 1996). One example of such insular vegetation is the Amazonian *canga*, which resembles a savanna (despite being different, see Devecchi et al. 2020) but consists of open vegetation growing on iron substrate (Giulietti et al. 2019, Andrino et al. 2020). These steppingstone-like outcrops of *canga* are scattered over an area that is 250 km long east to west, isolated by a matrix of rain forest, and comprises less than 150 km^2, representing c. 0.003% of the Brazilian Amazon. This biodiverse vegetation harbours edaphic endemic plants, including three endemic genera and 38 endemic species (Giulietti et al. 2019), and is fully protected only by the Parque Nacional dos Campos Ferruginosos (PNCF) (IUCN category II). This area has been offered as environmental compensation, a mechanism of Brazilian Legislation (Brasil 2000) aiming to recover the loss of *canga* areas caused by mining within the Floresta Nacional (FLONA) de Carajás (IUCN category VI). The PNCF encompasses an area of 28 km^2 of *canga* in two different blocks, the Serra da Bocaina and the Serra do Tarzan (Figure 1). The FLONA de Carajás is a sustainable use unit (IUCN category VI) and was created with the purpose of managing research, mining, processing, transport and distribution of mineral resources, with Companhia Vale do Rio Doce (VALE) as the holder of technical information on the area, implementer and operator of existing economic activities and beneficiary of relevant environmental licenses (Brasil 1998). This area includes a large mining operation surrounded by pristine rainforest, where the original *canga* outcrops once covered c. 105 km^2, however, satellite images obtained in 2016 highlighted that 28.3 km^2 of the *canga* was suppressed after three decades of exploitation (Souza-Filho et al. 2019). Placed within a mosaic of especially relevant UCs for the conservation of biodiversity, the PNCF is strategically located at the edge of a region known as the "deforestation arc" (Fearnside & Graça 2009, Domingues & Bermann 2012), with the highest rates of deforestation in the Amazon, as a result of vegetation suppression and heavy impact in adjacent areas

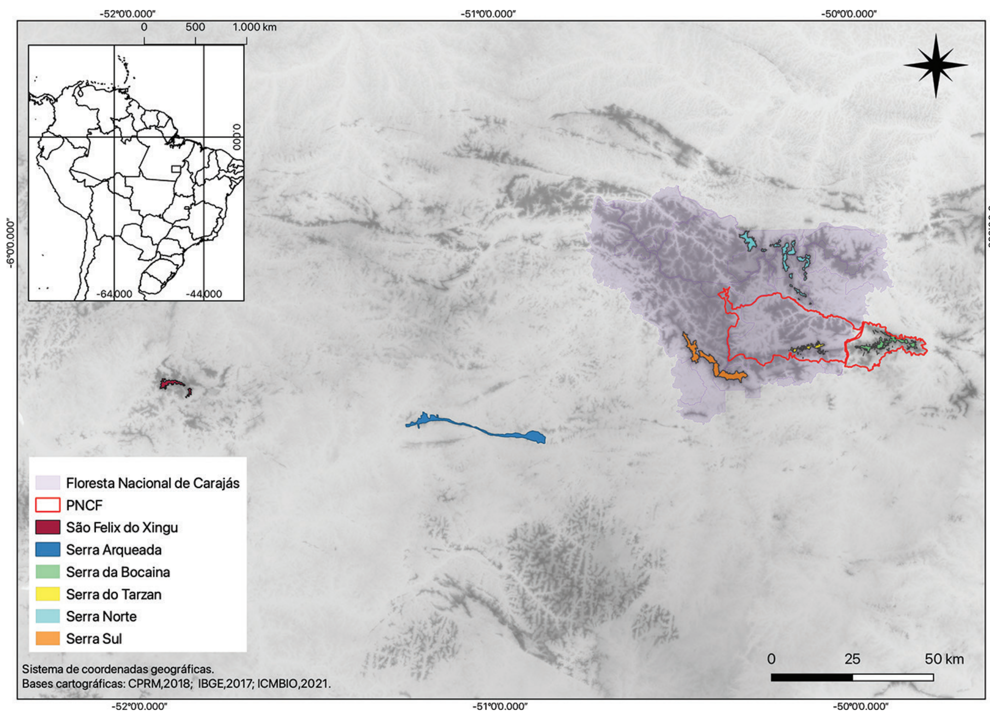

Figure 1. Geographic location of the Parque Nacional dos Campos Ferruginosos (PNCF) and other study sites (Map created by the authors with QGIS 3.18.1-Zürich © 2002-2019 QGIS Development Team available at https://www.qgis.org).

caused by agricultural development and urbanization (Mota et al. 2015, Souza-Filho et al. 2016).

Canga substrate is characterized by a high concentration of heavy metals, such as iron and manganese (Skirycz et al. 2014), high ground temperatures, and low pH, in addition to a high incidence of sunlight and seasonally low water availability that may last several months, enforcing limitations for the establishment of the plant community (Oliveira et al. 2015, Carmo & Jacobi 2016, Vasconcelos et al. 2016).

The high diversity and endemism (Viana et al. 2016, Mota et al. 2018, Giulietti et al. 2019, Zappi et al. 2019) indicate that species inhabiting *canga* have particular mechanisms, possibly adaptations, that allow their survival in such hostile environment (see Porto & Silva 1989, Jacobi et al. 2007, Zappi 2017). The vegetation on the *canga* of Carajás was studied by the Project "*Flora das Cangas da Serra dos Carajás*" (FCC), (Viana et al. 2016) that recorded and described 1131 plant species, including 89 bryophytes (Oliveira-da-Silva & Ilkiu-Borges 2018), 175 ferns, 11 lycophytes (Salino et al. 2018) and 856 seed plants (Mota et al. 2018).

Besides the PNCF and the FLONA de Carajás, there are also *canga* outcrops in the region that are not under any form of legal protection, such as the Serra Arqueada, located in Ourilândia do Norte and the Serra de Campos, near the town of São Félix do Xingu, both with published floristic lists (Andrino et al. 2020, Fonseca-da-Silva et al. 2020). These recent studies show that the distinct *canga* outcrops of Carajás have markedly different floristic composition. Therefore, the suppression of individual *canga* areas, which potentially leads to the imminent loss of part of the species richness (Zappi et al. 2019) found therein, must respect Brazilian legislation (Brasil 2000) that pursues No net loss (NNL) of species. In the core of the concept of NNL there is the idea of seeking for minimal loss of biodiversity while coping with social and economic prosperity (Ermgassen et al. 2019). Although debates concerning their potentials and limitations (Maron et al. 2020, Sonter et al. 2014, 2020, BBOP 2012), governments and industries accross the planet make use of different strategies, mostly offsets aiming to achieve NNL (Ermgassen et al. 2019).

