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Edaphic Endemism in the Amazon: Vascular Plants of the *canga* of Carajás, Brazil

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Abstract

Amazonia is one of the most diverse biomes worldwide, and, as well as luxuriant forest, it includes mountain areas which, despite their small surface area, display fascinating endemism. In these regions, the specificity of edaphic factors is mirrored by a highly specialised, isolated flora adapted to survive adverse conditions. The Serra dos Carajás in the Brazilian state of Pará is one of world's largest iron ore reserves. Known locally as *canga*, this ironstone formation occupies an area of 115.9 km^2, and supports *campo rupestre* of *canga* vegetation on outcrops that are mostly in the Floresta Nacional de Carajás (FLONA of Carajás) and Parque Nacional dos Campos Ferruginosos (PNCF). The recent publication of the Flora of the *canga*s of Carajás lists 856 species of seed plants and 186 species of ferns and lycophytes. This project assessed the *canga* endemic species growing in the region, and further expeditions guided by SDM were carried out in order to ascertain their distribution outisde the area. Departing from an initial list of 58 putative endemics, the final list comprises 38 species of vascular plants (c. 4% of the local flora). These are distributed in 31 genera and 22 families, including three monotypic genera: *Carajasia* (Rubiaceae), *Monogereion* and *Parapiqueria* (Asteraceae). From these, 24 are classified as Rare Species for Brazil and seven as Highly Restricted Endemic (EEO < 100 km^2). An illustrated account is provided, as well as further SDM to detect other possible areas of distribution based on the studied species. The knowledge generated is aimed at directing appropriate conservation plans for the area.

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Resumo
A Amazôna é um dos mais diversos biomas do mundo e inclui, bem como florestas luxuriantes, regiões montanhosas que, apesar de ocuparem uma área superficial relativamente pequena, apresentam endemismo fascinante. Ali, a especificidade de fatores edáficos é espelhada por uma flora isolada e altamente especializada para sobreviver em condições adversas. A Serra dos Carajás, no estado do Pará, é uma das maiores reservas de minério de ferro do mundo. Conhecidas localmente como cangas, as áreas de minério exposto ocupam uma área de 115,9 km^2, sobre as quais a vegetação de campo rupestre ocorre. A maioria destes afloramentos está incluída na Floresta Nacional de Carajás (FLONA of Carajás) e no Parque Nacional dos Campos Ferruginosos (PNCF). A publicação recente da Flora das cangas de Carajás listou 856 espécies de fanerógamas e 186 de samambaias e licófitas. Este projeto categorizou as espécies endêmicas da canga na região e valeu-se de expedições a áreas circunvizinhas delineadas por SDM, buscando estabelecer o endemismo dessas espécies fora da área contemplada na Flora. Partindo de uma lista inicial com 58 possíveis endêmicas, a lista final inclui 38 espécies de plantas vasculares (c. 4% da flora local). Estas são distribuídas em 31 gêneros e 22 famílias, incluindo três gêneros monotípicos: *Carajasia* (Rubiaceae), *Monogereion* e *Parapiqueria* (Asteraceae). Destas, 24 foram classificadas como plantas de distribuição restritas no Brasil e sete como endêmicas altamente restritas (EEO < 100 km^2). Uma lista ilustrada, bem como um mapa de SDM baseado na distribuição das esécies estudadas, para definir outras possíveis áreas de ocorrência são apresentados. The knowledge generated is aimed at directing appropriate conservation plans for the area.

Keywords Amazon Rainforest · Brazilian flora · *campo rupestre* · Conservation priorities · Iron-ore formations · Rarity

Introduction

Biodiversity loss, mainly attributed to habitat change and over-exploitation, pollution and invasive species (Marchese, 2015), demands urgent strategies to protect native species. Severe threats to natural habitats lead to current estimates suggesting that one in five of the world's plant species is threatened with extinction globally (Brummitt et al., 2015; Darbyshire et al., 2017). The presence of endangered, endemic and rare taxa in conjunction with species diversity is used to define Key Biodiversity Areas (KBAs) or Important Plant Areas (IPAs) around the globe, many of them focusing on tropical mountains (Harold & Mooi, 1994; Eken et al., 2004; Kasecker et al., 2009; Darbyshire et al., 2017). The KBA are interconnected sites that are large enough to support species for which they are important (Eken et al., 2004; Bakarr et al., 2007). Efforts to combine IPAs with zoological groups (Important Bird Areas) to evidence KBAs have been carried out for some countries in Europe (Melovski et al., 2012). The flora of these areas is often unique and represents a highly relevant reserve of biodiversity for the global prioritization of conservation efforts (Kier et al., 2005; Merckx et al., 2015). Recent studies show that between 26 and 49% of the plants found in the Atlas Mountains are endemic and strongly correlated to the altitudinal range (Rankou et al., 2013). In Brazil, the recognition of 752 KBAs by Kasecker et al. (2009) highlights 149 areas within the Amazon Rainforest biome, where the Serra dos Carajás is evidenced as a KBA with basis on 10 locally found rare species.

Analogous to the south-western Australian Banded Iron Formations (BIFs), the *canga* or ironstone formations in Brazil are considered ancient ecosystems, characterized by a rich savanna-like flora associated with the decomposition of the iron-rich substrate (Gibson et al., 2017; Nunes et al., 2015; Viana et al., 2016). In both countries, such areas provide unique island-like environments with high levels of species turnover between different sites, high levels of endemism and rare geographically restricted species (Gibson et al., 2010; Jacobi et al., 2007; Mota et al., 2018; Viana et al., 2016; Zappi et al., 2017b). Brazil is second only to Australia in mining and exportation of iron ore, creating many challenges for conservation of the vegetation growing in these areas (Gibson et al., 2017, 2010; Zappi et al., 2017b), and Carajás is the largest iron-ore reserve in the world (Duddu, 2014). In Brazil, *campo rupestre*, an open vegetation growing on a range of different rock types, generally found at the top of the mountains, has long been recognized as a distinct vegetation type (Silveira et al., 2016), while the iron-rich conglomerate is known as *canga*. *Campo rupestre* on *canga* (CRC hereafter) is found in the region of the Serra dos Carajás, in the state of Pará, one of the largest mineral provinces in the world, imbedded within the Amazon Rainforest (Viana et al., 2016), among other sites. In the case of the Serra dos Carajás, these open habitats are immersed in a forest matrix and isolated by altitude and substrate (Mota et al., 2015; Viana et al., 2016). The different surrounding vegetation isolates the open vegetation, precluding or decreasing gene flow between mountain tops, where distinct drivers create special conditions of speciation in the *campo rupestre* (Lanes et al., 2018; Moraes et al., 2012; Pereira et al., 2007).

The first botanical investigations of the CRC of the Serra dos Carajás date back to 1969, when botanists of the Museu Paraense Emílio Goeldi (MPEG) studied the area that corresponds today to the Carajás National Forest (FLONA of Carajás), created in February 1998 (Viana et al., 2016). The first list for this region included 232 species from 58 plant families (Silva et al., 1996). In January 2015, a multi-institutional project lead by Instituto Tecnológico Vale and Museu Paraense Emílio Goeldi to develop a complete Flora of the *canga* of the Serra dos Carajás was launched, and 116 families with 856 species of seed plants authenticated by almost 130 botanists worldwide were written up (Mota et al., 2018), in addition to 186 fern and lycophytes (Salino & Almeida, 2018) and 89 bryophytes (Oliveira-da-Silva & Ilkiu-Borges, 2018). The comprehensive floristic account represents an appropriate baseline to fill the local knowledge gap and to contribute towards the challenge of getting to know the plant diversity of the Amazon (Brazil Flora Group [BFG], 2015; Cardoso et al., 2017). Moreover, it addresses most of the difficulties to define or identify endemic species listed by Ferreira & Boldrini (2011), namely missing taxonomic and distribution data, scant sampling efforts, distributions associated with political and not ecological delimitation, and geographical extent being often underestimated.

Research developed both in the BIFs and CRC have highlighted considerable flora and fauna endemism (Borsali, 2012; Conceição et al., 2016; Gibson et al., 2017; Jacobi et al., 2007; Mota et al., 2018; Viana et al., 2016). Sustainable use of these areas implies investing time and effort to record and study the local biodiversity in order to determine authoritatively which species are to be considered important in terms of conservation (endemic, rare or threatened). In Brazil, the *Código Florestal* regulates the use of forests (MMA, 2012) aiming to protect the native vegetation, highlighting the protection of endemic, rare and endangered species within the planning and development of projects that affect natural habitats. The *Código Florestal* also determines that any project proposal involving land use and exploitation has to support the conservation of the biota and environmental services associated with the target area in order to minimize environmental impact (Feistauer et al., 2014).