Our major aim is to complement and review the floristic list of this recently created protected area, enabling us to compare the floristic similarity between it and other 14 Amazonian *canga* outcrops found outside the conservation units of full protection in the region. This data provides a basis to understand the floristic and phylogenetic complementarity of those patches to support conservation action. It is a major concern that PNCF reflects the overall plant diversity of Amazonian *canga*, as it is the only strictly protected area for this type of vegetation in the Amazon. We increased the sampling efforts in PNCF to obtain a more comprehensive plant list that would guide conservation practitioners.

Material and Methods

1. Study site

The PNCF located in southeastern Pará includes two *canga* areas on hilltops: Serra da Bocaina and Serra do Tarzan. Serra da Bocaina encompasses nearly 19.98 km^2 of *canga* outcrop at 770 meters a.s.l. surrounded by lowland forests and pastures. The *canga* outcrop can be accessed by the road PA 160 that links the city of Parauapebas to Canaã dos Carajás, entering Vila Sedere I, turning towards the main entrance of the PNCF that is located at coordinates 6°16'59.7''S, 49°58'16.2''W. Serra do Tarzan spreads over nearly 8.3 Km^2 of *canga* at 750 meters a.s.l., surrounded by well-preserved lowland forest formations. Access to the *canga* is gained by the PA 160 road from the town of Canaã dos Carajás towards the road that leads to SS11D (an iron ore mine). Serra do Tarzan's entrance is located at coordinate 6°23'12''S, 50°6'38''W. According to the classification of Köeppen, the climate in the region is tropical (Aw) (Alvares et al. 2013). The rainy season occurs between November and April with monthly mean precipitation of 229 mm, while the dry season occurs between June and September with monthly mean precipitation of 34 mm (ICMBIO 2016a).

Two main vegetation types can be recognized: the rock-dwelling, or *rupestre* ferruginous vegetation and the hydromorphic formations (Mota et al. 2015), see Table 1. The *rupestre* ferruginous vegetation includes shrubby vegetation on or amongst rocks, *campo rupestre* on *canga couraçada*, *campo rupestre* on nodular *canga* and low forest. The hydromorphic vegetation consists of swampy forests, temporary and perennial lagoons, intermittent watercourses, and *buriti* palm (*Mauritia flexuosa* L.) grooves. In addition to these, there are lowland forests associated to the ferruginous mountain ranges. The small heterogeneous environments resulting from the interactions of different substrate types, nutrients, relief, water availability, and vegetation may be recognized as micro-habitats (Jacobi et al. 2007, Alvares et al. 2013, Mota et al. 2018), see Table 1. All collections were conducted under current Brazilian legislation (permission nº 6332401, ICMBIO), processed using standard herbarium techniques (Mori et al. 2011), and deposited at Emilio Goeldi Museum (MG herbarium) in Belém, Pará, Brazil. Voucher material information can be found in the Table S1, Supplementary Material.

Before the creation of the PNCF, the Serra da Bocaina was surrounded by farmland (ICMBIO 2016b) while the Serra do Tarzan, on the other hand, was less exposed to anthropogenic disturbance as its boundary was set within the FLONA de Carajás, created 24 years ago, when the region was pristine (ICMBIO 2016b). Currently, with the expropriation of land around the Serra da Bocaina to integrate the PNCF, the surroundings of this outcrop are undergoing forest regeneration (ICMBIO 2017). Although the flora of the PNCF has been studied in the FCC, this area was undersampled for historic reasons. While sampling efforts were directed towards areas that were licensed or being licensed for mining (Mota et al. 2018), the accesses to the Serra da Bocaina and Serra do Tarzan were very difficult due to roads blocked by fallen trees.

Table 1. Two main types of vegetation are recognized in Amazonian *canga* including their sub-types (following Mota et al. 2015 and Andrino et al. 2020).

Types of vegetation	**Sub-types**
Rupestre ferruginous vegetation	shrubby vegetation on/or amongst rocks
	campo rupestre on *canga couraçada* or open *canga* slabs
	campo rupestre on nodular *canga* or nodular *canga*
	low forest or *capão de mata*
Hydromorphic vegetation	swamp forests
	temporary lagoons
	perennial lagoons
	intermittent water courses
	Buriti grooves (or Palm swamps)

2. *Plant collections and identification*

Additionally to the pre-existing collections made by the Flora de Carajás project (Viana et al. 2016), six field trips were carried out from September 2018 to February 2020 to the Serra da Bocaina, while the Serra do Tarzan was visited in July 2019 and August 2019. The field trips were performed both during the dry and rainy season in the two areas in order to collect fertile specimens of spermatophyte. We followed the methodology of Filgueiras et al. (1994), making non-systematics walks and collecting spermatophyte specimens in the different vegetation types listed by Mota et al. 2015 (Table 1) associated with the ferruginous *canga* of the study area. This methodology has been used successfully in floristic inventories (Andrino et al. 2020) in *canga* and elsewhere as it allows covering large areas while focusing on fertile material. Given the rarity of some of the species found in the *canga* (Giulietti et al 2019), this method aims to locate small populations occurring in habitats that are hard to sample (rock faces, forest understorey, water courses).

The material was identified by the authors using specific bibliography and comparison with MG herbarium specimens. Moreover, for specific families, plant specialists (referred to in the Acknowledgments session) have been contacted to help with identification (e.g. Myrtaceae, Cyperaceae, Poaceae, etc.).

To prepare our dataset we added the new collections to the final database of the FCC project, which had already listed 230 species for Serra da Bocaina and 228 species for Serra do Tarzan, totalling 351 species for PNCF. We also updated species lists from other areas of *canga* of the FLONA de Carajás including Serra Norte and Serra Sul (Mota et al. 2018), the floristic lists of Serra Arqueada (Fonseca-da-Silva et al. 2020) and Serra de Campos de São Félix do Xingu (Andrino et al. 2020). All floristic lists were added to the Plotsamples module of our Brahms (BRAHMS7 2018) database.

3. *Estimates of floristic sampling on Amazonian canga*

We estimated the completeness of our Amazonian *canga* inventory by performing a rarefaction to assess sampling coverage (Chao & Jost 2012), similarly to those performed in related work (Zappi et al. 2019) using iNEXT package (Hsieh et al. 2016) in R (R Core Team 2022). We considered each of the 16 mountaintops as a sampling site (Figure S2, Supplementary Material).

4. *Floristic and phylogenetic analyses*

The floristic lists of the studied canga were organized according to the respective localities for biogeographical comparisons: FLONA de Carajás Serras Norte (CRJ-SN) and Sul (CRJ-SS). Parque Nacional dos Campos Ferruginosos (Serra da Bocaina and Serra do Tarzan: PNCF-SB and PNCF-ST, respectively), Serra de Campos de São Félix do Xingu (SFX) and Serra Arqueada (ARQ-CAN). Moreover, each Serra of FLONA Carajás was subdivided as follows: Serra Norte: CRJ-SN1, CRJ-SN2, CRJ-SN3, CRJ-SN4, CRJ-SN5, CRJ-SN6, CRJ-SN7, CRJ-SN8; Serra Sul: CRJ-SS11A, CRJ-SS11B, CRJ-SS11C, CRJ-SS11D. The 16 studied sites and their corresponding area code, as well as the number of species at each site, are presented in Table 2.

A total of five species classified as aliens or invasives according to Giulietti et al. (2018) collected at SB were removed from the analysis: *Melinis minutiflora* P.Beauv., *Megathyrsus maximus* (Jacq.) B.K.Simon & S.W.L.Jacobs, *Cenchrus polystachios* (L.) Morrone,

Table 2. Amazonian *canga* study sites. Numbers in parenthesis correspond to edaphic endemic species.

Code	Area	Area Km²	Nº of species	Major areas	Species total
ARQ-CAN	Serra Arqueada	1.27Km²	146	Serra Arqueada	146
CRJ-SS11A	Serra dos Carajás – Serra Sul 11 A	15.27Km²	184	Serra Sul	539 (3)
CRJ-SS11B	Serra dos Carajás – Serra Sul 11 B	8.44Km²	208		
CRJ-SS11C	Serra dos Carajás – Serra Sul 11 C	6.26Km²	185		
CRJ-SS11D	Serra dos Carajás – Serra Sul 11 D	16.41Km²	434		
CRJ-SN1	Serra dos Carajás – Serra Norte 1	11.81Km²	388	Serra Norte	647 (3)
CRJ-SN2	Serra dos Carajás – Serra Norte 2	0.86Km²	130		
CRJ-SN3	Serra dos Carajás – Serra Norte 3	2.1Km²	222		
CRJ-SN4	Serra dos Carajás – Serra Norte 4	14.83Km²	312		
CRJ-SN5	Serra dos Carajás – Serra Norte 5	8.26Km²	294		
CRJ-SN6	Serra dos Carajás – Serra Norte 6	0.97Km²	100		
CRJ-SN7	Serra dos Carajás – Serra Norte 7	0.34Km²	114		
CRJ-SN8	Serra dos Carajás – Serra Norte 8	2.69Km²	104		
PNCF-SB	Parque Nacional dos Campos Ferruginosos – Serra da Bocaina	19.98Km²	408	Parque Nacional dos Campos Ferruginosos	560 (4)
PNCF-ST	Parque Nacional dos Campos Ferruginosos – Serra do Tarzan	8.3Km²	333		
SFX	Serra de Campos – São Félix do Xingu	9.04Km²	246	Serra de Campos	246 (1)

Leonotis nepetifolia (L.) R.Br., and *Urena lobata* L. (S1, Supplementary Material). Taxa not identified at species level were not included in the analyses as well, while new species, currently under publication were kept in both analyses and the spreadsheets, e.g. *Diastema* sp. (Chautems et al. 2018) and *Croton* sp. (Costa et al. 2018).

The species names were standardized following internal and automatic dictionaries of Brahms and also the online tool Plantminer (Carvalho et al. 2010). Once we had the correct scientific names we transformed the final list into a presence and absence matrix (Table S4, Supplementary Material), showing which species occurred at each site.

The data matrix was analyzed in the Past 4.04 software (Hammer et al. 2001) to carry out multivariate analyses using ordination — Non-metric multidimensional scaling (NMDS), and clustering methods — Unweighted Pair Group Method mean (UPGMA), both analyses using Sørensen (Bray-curtis) distance. Moreover, comparative analyses were performed with the online tool jvenn (Bardou et al. 2014), making Venn diagrams to verify the floristic overlap between the studied areas.

We reconstructed a phylogenetic tree with all the species collected across all the areas with the purpose to compare the phylogenetic structure of *canga* species in PNCF and other areas in Carajás. The species list was extracted from the matrix used for biogeographic analysis (S1, Supplementary Material). Names of subspecies and varieties were transformed as follow: Mimosa_acutistipula_var_ferrea changed to Mimosa_acutistipula.ferrea. The list was formatted for uploading into Phylocom 4.2 (Webb et al. 2008) using Plantminer (Carvalho et al. 2010). To reconstruct our phylogenetic tree we used the megatree R20160415. new (Gastauer & Meira Neto 2017) and calibrated with ages estimate proposed by Magallón et al. (2015). The regional tree obtained from our species list and their distribution across the different areas was visualized using iTol (Letunic & Bork 2016). We highlighted selected families with the greater number of species and a few others for discussion.

Results

1. Flora of the PNCF

We collected 410 additional specimens representing 225 species, 178 genera, and 81 families in the *canga* of the PNCF. Our floristic survey added 158 species to the list published in 2018 (Mota et al. 2018). There were specifically 119 new species records for Serra da Bocaina and 39 new records for Serra do Tarzan. Serra da Bocaina currently has 408 listed species while Serra do Tarzan has 333 listed species. Thus, PNCF currently has 559 angiosperms species listed and one gymnosperm species — *Gnetum nodiflorum* Brongn. — totalling 560 species (Table 2; Table S1, Supplementary Material). Some species that represent new records for the PNCF are illustrated in Figure 2.

The 10 families with the greater number of species correspond to 45% of the total sampling for the PNCF. They are Poaceae (53 spp.), Fabaceae (52 spp.), Cyperaceae (36 spp.), Rubiaceae (35 spp.), Asteraceae (20 spp.), Melastomataceae (19 spp.), Convolvulaceae and Solanaceae (13 spp.), Lamiaceae and Malvaceae (12 spp.) (S2, Supplementary Material). We also highlighted a noticeable increase in the sampling of three families, now with double or more species than in the previous list (Mota et al. 2018): Euphorbiaceae (16 spp.), Myrtaceae (16 spp.) and Orchidaceae (12 spp.).

We recorded a further edaphic endemic species (i.e. endemism associated to the type of substrate) to the Serra do Tarzan — *Erythroxylum carajasense* (Plowman) Costa-Lima [Erythroxylaceae] — this area now has 23 listed edaphic endemic species (Giulietti et al. 2019). In the Serra da Bocaina we recorded three extra edaphic endemic species: *Anemopaegma carajasense* A.H.Gentry ex Firetti-Leggieri [Bignoniaceae], *Syngonanthus discretifolius* (Moldenke) M.T.C.Watan.z , [Eriocaulaceae] and *Peperomia albopilosa* D.Monteiro [Piperaceae], increasing to 26 the number of edaphic endemic species listed in this area (S1, Supplementary Material). Our survey also recorded four new occurrences for Pará state and Amazonian Brazil: *Croton gracilipes* Baill. [Euphorbiaceae], *Gurania eriantha* (Poepp. & Endl.) Cogn. [Curcubitaceae], *Sabicea grisea* Cham. & Schltdl [Rubiaceae], and *Triphora uniflora* A.C.Ferreira, Baptista & Pansarin [Orchidaceae].