In this study, we aim to i) establish a baseline of the edaphic endemism and investigate the rarity of these plant species occurring in the CRC at Carajás; ii) assess these plant species in the Serra dos Carajás using Species Distribution Modelling (SDM); iii) considering endemism and high biodiversity are not always positively correlated (Lamoreux et al., 2006), we investigate this aspect in the CRC of Carajás; and iv) develop a basis to guide multi-disciplinary research towards protecting endemic and rare species in the CRC of Carajás and worldwide.

Methods

Study Area

The Serra dos Carajás spreads over 250 km East-West in southeastern Pará and comprises several distinct plateaus at altitudes between 600 and 760 m a.s.l. (Fig. 1). A series of conservation units with different protection categories encompass the majority of the remaining forests of the region, covering approx. 12,000 km^2 (STCP, 2003; Viana et al., 2016). The *Floresta Nacional de Carajás*, or FLONA of Carajás, and the recently created *Parque Nacional dos Campos Ferruginosos*, or PNCF (June 2017) represent two major conservation areas including parts of the municipalities of Parauapebas and Canaã dos Carajás. Within these areas, vast sways of tall forest surround mountain-tops that are rich in iron-ore, where the *campos rupestres* on *canga*

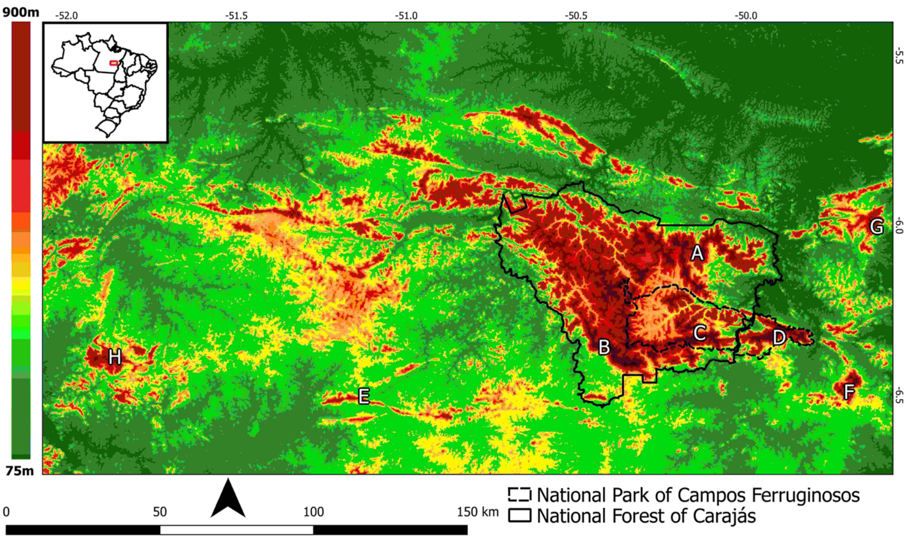

Fig. 1 Outcrops that form the Serra dos Carajás, Pará, Brazil: Carajás National Forest (FLONA of Carajás): Serra Norte (A) and Serra Sul (B); National Park of Campos Ferruginosos (PNCF): Serra do Tarzan (C) and Serra da Bocaina (D); Serra Arqueada (E); Serra do Cristalino (F); Serra Leste (G); Serra de Campos (São Félix do Xingu) (H)

occur. The total area of CRC in the region of Carajás is 115.8 km^2, of which 77 km^2 are distributed between two main areas: *Serra Norte* and *Serra Sul* outcrops, included in the FLONA of Carajás (Souza-Filho et al., 2019) and are estimated to cover around 5% of this total area (STCP, 2016). The remaining *canga* areas occur within the PNCF, namely the Serra do Tarzan and Serra da Bocaina, while some are found outside protected areas, such as the Serra Arqueada, Serra do Cristalino, Serra Leste and Serra de Campos – São Félix do Xingu (Souza-Filho et al., 2019).

Assessment of endemism and rarity

There is no universal methodology to determine whether a species is endemic to a given place apart from the study of its distribution. Herewith we considered as locally endemic of the CRC of Carajás all vascular plants growing within the limits of the *canga* vegetation, but not the plants that also grow on other substrates on open vegetation (e.g. granitic outcrops) or in the forest below or surrounding the iron-ore outcrops, in an attempt to follow the concept of edaphic endemism (Shaw, 1989; Kruckenberg, 2002), where a plant species remains faithful to a specific substrate throughout its distribution. To our best knowledge, only plants growing on *canga*, be it in grooves or in the transition areas, were included. Twenty-seven one-week field expeditions to locate putative endemic species were carried out between May 2016 and March 2018 (Table 1, Fig. 2). The following steps were taken in order to list all the taxa referred to as endemic from the CRC of Carajás:

Herbarium and Protologue Searches

Searches in the following herbaria BHCB, HCJS, IAN, INPA, MBM, MG, NY and RB (acronyms according to Thiers (2011) were carried out to locate type-specimens collected in Carajás (search terms used were "type" or "types" and "Marabá" or "Parauapebas" or "Canaã dos Carajás" or "Serra dos Carajás" or "Carajás"). Supplementary searches were performed in the Global Plants Database (JStor, 2018) and SCOPUS Database (SCOPUS, 2018) to include plant-specimens housed in less obvious collections. Twenty recently described taxa were also brought to our attention by the authors themselves (Table S1). Protologues for all taxa found were obtained to verify that the type-specimens were from the region and to assess the total species distribution. An initial list was produced (Table S2, 73 taxa) then refined to prepare a list of "putative endemics" where the distribution given at the point of description of the taxa was only Carajás (Table S3, 59 taxa).

List comparison

The resulting list (Table S3) was compared with the Brazilian Red List of Plants (Martinelli & Moraes, 2013) and Rare Plants from Brazil (Giulietti et al., 2009) in order to check whether the taxa were already classified as threatened or considered rare. Further distribution comparisons were made with already published data from the Flora of the *canga* of the Serra dos Carajás series, chiefly from the following families: Apocynaceae, 2 pp. (Fernandes et al., 2018), Araceae, 1 sp. (Coelho, 2018), Asteraceae, 4 spp. (Cruz et al., 2016), Bignoniaceae, 2 spp. (Lohmann et al., 2018), Blechnaceae (Salino et al., 2017), Convolvulaceae, 3 spp. (Simão-Bianchini et al., 2016), Cyperaceae, 3 spp. (Nunes et al., 2016), Eriocaulaceae, 2 spp. (Watanabe et al.,

Table 1 Areas surveyed during this study to ascertain the endemism of the species from the *canga* of Carajás (see also Fig. 2)

Month	Year	Province	Municipality	Locality	Latitude	Longitude	Altitude (m)	Endemic found
May	2016	AM	Barcelos	Serra do Aracá	00°51′44”N	63°20′41”W	1034	No
May	2016	AM	Barcelos	White sand fields	00°28′19”N	63°23′39”W	55	No
May	2016	PA	São Félix do Xingu	Serra de Campos	06°23′ 34”S	51°52′40”W	660	Yes (13)
May	2016	PA	São Félix do Xingu	Serra Arqueada	06°30′ 27”S	51°09′44”W	699	Yes (9)
May	2016	PA	Curionópolis	Serra do Cristalino	06°27′ 12”S	49°40′32”W	760	Yes (9)
July	2016	PA	São Geraldo do Araguaia	Serra das Andorinhas	06°12′53”S	48°31′15”W	410	No
July	2016	TO	Araguatins	Transamazônica highway	05°46′37”S	48°03′06”W	250	No
July	2016	TO	Tocantinópolis	Transamazônica highway	06°13′43”S	47°28′56”W	275	No
July	2016	TO	Ananás	TO-210 highway	06°22′7”S	48°02′05”W	390	No
Oct	2016	PA	Santarém	Alter do Chão	02°28′36”S	54°55′37”W	18	No
Oct	2016	PA	Monte Alegre	Parque Estadual de Monte Alegre	02°01′13”S	54°10′54”W	255	No
Nov	2016	PA	Marabá	Serra do Cururu	05°51′ 58”S	50°13′15”W	610	No
Mar	2017	PA	Curionópolis	Serra Leste	05°59′ 33”S	49°37′ 07”W	660	Yes (4)
April	2017	PA	Redenção	Redenção Rocky Fields	08°04′23”S	50°10′05”W	500	No
April	2017	PA	Cumaru do Norte	Santa Teresa Highway	07°54′52”S	50°26′06”W	250	No
April	2017	PA	Rio Maria	Radio Tower Hill	07°18′34”S	49°58′45”W	250	No
April	2017	PA	Bannach	Local Road	07°38′35”S	50°22′22”W	580	No
April	2017	PA	São Félix do Xingu	Serra de Campos	06°23′43”S	51°54′15”W	640	Yes (13)
April	2017	PA	Curionópolis	Serra do Cristalino	06°27′28”S	49°40′40”W	765	Yes (14)
April	2017	PA	Ourilândia do Norte	Serra Arqueada	6°30′33”S	51° 9′23”W	620	Yes (8)
June	2017	PA	Canaã dos Carajás	Níquel do Vermelho	6°28′11”S	49° 54’15 W	270	No
June	2017	PA	Viseu	Apeú-Salvador	00°55′22”S	46°11′18”W	10	No
July	2017	PA	Santarém	Reserva Extrativista Tapajós Arapiuns	02°24′15”S	55°′03’02”W	20	No
July	2017	PA	Belterra	Floresta Nacional do Tapajós	03°02′58”S	54°57′54”W	20	No