2. Sampling cover for Amazonian canga

The specimen number studied for PNCF (650 for the Serra da Bocaina and 500 for the Serra do Tarzan) represent comparable sampling to the other 14 outcrops (12 sites inside the FLONA de Carajás and two outside), which vary between 1699 and 176 specimens per sampled site, depending in the collecting effort and size of the outcrop, with a mean of 565 specimens collected per site. The rarefaction curve (Figure S3, Supplementary Material) indicates that we have a high sample coverage (nearly 90%) for Amazonian *canga*, considering all outcrops.

3. Floristic and phylogenetic similarity among Amazonian canga sites

The matrix used for floristic comparisons included 1021 species (a total of 3807 records) belonging to 16 areas (Table 2; Table S4, Supplementary Material). Our results revealed that 140 species are exclusive from PNCF compared with the other studied *canga* sites, corresponding to 14% of the total sampling in the matrix (S1, Supplementary Material), and 25% of the PNCF flora itself (Figure 3).

We found 61 species shared with Serra Norte, 42 species with Serra Sul, four species with ARQ-CAN, and six species with SFX (Figure 3). When the four *canga* areas are compared separately with the PNCF, our results showed 65% of SFX flora is also present in PNCF, representing the greater overlap. Following that, Serra Sul shares 58% of its flora with PNCF, Serra Arqueada 56%, and Serra Norte 54% (S3, Supplementary Material). Analysing specifically the list from PNCF, SB, and ST have 181 overlapping species, corresponding to respectively 44.47% and 54.35% of the flora of each area (Figure S5, Supplementary Material).

The UPGMA analysis resulted in assemblages with a cophenetic correlation of 0.9548 (Figure 4a). Serra Arqueada appears as the most dissimilar area, outside two major clusters formed by the other sites. A bigger group formed at a mean similarity level of ca. 0.35 includes PNCF, Serra Sul, SFX, and part of Serra Norte, while a smaller cluster is formed by the remaining Serra Norte sites. In the NMDS analysis with a stress of 0.11549, (Figure 4b) we found that areas CRJ-SN1 and CRJ-SN4 had the smallest relative distance from each other. Serra do Tarzan had a smaller relative distance with areas CRJ-SN1, CRJ-SN3, CRJ-SN4, CRJ-SN5, and CRJ-SS11D than with Serra da Bocaina. ARQ-CAN showed again the greatest relative distance from the other sites, followed by SFX, being both not located within any officially protected area.

While in the NMDS (Figure 4b) ST appears more or less equally distant from SB and part of Serra Norte, (CRJ-SN1 – see Table 2 for abbreviations), the UPGMA analysis (Figure 4a) indicates that the two first sites have a greater similarity of c. 50%, and part of Serra Norte is less similar with both ST and SB (c. 42%). In fact, the other blocks of Serra Norte (CRJ-SN2, 6-8, Figure 4a) are even more dissimilar, with c. 35% of similarity in relation to other *canga* areas (except Serra Arqueada).

Our Amazonian *canga* megatree allowed us to visualise a spread of lineages across different areas (Figure 5). As a general pattern, a coinciding representation of lineages was seen in the PNCF and the FLONA de Carajás (Serra Norte and Serra Sul). The same major clades also appear in SFX and ARQ-CAN, however with less diversity. Nonetheless, some frequent lineages occurring in other areas are not well represented in SFX and ARQ-CAN, such as Cyperaceae, Poaceae, and Asteraceae. Some other clades did not present a strict correlation of lineages across all areas. For example, magnoliids and Alismatales appear more consistently represented in Serra Norte and Serra Sul (FLONA de Carajás) than in PNCF, ARQ-CAN, and SFX. Orchidaceae and Poaceae are also better represented in FLONA de Carajás, with several small different lineages absent in the Parque (PNCF). Commelinales is under-represented in the PNCF when compared with FLONA de Carajás. Zingiberales are better represented in the PNCF than elsewhere. Regarding the eudicots, Santalales and Polygonaceae are slightly better represented outside PNCF. The asterid clade (Asteraceae, Convolvulaceae, Solanaceae, Apocynaceae) is roughly equally represented in FLONA and PNCF while within rosids there are a few missing clades of Fabaceae, Melastomataceae, and Sapindaceae in the PNCF.

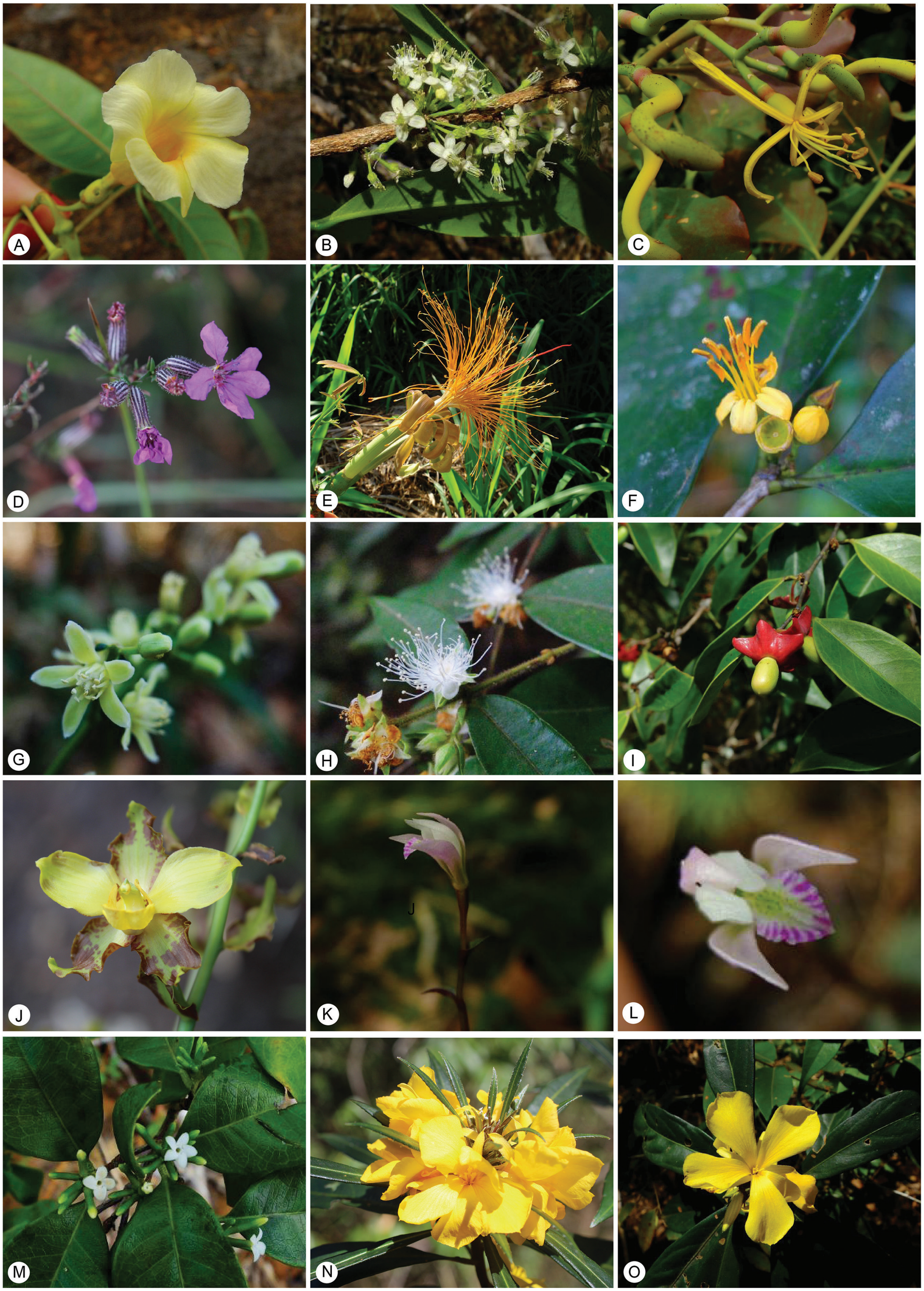

Figure 2. Species found in the Parque Nacional dos Campos Ferruginosos (PNCF), a. *Odontadenia* nitida (Vahl) Müll.Arg., *B,T, b. *Erythroxylum carajasense* (Plowman) Costa-Lima, c. *Psittacanthus eucalyptifolius* (Kunth) G.Don, *B, d. Cuphea *carajasensis* Lourteig, e. *Pachira paraensis* (Ducke) W.S.Alverson, *B, f. *Mouriri cearensis* Huber, *T, g. *Trichilia* micrantha Benth., h. *Myrcia bracteata* (Rich.) DC., *B, i. *Heisteria ovata* Benth, *T, j. *Cyrtopodium andersonii* (Lamb. ex Andrews) R.Br., k-l. *Triphora uniflora* A.C.Ferreira, Baptista & Pansarin, *B, m. *Cordiera myrciifolia* (K.Schum.) C.H.Perss. & Delprete, *B, n-o. *Turnera glaziovii* Urb., *B. *B,T new records for both areas within PNCF. *B new records for the Serra da Bocaina. *T new records for the Serra do Tarzan. s a-i, k-m, o – DCZ; j, n – TLFS.

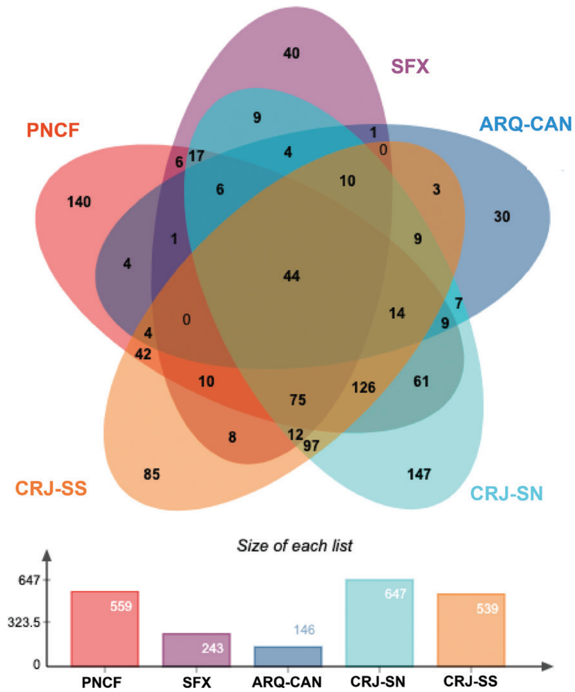

Figure 3. Venn diagram comparing the number of seed plant species exclusively found at the Parque Nacional dos Campos Ferruginosos (PNCF) and shared with other *canga* areas at the Floresta Nacional de Carajás (Serra Norte e Serra Sul), Serra Arqueada (ARQ-CAN), and Serra de Campos de São Félix do Xingu (SFX).

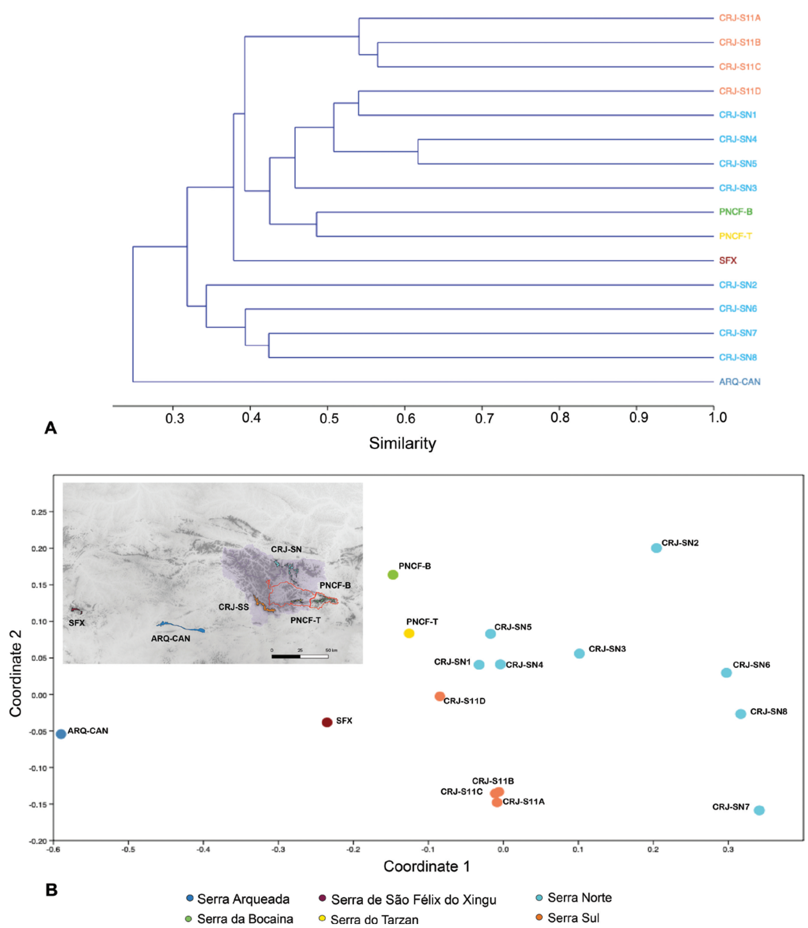

Figure 4. Multivariate analyses of floristic similarity between studied areas. A. Median association (UPGMA), cophenetic correlation coefficient: 0.9548. B. Map showing *canga* outcrop location and ordination analysis using multidimensional, non metric scaling (NMDS), stress value: 0.1549. (Map created by the authors with QGIS 3.18.1-Zürich © 2002-2019 QGIS Development Team available at https://www.qgis.org).