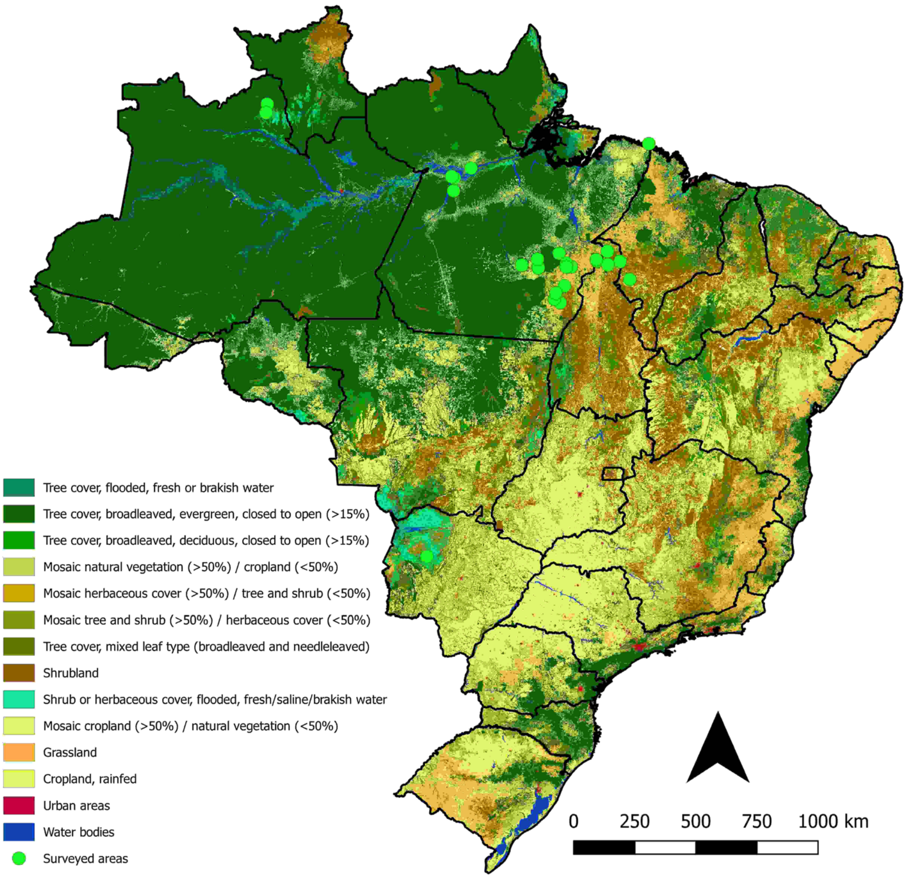

Fig. 2 Distances in Kilometers between the main outcrops of *canga* in the Serra dos Carajás, Pará, Brazil, used to ascertain plant species rarity

2017), Erythroxylaceae, 2 spp. (Costa-Lima & Loiola, 2018), Gentianaceae, 1 sp. (Guimarães et al., 2018), Gesneriaceae, 1 sp. (Chautems et al., 2018), Isoetaceae, 2 spp. (Pereira et al., 2017), Leguminosae, 4 spp. (Mattos et al., 2018), Lentibulariaceae, 1 sp. (Mota & Zappi, 2018), Lythraceae, 1 sp. (Cavalcanti et al., 2016), Melastomataceae, 3 spp. (Rocha et al., 2017), Orchidaceae, 2 spp. (Koch et al., 2018), Orobanchaceae, 1 spp. (Scatigna & Mota, 2017), Picramniaceae, 1 sp. (Pirani & Devecchi, 2016), Piperaceae, 2 spp. (Monteiro, 2018), Poaceae, 4 spp. (Viana et al., 2018), Rubiaceae, 7 spp. (Zappi et al., 2017a), Rutaceae, 1 sp. (Pirani & Devecchi, 2018), Sapotaceae (Terra-Araujo & Zappi, 2018), Selaginellaceae (Góes-Neto et al., 2016), Styracaceae (Viana & Mota, 2016), Thymelaeaceae, 1 spp. (Mota & Giulietti, 2016), Vitaceae (Lombardi, 2016) and Xyridaceae, 1 spp. (Mota & Wanderley, 2016).

Rarity

The rarity of the taxa confirmed as edaphic endemics was ascertained, using the criteria recommended by Rapini et al. (2009), that considers as rare the plant species with records of up to 150 km distance between each other and distributed over an area up to 10,000 km^2. This area is equivalent to the Extent of Occurrence (EOO) used by IUCN (2014) to prepare conservation assessments. Likewise, the Area of Occupancy (AOO) used by IUCN (2014) was ascertained. The endemic species were classified as Highly Restricted Endemic (HRE) – with <100 km^2 of EOO or Range Restricted Endemic (RRE) – with <5000 km^2 but >100 km^2 of EOO (Darbyshire et al., 2017). Distances between outcrops are shown in Fig. 3.

Distribution models

Species distribution model forecasts potential distributional areas based on environmental conditions where species were found (Elith & Leathwick, 2009), representing the most suitable areas for species occurrence (Phillips, 2008). We relied on a previous potential distribution model prepared for Amazonian Eriocaulaceae (Giulietti et al., 2016), a herbaceous plant family that occurs in *campo rupestre* and other open vegetation types, as a predictor for new occurrences of putative endemics. This model aimed to highlight areas that might harbor the same species that were found on CRC of Carajás. Approximately one thousand specimens collected were deposited at the MG herbarium and sent to plant specialists (Figs. 4, 5, 6, 7, 8 and 9).

New potential distribution models were prepared using the final list of 38 endemic species produced here. Occurrence records of the confirmed endemic taxa were organized into a database. From the environmental variables obtained from Worldclim website (Hijmans et al., 2005), we selected six variables through a Pearson correlation analysis (0.75 threshold), with a resolution of 30 arc-seconds (approximately 1 km^2): Annual mean temperature, Isothermality, Temperature Seasonality, Max Temperature of Warmest Month, Precipitation of Wettest Month and Precipitation of Driest Month. Despite the importance of altitude to our selected plants, this variable was excluded due to high correlation with temperature. We are also aware of the importance of soil type to the selected plants, but there is no such information with an equivalent resolution to all study areas available, which hindered the use of this variable during our modeling procedure.

The distribution models were generated using the Maxent algorithm, implemented in the dismo package (Hijmans, 2015) for R (R Core Team)(Fielding & Bell, 1997).