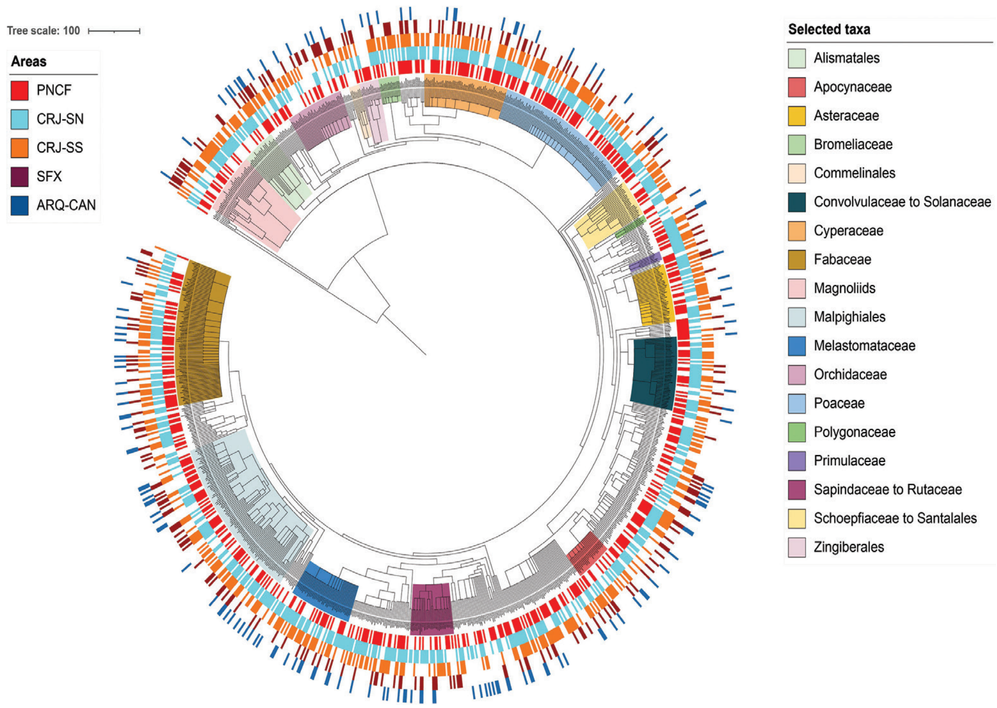

Figure 5. Amazonian *canga* megatree. The innermost ring (red) represents lineages present in the Parque Nacional dos Campos Ferruginosos. Lineages present in the FLONA de Carajás (CRJ-SN (light blue) and CRJ-SS (orange)) and other Amazonian *canga* appear in the following two rings. The two outermost rings, purple and dark blue represent São Félix do Xingu and Serra Arqueada respectively.

Discussion

Following the collecting effort carried out for this specific research, the flora of the Amazonian *canga* now comprises a total of 1022 species of Spermatophyta (1021 angiosperms). This study specifically focused on the PNCF, the only strictly protected area of Amazonian *canga* adding 158 species to the pre-existing list (Mota et al. 2018), resulting in a total of 559 species of angiosperm and one species of gymnosperm (see also item 4, Sample limitations). Regarding the total list of PNCF, we verified that 140 species are found, until the present moment, only in this site, being absent from other Amazonian *canga* sites (Figure 3), highlighting the relevance of PNCF for conservation.

1. *Restricted species and endemism*

The PNCF includes four species restricted to the *canga* of Carajás: *Ichthyothere* sp. 1 (Asteraceae, under description), *Rhynchospora unguinux* C.S.Nunes & A.Gil (Cyperaceae, see Schneider et al. 2019), *Cyperus* sp. 2 (Cyperaceae, under description), and *Spermacoce* sp. 1. (Rubiaceae – under description). The presence of these four new exclusive edaphic endemic species in this area will increase the list of endemics (Giulietti et al. 2019) to 42 species and demonstrates the importance of having a complete management plan for the PNCF. From the other 136 species exclusive to PNCF, 20% are restricted to the Amazon while the other 80% are more broadly distributed. PNCF is a conservation unit dedicated to the protection of *canga* vegetation, however, it also contributes to safeguarding widely distributed species both in the Amazon and in other Brazilian biomes.

PNCF hosts 30 out of the 42 *canga* edaphic endemics from Carajás (Giulietti et al. 2019), representing c. 71% of the Amazonian *canga* species that are unique for the area of Carajás, being crucial for their conservation. The new collections represent an important improvement in the knowledge of the flora of Carajás. The number of species from Serra Norte and Serra Sul (CRJ-SN1-8 and CRJ-SS11A-D) that were not recorded thus far at the PNCF equals 296 and 225, respectively (S4, Supplementary Material). This information is essential for conservation purposes as we can now assure which species are under protection within the PNCF. However, it would be very important to understand the size and dynamics of their populations to ascertain whether those are sufficient for the survival of these species within the study area. Six edaphic endemic species are so far only found in the *canga* vegetation of the FLONA de Carajás (and absent in the PNCF), Serra Norte: *Ipomoea cavalcantei* D.F.Austin (Convolvulaceae), *Paspalum carajasense* S.Denham (Poaceae), and *Daphnopsis filipedunculata* Nevling & Barringer (Thymelaeaceae); and in the Serra Sul: *Parapiqueria cavalcantei* R.M.King & H.Rob. (Asteraceae), *Carajasia cangae* R.M.Salas, E.L.Cabral & Dessein (Rubiaceae), and *Isoetes cangae* J.B.S.Pereira, Salino & Stützel (Isoetaceae). Therefore the concept of NNL of species is not met by the creation of the PNCF, and their survival is being pursued by VALE through other projects involving these species within the area of the FLONA de Carajás (Babiychuk et al. 2017, Watanabe et al. 2018, Zandonadi et al. 2019, Guimarães et al. 2023). Examples are the *ex-situ* cultivation of *Isoetes cangae* and *I. serracarajensis* (Zandonadi et al. 2019) and investigations to support *ex-situ* cultivation of other endemic species (e.g. *Ipomoea cavalcantei*) (Santos et al. 2023). It is very important to highlight that the distribution area of such species will undergo further habitat loss and degradation, with the almost complete disappearance of Serra Norte blocks SN4, SN5 and Serra Sul S11D, which should be considered when planning for the future use of the *canga* outcrops in the FLONA de Carajás. Our study reinforces the importance of evaluate different aspects of sites selected for offseting purposes and integrating an array of different offsets mechanisms in order to guarantee biodiversity conservation (Maron et al 2010, Sonter et al. 2018).