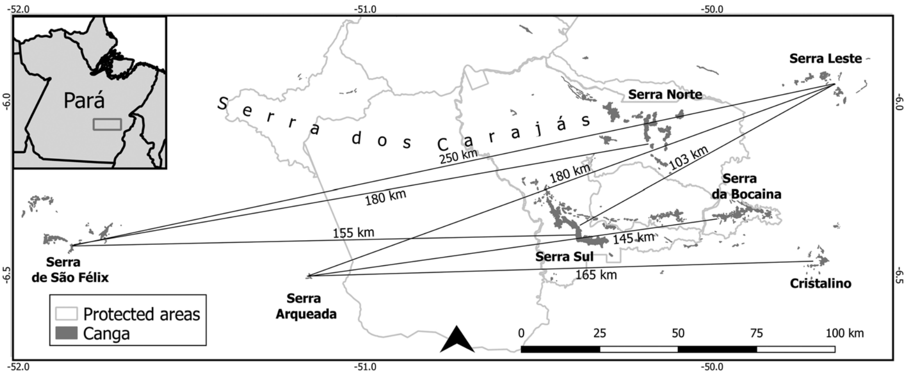

Fig. 3 Areas surveyed in this study to determine the endemic species of the Serra dos Carajás, Pará, Brazil (see also Table 1)

Maxent needs at least 10 records to build the models, and because of this, taxa with less than 10 records could not be analyzed. Thus, from the 38 species listed here, it was possible to model only 28. We used only spatially independent records (occurrence records reported for different cells of 30 arc-seconds) to construct the models. Maxent also requires information about locations where species are absent; but since this type of data for such geographical extension is difficult to obtain, the algorithm automatically generates pseudo-absence data randomly throughout the modeling area. The occurrence dataset was divided into three subsets and three modeling procedures were performed using two-thirds of the data for training and one-third for test. To evaluate the performance of each model, we calculated the area under the receiver operating curve (AUC) (Fielding & Bell, 1997), which ranges from 0 to 1, and True Skill Statistic (TSS) (Allouche, Tsoar, & Kadmon, 2006), which varies between −1 and 1. We maintained the models with AUC > 0.7 and TSS > 0.6 which values indicate a good performance (Fielding & Bell, 1997; Allouche et al., 2006). All analyses were carried out in R environment (R Core Team, 2018).

We use a threshold of 70% of occurrence probability to transform the final obtained models for each species on binary models (0 or 1). After this, all models were summed using ArcGIS (ESRI, 2018); thus, the ensemble model highlights the areas with the highest suitability for the 28 analyzed species, which are represented as the areas with the highest probability of occurrence.

Results and Discussion

Precise diagnosis of endemism of CRC

The initial list of 73 taxa (Supplementary material Table S2) that had type-specimens from Carajás was reduced, through the discarding of records that were known to have wider distribution at the point of description, resulting in a list of 58 putative endemic taxa including 53 angiosperms and five ferns and lycophytes (Supplementary material Table S3). The study of newly prepared floristic treatments for the Flora of the *canga* of the Serra dos Carajás (Mota et al., 2018) and recent field surveys (Table 1) contributed to the exclusion of 20 taxa from the putative species list for the following reasons:

1. ***Wide distribution***. Taxa that have been found to have wider geographic distribution than initially suggested were excluded. Two of these taxa were synonymized into species with wider distribution, namely *Ipomoea carajasensis,* recently included in the synonymy of *I. maurandioides*, a species with distribution in Brazil, Bolivia, Paraguay and Argentina (Wood et al., 2015); and *Bulbostylis carajana*, which was sunk into *Bulbostylis conifera* (Nunes et al., 2016). Apart from these, *Ipomoea marabaensis* (discovered elsewhere in Pará and extending to Tocantins), *Centrosema carajasense* (found in Mato Grosso), *Mimosa acutistipula* var. *ferrea* (collected in Maranhão), *Mormodes paraensis* (new collection in Roraima), *Borreria semiamplexicaulis* (collected in Maranhão), *Pradosia granulosa* (also collected in Maranhão), and *Pilocarpus carajaensis* was found elsewhere in the state of Pará. Two fern species, *Blechnum areolatum* and *B. longipilosum* were also collected in Maranhão after their description.

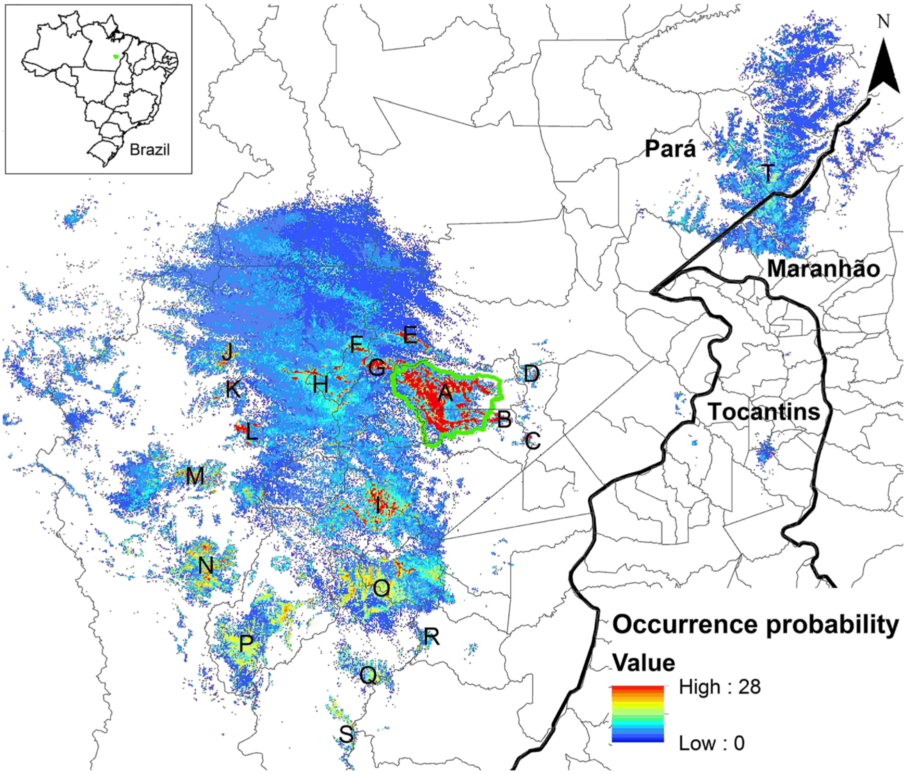

Fig. 4 Areas with the highest probability of occurrence of the endemic species found in the Serra dos Carajás, Pará, Brazil (green border) in a model comprising 28 species. (A) FLONA of Carajás (Mun. Canaã dos Carajás and Parauapebas); (B) National Park of Campos Ferruginosos (Serra do Tarzan and Serra da Bocaina – Mun. Canaã dos Carajás); (C) Serra do Cristalino and Serra do Rabo (Mun. Canaã dos Carajás and Curionópolis); (D) Serra Leste or Serra do Sereno (Mun. Curionópolis); (E) Serra do Cinzento (Mun. Marabá); (F) Border between Municipalities of Marabá and São Félix do Xingu; (G) Border between Municipalities of Marabá and Parauapebas; (H) Border between Municipalities of São Félix do Xingu, Marabá and Parauapebas; (I) Serra da Seringa (Mun. Água Azul do Norte and Ourilândia do Norte); (J) Serra do Bacajá (Mun. São Félix do Xingu); (K. L. M) Areas in the Municipality of São Félix do Xingu; (N) Serra da Fortaleza (Mun. São Félix do Xingu); (O) Serra do Trairão (Bannach); (P) Serra do Cubencranquém (Mun. Ourilândia do Norte); (Q) Serra dos Gradaús (Mun. Cumaru do Norte); (R) Serra dos Gradaús (Mun. Cumaru do Norte and Redenção); (S) Serra dos Gradaús (Mun. Cumaru do Norte and Santa Maria das Barreiras); (T) Border of Municipality of Dom Eliseu; (U) Border of Municipality of Rondon

2. *Borreria semiamplexicaulis* and *Ipomoea marabaensis* were included as Rare for Brazil (Giulietti et al., 2009). However, these occur in other areas of the state of Pará and elsewhere (Zappi et al., 2017a), with *I. marabaensis* also occurring in Tocantins (Simão-Bianchini et al., 2016) and their status as rare plants needs to be reevaluated.
3. ***Exclusive to the forest.*** This group of 4 taxa occurred only in the lowland forest environment: *Jacaranda carajasensis* is a tree restricted to the FLONA of Carajás and listed as threatened (Critically Endangered) because of its narrow distribution (Gentry, 1992; MMA, 2014). *Heliconia carajaensis* is a poorly understood giant