2. *Biogeography of Amazonian canga*

According to Mota et al. (2018), the richest plant families in the PNCF were Poaceae (40 spp.), Rubiaceae and Fabaceae (30 spp. both), Cyperaceae (26 spp.), Asteraceae (17 spp.), Convolvulaceae, Solanaceae, Melastomataceae and Lamiaceae (11 spp. each one), and Malvaceae (nine spp.). These families added up 196 species representing 53% of the total amount recorded in the floristic list published in 2018. The extensive collection effort carried out during our study has also increased the number of species recorded for these families (Figure S2a, Supplementary Material), which keep the status of the top 10 richest but currently represent 45% of the species of the PNCF. As pointed out by previous work, almost half of the *canga* flora is represented by a few or single species which might be related to the existence of several micro-habitats often present in this environment (Mota et al. 2018, Andrino et al. 2020, Fonseca-da-Silva et al. 2020). These micro-habitats are a reflection of the strong topographic variation and different distribution of soil nutrients across the substrate (Borges et al. 2017). The maintenance of the same better represented families also indicates that the sampling resulting from our efforts was evenly distributed, however, for three large plant families (Orchidaceae, Euphorbiaceae and Myrtaceae) the present work brings many newly recorded species for the PNCF. It is possible that the knowledge regarding these plant groups may be still under development, and that the relevant flora chapters (Costa et al. 2018, Kock et al. 2018, Trindade et al. 2018) prepared for them underestimated their diversity.

Our multivariate analysis highlighted that, in general, the Amazonian *canga* sites that compose the Carajás complex have moderate to low floristic similarity (35 to 42% of similarity), pointing to a high beta diversity among the *canga* sites, although some components are shared across all study sites. This can also be seen in our megatree, which obviates a strong correlation of lineages, with certain lineages being better represented in some sites than in others (Figure 5). On the other hand, when taking into account the region´s phytogeography, these *canga* outcrops form a cohesive floristic group distinct from other Amazonian open vegetation (Devecchi et al. 2020), for example the Amazonian savannas.

Comparing all Amazonian *canga* localities studied, the lowest species richness was found in the two totally unprotected sites of Serra Arqueada and São Félix do Xingu (see also item 4, Sample limitations), however, these have rather distinct species composition, with unique endemic species found in the latter site (*Mimosa dasilvae* A.S.Silva & R.Secco and a new species of Lauraceae, currently being described). The contribution of these two sites towards the floristic dissimilarity (Figure 4a) is also clearly visible in our megatree (Figure 5), where both sites contribute with less lineages. Both sites are isolated and geographically distant from the PNCF (Figure 1). Those two sites are also smaller (Table 2), and it has been found that the size of the area occupied by Amazonian *canga* appears to have a positive correlation with the site diversity independently of the geographic proximity between sites (Andrino et al. 2020), because a larger area would foster more variety of species specific to micro-habitats (Andrino et al. 2020). Therefore, the species sharing observed between PNCF and FLONA de Carajás (Figure 3; S5, Supplementary Material) and the higher floristic similarity between these areas (Figures 4a, 5) may be linked to their larger size and higher number of vegetation types found within them (Mota et al. 2015). Nonetheless, São Félix do Xingu presents the greater relative overlap of species with PNCF when compared to the other areas (Figure S5, Supplementary Material) with c. 65% of species shared.

The mosaic of vegetation types found in the *canga* (Table 1) may explain the different floristic composition found between the sites. The absence of deep, perennial lagoons and swamp forest among the hydromorphic vegetation types listed by Mota et al. (2015) for instance, probably meant that aquatic species such as *Apalanthe granatensis* (Humb. & Bonpl.) Planch., *Ottelia brasiliensis* (Planch.) Walp. (Hydrocharitaceae, see Hall & Gil 2016) and *Nymphaea rudgeana* G.Mey (Nymphaeaceae, see Lima 2018) were not found in the PNCF because of the absence of this type of micro-habitat. In this sense, it is not unexpected that magnoliids and Alismatales, lineages often associated with water, appear underrepresented in the PNCF when compared to FLONA de Carajás sites (Figure 5). The less represented Commelinales in the PNCF when compared to the FLONA de Carajás may be a reflection of the absence of some of the hydromorphic vegetation subtypes (perennial lagoons, see Table 1), as many species of this clade are associated with aquatic habitats. The hydromorphic vegetation is significant for the Carajás flora, insofar as it contributes with the majority of *canga* exclusive species (Mota et al. 2018). Therefore, the lack of certain types within this category contributes to the difference between the areas. On the other hand, the more striking presence of Zingiberales in comparison with all other areas may be an effect of the topography of Serra da Bocaina and Serra do Tarzan, where the steep sides are densely forested, an environment preferred by species of this lineage. Therefore, the micro-habitats provided by the vegetation types and sub-types (Table 1) are fundamental to harbour divergent lineages of angiosperms and, despite the difficulty of accurately mapping such environments because of their reduced scale and even temporary absence (i.e. during the dry season some of these may not be noticeable), our megatree serves as a proxy to identify the differences between the study areas.

Our results indicate the proportion of shared overall species between PNCF and the other sites is only moderate to low (S5, Supplementary Material). Furthermore, some species are exclusive from the PNCF even considering that some specific *canga* vegetation types are not found there, making its flora distinct from all other studied sites. These new data reinforce the urgency of having a strong and detailed management plan for the PNCF.

3. *Further conservation needs in the Amazonian canga*

With the exception of the PNCF, the areas contemplated by the present research are under pressure either by mining (FLONA de Carajás) or surrounding deforestation and illegal mining (SFX and ARQ-CAN). Even if legal mining activities are highly regulated by the government at Federal and State level, the present data highlight that the conservation of endemic *canga* species is threatened by large-scale mining, as already recorded by Martins et al. (2018) and also seen in the *canga* of Minas Gerais (Kamino et al. 2020). According to Souza-Filho et al. (2019), the FLONA de Carajás management plan does not specify a minimum area of *canga* that must be preserved. Through our efforts we highlight the importance of the PNCF but also make obvious that more canga areas must be preserved within the FLONA de

Carajás in forthcoming updates of its management plan. Ilegal mining activities also occur in the region and represent an important factor for biodiversity loss (Pivello et al. 2021, Antonelli 2022). Intensification of land conversion into pasture and agribusiness is also responsible for raising greenhouse gas emissions in places such as São Félix do Xingu, the Brazilian municipality that was top of the emission list in 2018 (Albuquerque et al. 2021), as well as being among the 10 municipalities with accumulated fire foci during the last five years (INPE 2021). Serra Arqueada was recently a victim of possibly criminal fires (G1 PA 2021), showing how the *canga* found outside protected areas is under threat due to multiple anthropogenic pressures. These two sites have a distinctive flora (6% of São Félix do Xingu and 20% of Serra Arqueada). The Serra Arqueada (S2, Supplementary Material) is home to 64 species (c. 48% of the flora) that are not protected in the PNCF, such as the orchid *Galeandra cristata* Lindl. and the threatened grass *Axonopus carajasensis* Bastos (Martinelli & Moraes 2013). The latter species is a *canga* edaphic endemic (Giulietti et al. 2019) and is only known from CRJ-SN1 and CRJ-SS11D, requiring special attention. Around 35% of the species recorded at SFX (86 spp. – Figure S3, Supplementary Material) were not recorded for the PNCF, among them the edaphic endemic legume *Mimosa dasilvae* A.S.Silva & R.Secco, only known from this site. Therefore, it is paramount to indicate these two sites as priorities for conservation.