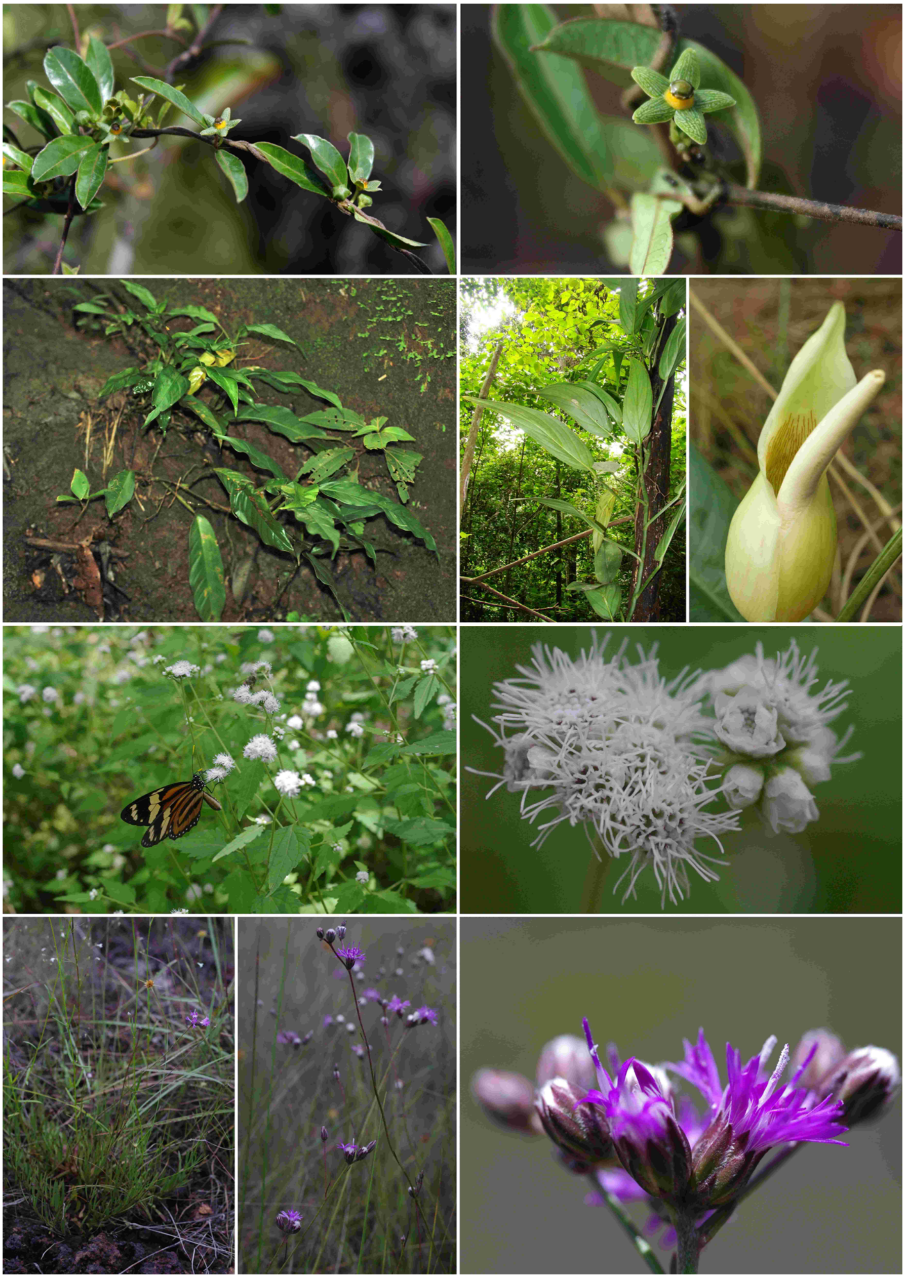

Fig. 5 Portraits of endemic species from the Serra dos Carajás, Pará, Brazil (Apocynaceae to Asteraceae I): *Matelea microphylla* (Apocynaceae), habit and flower - photos F. Marino; *Philodendron carajasensis* (Araceae), habit, foliage and inflorescence: photos A Arruda, N. Mota and B. Ranieri; *Cavalcantia glomerata* (Asteraceae), plant visited by butterfly and inflorescence in detail: photos P.L. Viana; *Lepidaploa paraensis* (Asteraceae), habit, inflorescences and detail showing florets: photos P.L. Viana

Fig. 6 Portraits of endemic species from the Serra dos Carajás, Pará, Brazil (Asteraceae II to Convolvulaceae): *Monogereion carajensis* (Asteraceae), habit and detail of the inflorescence: photos P.L. Viana; *Parapiqueria cavalcantei* (Asteraceae), habit, whole plant and detail of the inflorescence: photos N. Mota and P.L. Viana; *Anemopaegma carajasensis* (Bignoniaceae): flowers, habit and fruit: photos: P.L. Viana and N. Mota; *Ipomoea cavalcantei* (Convolvulaceae), flowers and two views of the habit: photos P.L. Viana

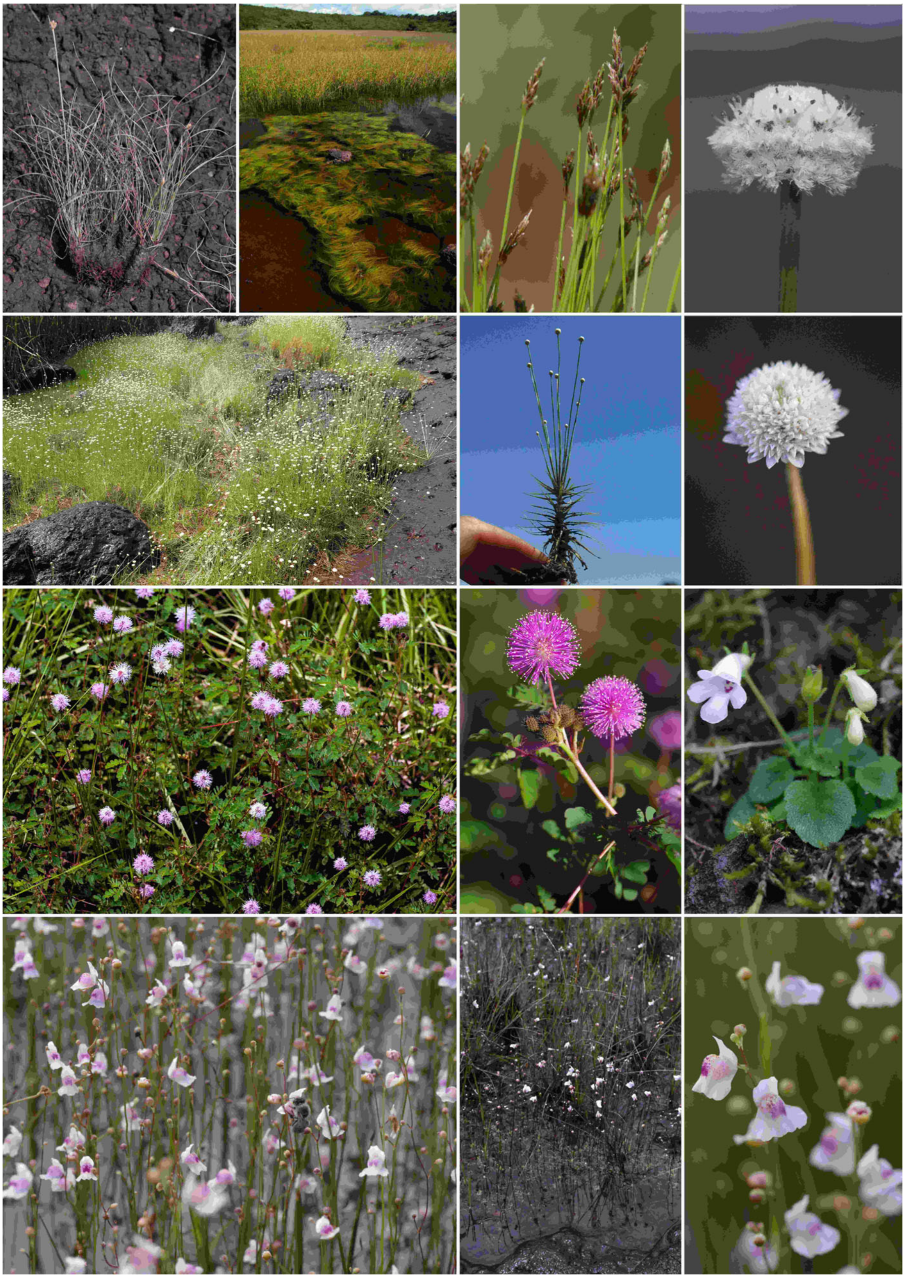

Fig. 7 Portraits of endemic species from the Serra dos Carajás, Pará, Brazil (Cyperaceae to Gesneriaceae): *Bulbostylis cangae* (Cyperaceae), habit: photo P.L. Viana; *Eleocharis pedrovianae* (Cyperaceae), aquatic habit and inflorescences: photos P.L. Viana; *Eriocaulon carajasensis* (Eriocaulaceae), detail of inflorescence: photo N. Mota; *Syngonanthus discretifolius* (Eriocaulaceae), population, habit and inflorescence: photos M. Watanabe and J.M. Rosa; *Mimosa skineri* (Fabaceae), habit and detail of inflorescences: photos P.L. Viana; *Sinningia minima* (Gesneriaceae), whole plant: photo N.F. Mota; *Utricularia physoceras* (Lentibulariaceae), population shots and detail of flowers: photos: P.L. Viana

Fig. 8 Portraits of endemic species from the Serra dos Carajás, Pará, Brazil (Lythraceae to Poaceae): *Cuphea carajasensis* (Lythraceae), habit and flower colour variation within the population: photos: N. Mota and P.L. Viana; *Pleroma carajasensis* (Melastomataceae), inflorescence and habit: photos P.L. Viana; *Buchnera carajasensis* (Orobanchaceae), flower: photo N. Mota; *Picramnia ferrea* (Picramniaceae), habit with yellow fruits and detail of male inflorescence: photos N. Mota; *Peperomia albopilosa* (Piperaceae), whole plant and detail of infructescence: photos N. Mota; *Paspalum cangarum* (Poaceae), inflorescence and detail showing open flowers: photos P.L. Viana; *Axonopus carajasensis* (Poaceae): detail showing open flowers: photo P.L. Viana; *Sporobolus multiramosus* (Poaceae), habit and detail of inflorescence: photos P.L. Viana

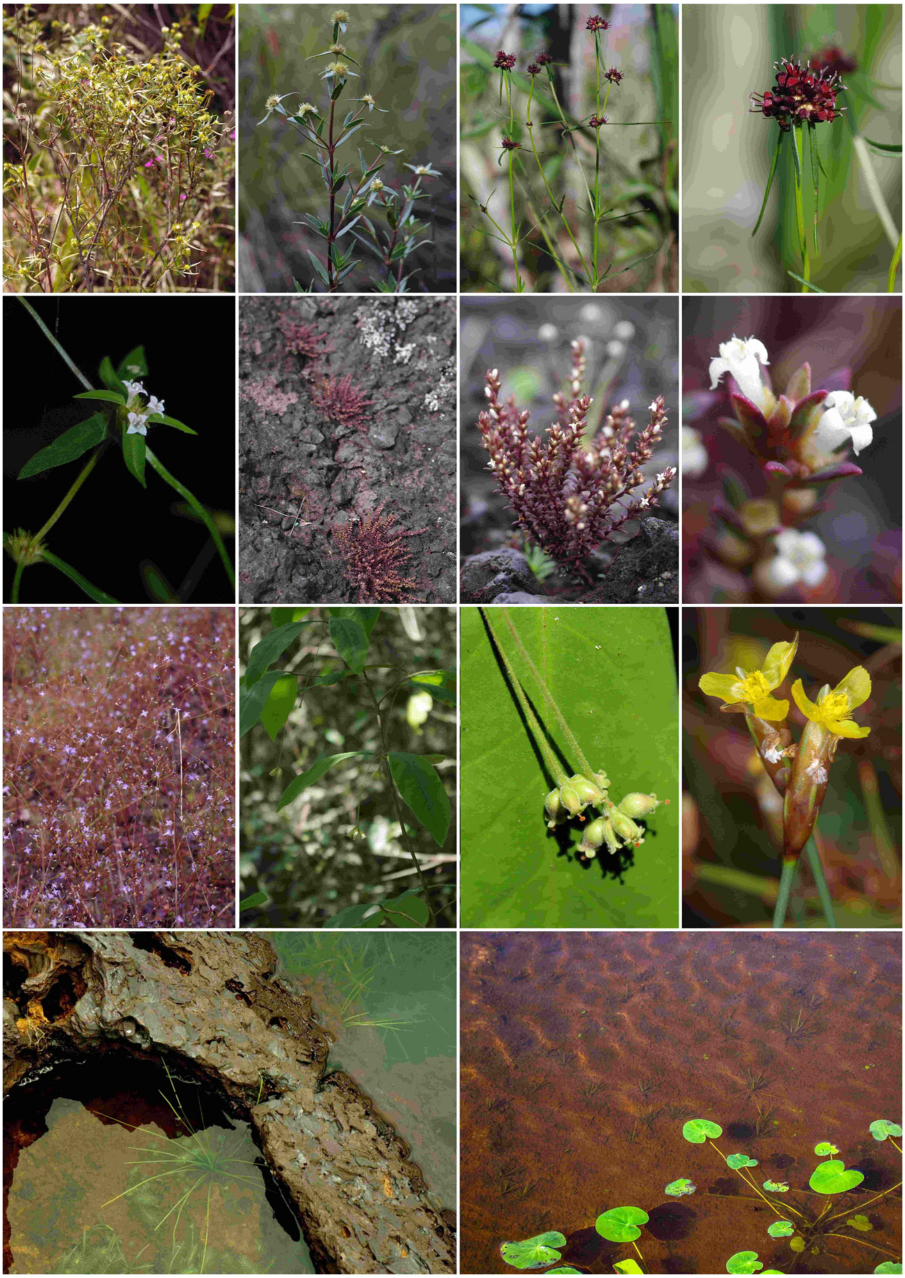

Fig. 9 Portraits of endemic species from the Serra dos Carajás, Pará, Brazil (Rubiaceae to Xyridaceae): *Borreria carajasensis* (Rubiaceae), habit and plant: photos P.L. Viana; *Borreria elaiosulcata* (Rubiaceae), habit and detail of inflorescence: photos P.L. Viana; *Borreria heteranthera* (Rubiaceae), inflorescence: photo A. Arruda; *Carajasia cangae* (Rubiaceae), habit, whole plant and flowers in detail: photos P.L. Viana; *Perama carajasensis* (Rubiaceae), habit: photo P.L. Viana; *Daphnopsis filipedunculata* (Thymelaeaceae), habit and detail of inflorescence: photos N. Mota and F. Marino; *Xyris brachysepala* (Xyridaceae), inflorescence: photo C. Hall; *Isoetes cangae* (Isoetaceae), aquatic habit: photo A. Arruda; *Isoetes serracarajensis* (Isoetaceae), aquatic habit: photo N. Mota

herb from forest understorey, not recorded in the Brazilian species list (FBO 2020, under construction). *Voyria alvesiana* (Guimarães et al., 2018) is found on ombrophylous forest and has no records from the *canga* so far. *Selaginella stomatoloma*, the only heterosporous lycophyte listed, is a diminutive shade-loving rupicolous plant which grows in dense lowland to premontane forests and is known only from three collections, all from Carajás (Valdespino, 2015), none of these from the *canga* study area.

4. ***Local canga and forest.*** Therefore, despite being found only locally, *Mouriri cearensis* subsp. *carajasica*, is found both associated with *canga* and in the dense rainforest surrounding the outcrops. *Hypolytrum paraense* occurs more often in the transitional area between *canga* and tall forest (Nunes et al., 2016).
5. ***Not exclusive to ferruginous substrate.*** Taxa that do not grow exclusively in CRC, thus not being considered edaphic endemic (sensu Kruckenberg, 2002). *Marsdenia bergii* is a robust climber that occurs in CGC however its distribution is not restricted to this substrate and, despite being classified as Rare for Brazil (Giulietti et al., 2009), has been found growing on granite within the area of the FLONA of Carajás (Fernandes et al., 2018), alongside *Mitracarpus carajasensis* (Zappi et al., 2017a) and *Brasilianthus carajensis*. It is possible that both species are new arrivals in the granite outcrop, following the opening of roads that link the outcrops, mining plants and other mines, as was established by (P.L.Viana, pers. comm.).

In terms of threatened species, the findings of this work reflect the need for revision of the categorization of some species currently considered as Vulnerable. In the case of *Ipomoea carajasensis*, this taxon was found to be part of a wider species concept, nowadays known as *I. maurandioides* (Wood et al., 2015). *Pradosia granulosa*, classified as Vulnerable based on its restricted distribution (Martinelli & Moraes, 2013) has been recorded throughout the state of Pará and its IUCN category may need to be re-examined.