The risk faced by *canga* species, especially the endemics, has been addressed through different research lines. For example, new sampling areas were defined and surveyed, in order to certify the distribution of *canga* specie (Giulietti et al. 2019). The impact of climate change was also anticipated, by defining potentially vulnerable species and priority protection areas under future climate (Giannini et al. 2021). Detailed molecular studies have been carried out (Vasconcelos et al. 2021) especially involving endemic species (Babiychuk et al. 2017, Lanes et al. 2018, Carvalho et al. 2019, Silva et al. 2020). Specifically, endemic hydromorphic species have also been analysed in detail (Nunes et al. 2018, Caldeira et al. 2019, Dalapicolla et al. 2021, Pereira et al. 2021). Loss of biodiversity can also reduce vegetation types, micro-habitats, abiotic values, and ecosystem services (Mace et al. 2012), and needs to be properly addressed through conservation planning. Floristic similarity between the two outcrops found within PNCF, SB and ST was 48% (Figure 4a), close to figures found before (51% in Zappi et al. 2019; 45% in Fonseca-da-Silva et al. 2020 and Andrino et al. 2020). This discrete increment was brought about by the increase in sampling and it does not change the fact that the floristic similarity between these two blocks continues to be moderate signalling to the existence of distinct *canga* floras within the park area. Both UPGMA and NMDS analyses showed that, despite forming a single conservation unit (PNCF), the Serra da Bocaina and the Serra do Tarzan have distinct floras, denoted by their floristic similarity below 50% or by the ordination analysis results.

These two outcrops have a history of different environmental impacts. Originally included within Fazenda São Luís, Serra da Bocaina is surrounded by pasture and the outcrops can be reached from several directions, while Serra do Tarzan, surrounded by relatively untouched dense forest, can be accessed only by an entrance road that is frequently closed due to fallen trees. This difference in surrounding vegetation and land use history justifies the records of exotic species so far only in SB: *Melinis minutiflora* P.Beauv., *Megathyrsus maximus* (Jacq.) B.K.Simon & S.W.L.Jacobs, *Cenchrus polystachios* (L.) Morrone, *Leonotis nepetifolia* (L.) R.Br., and *Urena lobata* L. In addition to these species, the fern *Pteridium esculentum* (G. Forst.) Cockayne (Dennstaedtiaceae) is widely distributed both on the edges of the trails and near the *canga*, occupying the space opened up by frequent, sometimes criminal fires. This fern is referred for some Brazilian regions and in other countries as a problem plant because, besides producing vast quantities of biomass, it rapidly expands its rhizome making the re-establishment of native vegetation extremely difficult (Guerin & Durigan 2015). Effective control measures for these invasive and native problem species in Serra da Bocaina need to be included in management plans for PNCF.

The presence of alien species in Serra da Bocaina shows that this site is under more pressure from habitat disturbance and native vegetation loss than Serra do Tarzan, which appears to be better preserved. Bellard et al. (2016) demonstrated that the main threats to biodiversity are the loss of plant communities through farming, the use of biological resources, urbanization, and the establishment of exotic species. Thus, although Serra da Bocaina is now included in a strictly protected area (i.e. IUCN category II), carefully applied management measures are needed to recover the vegetation that surrounds the *canga* and prevent uncontrolled access both to the PNCF and its *canga* areas.

4. *Sample limitations*

We acknowledge some limitation in comparing the different areas may exist due to differences in the sampling effort dedicated to the Serra do Tarzan. Considering the great effort carried out by present and previous work, and also by the result of the rarefaction curve (S3, Supplementary Material) we assume that the *canga* is well sampled as a whole for the purpose of this study. The species from Serra do Tarzan are evaluated mostly considering its role as a legal protected area together with Serra da Bocaina. The data here represents an important step towards our overall knowledge on Amazonian *canga* flora. Furthermore, the analysis presented here does not intend to draw a final conclusion, but instead, it aims to investigate whether the protected areas are an appropriate representation of the Amazonian *canga* biodiversity and to point to new directions for research and conservation planning attempting to address any remaining questions. Some of the relationships seen in the present work confirm recent findings (Zappi et al. 2019, Andrino et al. 2020, Fonseca-da-Silva et al. 2020). However, the new collections enabled by this research have increased the sampling of the PNCF, corroborating with more robust floristic comparative data between the *canga* sites of Carajás. Finally, the new data contribute to highlight the high beta diversity of the study area.

Conclusion

The PNCF has a significant role as a strictly protected area, contributing to protect both widespread and unique plant species of the Amazonian *canga*. Detailed study of the flora of PNCF is fundamental as a basis for the authorities and conservation practitioners to develop conservation and management strategies for *canga* vegetation. The extreme importance of this vegetation and the urgency of its conservation are evident, and it is paramount to protect them from all potential threats. The presence of species from *canga* in the PNCF goes towards ensuring their future existence in the *canga* of Carajás. However, in isolation, the PNCF does not adequately cover the entire flora of the Amazonian *canga*. Considering the uniqueness of the Serra Arqueada and São Félix do Xingu, still unprotected *canga* areas of the Carajás complex, we highlight them as priority areas to be included in conservation plans.

Supplementary Material

The following online material is available for this article:

Table S1 – PNCF species list with voucher material information.

Figure S2 – A. Comparison of species number per sampled family in Mota et al. (2018) and current work. B. Families with increased sampled richness in the current study.

Figure S3 – Rarefaction graphic for Amazonian *cangas* showing sample coverage.

Table S4 – Species list showing which species occurred at each site and data matrix used in PNCF analysis.

Figure S5 – Venn diagrams showing exclusive and overlapping species between studied sites**. A-D.** Comparison between PNCF and different areas separately. **E.** Comparison between Serra da Bocaina and Serra do Tarzan.

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Associate Editor

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Author Contributions

Livia Gadelha Silva: contributed to data collection; contributed to data analysis and interpretation; contributed to data analysis and interpretation; Contributed to manuscript preparation.

Juliana Lovo: substantial contribution in the concept and design of the study; contributed to data collection; contributed to data analysis and interpretation; contributed to manuscript preparation.

Taiana Laura da Fonseca-da-Silva: Contributed to data collection.

Pablo Riul: contributed to data analysis and interpretation.

Cíntia Luíza Silva-Luz: contributed to manuscript preparation.

Daniela C. Zappi: substantial contribution in the concept and design of the study; contributed to data collection; contributed to manuscript preparation.

Conflicts of Interest

All authors declare they have no conflict of interest.

Data Availability

All datasets produced during this work is available as Supplementary Material in the Figshare repository: https://figshare.com/s/b7f873442d81f4f6977a

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