Categories of Endemism According to Species Distribution Data

The final list of edaphic endemics of CRC Carajás comprises 38 species of vascular plants distributed in 31 genera and 22 families (Table 2; Supplementary Information S4), including three monotypic genera: *Carajasia* (Rubiaceae – Fig. 9), *Monogereion* and *Parapiqueria* (Asteraceae – Fig. 6). From these endemic species, 24 can be classified as Rare Species for Brazil (Table 2), based on their restricted geographic distribution, with an extent of occurrence (EOO) of less than 10,000 km^2 and locations less than 150 km (according to Rapini et al., 2009). For the 14 remaining species, even though nine present 5,000 km^2 < EOO > 10,000 km^2, we did not find a fit within the criterion of distance between outcrops explained above (Table 2).

A total of 30 species that present EOO smaller than 5,000 km^2 have been classified as either Highly Restricted Endemic (HRE) or Range Restricted Endemic (RRE) (Darbyshire et al., 2017). The Highly Restricted Endemic were the lycophyte *Isoetes cangae* (Fig. 9) as well as six angiosperms from the FLONA of Carajás: *Carajasia cangae*, *Daphnopsis filipedunculata*, *Ipomoea cavalcantei*, *Parapiqueria cavalcantei*, *Paspalum carajasense*, alongside *Mimosa dasilvae*, from outsde the FLONA of Carajás and the PNCF. The remaining 23 species were classified as Range Restricted Endemic (RRE) (Table 2).

The 38 endemic species can be categorized in four groups according to their specific conservation requirements (Table 2):

(1) A single taxon, *Mimosa dasilvae*, is restricted to the Serra de Campos in São Félix do Xingu. It also was classified as both HRE and Rare for Brazil.
(2) Twenty are relatively widely distributed in the CRC throughout the region, including FLONA of Carajás. PNCF, Serra Arqueada, Serra do Cristalino, Serra Leste and Serra de Campos. Of these, 11 were classified as RRE with EOO between 113 and 4903 km^2.
(3) Nine angiosperm taxa are restricted to the FLONA of Carajás and PNCF. These are: *Bulbostylis cangae, Cavalcantia glomerata, Erythroxylum carajasense, E. nelson-rosae, Lepidaploa paraensis, Paspalum cangarum, Philodendron carajasense, Picramnia ferrea* (Fig. 8) and *Sinningia minima* (Fig. 7). All of them were classified as RRE. *Erythroxylum nelson-rosae* and *Picramnia ferrea* were already considered rare for Brazil (Giulietti et al., 2009).
(4) Eight taxa are exclusively from the FLONA of Carajás. From those, only two are found both in the Serra Norte and Serra Sul: the herbaceous *Axonopus carajasensis* and *Peperomia pseudoserratirhachis*, both classified as RRE. Three species are found only in the Serra Norte: a liana, *Ipomoea cavalcantei*, herbaceous *Paspalum carajasensis* and the treelet *Daphnopsis filipedunculata,* all classified as HRE. Three species are exclusive to the Serra Sul: the monotypic herbaceous genera *Carajasia cangae* and *Parapiqueria cavalcantei* and the aquatic lycophyte *Isoetes cangae*, and all of these also fit within HRE. *Axonopus carajasensis* and *Ipomoea cavalcantei* have already been recorded as Rare for Brazil (Giulietti et al., 2009), and also endangered (Martinelli & Moraes, 2013; MMA, 2014). In spite of the type specimen of *P. cavalcantei* being originally from the Serra Norte (specimen *Cavalcante 2162* – RB), current collections are all from the Serra Sul.

The ensemble of species distribution modelling highlighted 20 areas with the highest suitability for 28 endemic species to occur (Fig. 4). The majority of these areas are found westwards from the FLONA of Carajás, with only three eastwards and two towards the northeast, in the border between the states of Pará and Maranhão. Most of these areas (13) are found at relatively high altitudes (above 600 m a.s.l.).

Comparing our Findings with Global Evidence

According to (Gibson et al., 2010), the vegetation and flora patterns in the BIFs from South West Australia appear to be related to local topographical factors and the long period of time these landscapes have remained unglaciated and above the sea level. The plant communities found there differ in composition from the surrounding Mediterranean type matrix and exhibit high levels of endemism. Zappi et al. (2017b) studied the flora of *campo rupestre* over quartzitic and *canga* substrates in the Espinhaço Range, in Eastern Brazil, an area that occupies 66,450 km^2 and is home

Table 2 List of endemic species from Carajás (Pará, Brazil), including FLONA of Carajás **(FC)**, Parque Nacional dos Campos Ferruginosos **(PNCF)**, Serra Arqueada **(SA)**, Serra do Cristalino **(SC)**, Serra Leste **(SL)** and Serra de Campos - São Félix do Xingu **(SF)**. Area of Occupancy **(AOO)** and Extent of Occurrence **(EOO)**. Highly Restricted Endemic **(HRE)**, Range Restricted Endemic **(RRE)**; [x = occurs, = old record, population not found again]. For images see Plates 5–9

	Family	Species	Publication year	FC		PNCF		SA	SC	SL	SF	EOO (Km2)	AOO (Km2)	Ende-mism	Rare	Habit
				Serra Norte	Serra Sul	Tarzan	Bocaina									
Angiosperms																
1	Apocynaceae	*Matelea microphylla* Morillo – Fig. 5	1988	X	X			X	X			4436	20	RRE		Liana
2	Araceae	*Philodendron carajasense* E.G.Gonç. & A.J.Arruda – Fig. 5	2013	X	X		X					1363	44	RRE	X	herb
3	Asteraceae	*Cavalcantia glomerata* (G.M.Barroso & R.M.King) R.M. King & H. Rob. – Fig. 5	1980	X	X		X					1394	44	RRE	X	subshrub
4	Asteraceae	*Lepidaploa paraensis* (H.Rob.) H.Rob. – Fig. 5	1994	X	X	X	X					1376	68	RRE	X	subshrub
5	Asteraceae	*Monogereion carajensis* G.M.Barroso & R.M.King* - Fig. 6	1971	X	X	X	X		X	X	X	7654	100	–		shrub
6	Asteraceae	*Parapiqueria cavalcantei* R.M.King & H.Rob. – Fig. 6	1980		x							5	12	HRE	X	subshrub
7	Bignoniaceae	*Anemopaegma carajasense* A.H.Gentry ex Firetti-Leggieri & L.G.Lohmann – Fig. 6	2018	X	X	X					X	4195	40	RRE		shrub
8	Convolvulaceae	*Ipomoea cavalcantei* D.F.Austin** - Fig. 6	1981	X								82	48	HRE	X	liana
9	Cyperaceae	*Bulbostylis cangae* C.S.Nunes & A.Gil – Fig. 7	2017	X	X	X						709	24	RRE	X	herb
10	Cyperaceae	*Eleocharis pedrovianae* C.S.Nunes, R.Trevis. & A.Gil – Fig. 7	2016	X	X	X	X				X	4903	72	RRE		herb
11	Eriocaulaceae	*Eriocaulon carajense* Moldenke – Fig. 7	1973	X	X		X				X	4756	40	RRE		herb
12	Eriocaulaceae	*Syngonanthus discretifolius* (Moldenke) M.T.C.Watan. – Fig. 7	2015	X	X	X					X	4464	108	RRE		herb

Table 2 (continued)

	Family	Species	Publication year	FC		PNCF		SA	SC	SL	SF	EOO (Km2)	AOO (Km2)	Ende-mism	Rare	Habit
				Serra Norte	Serra Sul	Tarzan	Bocaina									
13	Erythroxylaceae	*Erythroxylum carajasense* (Plowman) J.L.Costa	2017	X	X		X					1287	48	RRE	X	shrub
14	Erythroxylaceae	*Erythroxylum nelson-rosae* Plowman**	1986	X	X	X	X					1285	60	RRE	X	shrub
15	Gesneriaceae	*Sinningia minima* A.O.Araujo & Chautems – Fig. 7	2015	X	X		X					1461	88	RRE	X	herb
16	Leguminosae	*Mimosa dasilvae* A.S.L.Silva & Secco	2000								X	–	4	HRE	X	shrub
17	Leguminosae	*Mimosa skinneri* Benth. var. *carajarum* Barneby* - Fig. 7	1991	X	X	X	X	X	X	X	X	7633	132	–		subshrub
18	Lentibulariaceae	*Utricularia physoceras* P.Taylor – Fig. 7	1986	X	X	X	X		X			2030	96	RRE	X	herb
19	Lythraceae	*Cuphea carajasensis* Lourteig – Fig. 8	1987	X	X	X	X		X	X	X	7778	156	–		subshrub
20	Melastomataceae	*Pleroma carajasense* K.Rocha, R.Goldenb. & F.S.Mey - Fig. 8	2017	X	X			X			X	6496	72	–		shrub
21	Orchidaceae	*Uleiorchis longipedicellata* A.Cardoso & Ilk.-Borg.	2015	X						X		156	12	RRE	X	herb
22	Orobanchaceae	*Buchnera carajasensis* Scatigna & N.Mota – Fig. 8	2017	X	X	X	X		X		X	5419	72	–		herb
23	Picramniaceae	*Picramnia ferrea* Pirani & W.W.Thomas – Fig. 8	1988	X	X	X	X					1774	56	RRE	X	shrub
24	Piperaceae	*Peperomia albopilosa* D.Monteiro – Fig. 8	2018	X	X						X	3878	44	RRE		herb
25	Piperaceae	*Peperomia pseudoserratirhachis* D.Monteiro	2018	X	X							152	16	RRE	X	herb
26	Poaceae	*Axonopus carajasensis* M.Bastos** - Fig. 8	1991	X	X							564	16	RRE	X	herb
27	Poaceae	*Paspalum cangarum* C.O.Moura, P.L.Viana & R.C.Oliveira – Fig. 8	2018		X		X					252	20	RRE	X	herb

Table 2 (continued)

	Family	Species	Publication year	FC		PNCF		SA	SC	SL	SF	EOO (Km2)	AOO (Km2)	Ende-mism	Rare	Habit
				Serra Norte	Serra Sul	Tarzan	Bocaina									
28	Poaceae	*Paspalum carajasense* S.Denham	2005	X								53	16	HRE	X	Herb
29	Poaceae	*Sporobolus multiramosus* Longhi-Wagner & Boechat – Fig. 8	1993	X	X	X	X		X			1937	56	RRE	X	herb
30	Rubiaceae	*Borreria carajasensis* E.L.Cabral & L.M.Miguel – Fig. 9	2012	X	X		X	X			X	5869	88	–		herb
31	Rubiaceae	*Borreria elaiosulcata* E.L.Cabral & L.M.Miguel – Fig. 9	2012	X	X	X	X		X			2203	160	RRE	X	herb
32	Rubiaceae	*Borreria heteranthera* E.L.Cabral & Sobrado – Fig. 9	2015	X	X	X	X		X			1936	64	RRE	X	herb
33	Rubiaceae	*Carajasia cangae* E.L.Cabral & Dessein – Fig. 9	2015		X							37	36	HRE	X	herb
34	Rubiaceae	*Perama carajensis* J.H.Kirkbr. – Fig. 9	1980	X	X	X	X	X	X	X	X	8922	1283	–		herb
35	Thymelaeaceae	*Daphnopsis filipedunculata* Nevling & Barringer – Fig. 9	1993	X								37	20	HRE	X	shrub
36	Xyridaceae	*Xyris brachysepala* Kral – Fig. 9	1988	X	X	X	X		X	X	X	6412	140	–		Herb
Lycophytes																
37	Isoetaceae	*Isoetes cangae* J.B.S.Pereira, Salino & Stützel – Fig. 9	2016		X							–	4	HRE	X	herb
38	Isoetaceae	*Isoetes serracarajensis* J.B.S.Pereira, Salino & Stützel – Fig. 9	2016	X	X	X	X		X			1472	36	RRE	X	herb

for over 5,000 species (Silveira et al., 2016), with approximately 40% of them apparently endemic (Brazil Flora Group [BFG], 2015). In the CRC of Carajás, restrictions to plant establishment include shallow, stony soil, high levels of insolation, elevated temperatures, temporarily waterlogged substrate and the presence of potentially toxic metal concentration (Schaefer et al., 2016). However, an area of *canga* that adds up to mere 115 km^2 (Souza-Filho et al., 2019) hosts a total of 856 species of seed plants (Mota et al. 2018). The present study shows that 38 (over 4%) of the angiosperm species are endemic to the CRC of Carajás. Studies developed in the *campo rupestre* of the Serra do Cipó, in Minas Gerais (Giulietti et al., 1987), have found 1590 species distributed in an area of approximately 200 km^2, where the endemism is strongly correlated to different plant families, with forest dwelling taxa with almost no endemic taxa, while species that grow in open vegetation surpass 40% of endemism for the Velloziaceae. Pirani et al. (2015) evaluated the endemism in 2943 species in the same region, and found that 196 (6.6%) were endemic to the area. It is important to highlight that these data did not take into account the edaphic endemism, being limited to the geography of the species. However, while 114 plant families yielded no endemism, endemism was concentrated in seven families, namely the Melastomataceae (5 out of 149 spp., 3.3% endemic), Asteraceae (12 out of 301 spp., 4.3% endemic), Poaceae (10 out of 198 spp., 5% endemic), Rubiaceae (5 out of 91 spp., 5.1% endemic), Xyridaceae (11 out of 60, spp. 18% endemic), Eriocaulaceae (49 out of 133 spp., 36.8% endemic) and Velloziaceae (24 out of 61 spp., 40% endemic).

When considering the CRC of Carajás, with the exception of the Velloziaceae, all above listed families have endemic species: Asteraceae, 34 spp., with two genera and 4 species (i.e. 12%) endemic (Cruz et al., 2016); Melastomataceae, 63 spp., one edaphic endemic species (Rocha et al., 2017); Poaceae, 87 spp., 4 species (i.e. 4.6%) endemic; Rubiaceae, 48 spp., with one genus and 5 species (i.e. 10%) endemic (Zappi et al., 2017a); Eriocaulaceae, 10 spp., 2 (i.e. 20%) endemic (Watanabe et al., 2017); and Xyridaceae, 4 spp. of which one is endemic (Mota & Wanderley, 2016; Mota et al., 2018). Therefore the proportion of endemic species in Carajás is comparable to what is found for the Serra do Cipó in the Cadeia do Espinhaço (Eastern Brazil), and also for the *canga* in the Quadrilátero Ferrífero, where a survey of nearly a thousand species reports between 27 (Borsali 2012) and 36 endemic species in an area that covers 102 km^2 (Carmo & Jacobi, 2013). Furthermore, the inclusion of substrate specificity leads to a narrower endemism concept in our analyses. Other iron-ore sites worldwide, such as the 25 BIF ranges surveyed in Western Australia, have recorded over an area of approx. 650 km^2 (Gibson et al., 2017) over 1700 taxa of which 24 were found to occur on individual sites while a further six taxa were restricted to a group of ranges, resulting in 1.8% species endemism. Detailed studies such as the ones developed for Carajás (Mota et al., 2018) have revealed that a large number of species initially considered as single site endemics from the CRC are distributed more widely than previously thought, but their total range is still restricted to iron-ore outcrops in the region. Meanwhile, after all the sampling effort invested, there are some species that remain recorded for a single site, such as *Mimosa dasilvae* and the six species exclusive from the FLONA of Carajás (see Table 2).

Out of the 38 endemic species from the CRC, 24 were classified as rare for Brazil (Table 2), of which six (*Axonopus carajasensis*, *Eriocaulon carajense*, *Erythroxylum nelson-rosae*, *Ipomoea cavalcantei*, *Picramnia ferrea* and *Utricularia physoceras*) were already rare as referred by Giulietti et al. (2009), amongst others that were found not to be CRC endemic after the present research (such as *Ipomoea marabaensis*, *Marsdenia bergii*). The CRC of Carajás are now the second Key Biodiversity Area in northern Brazil, after the Reserva Florestal Adolpho Ducke, with 25 rare species, and the Serra do Aracá, with 10 species (Kasecker et al., 2009).

The vascular plants from the *canga* of the Serra dos Carajás include 1034 species of vascular plants (856 seed plants: Mota et al., 2018 + 156 ferns and lycophytes: Salino & Almeida, 2018) in an area covering at most 150 km^2, with seven HRE and 23 RRE species. These numbers highlight a unique flora that compares favourably to the 1109 plant species of vascular plants reported for the Quadrilátero Ferrífero of Minas Gerais (ca. 7200 km^2) (Carmo & Jacobi, 2013) and the 1700 species found over 600 km^2 in the Australian BIFs (Gibson et al., 2017). In the latter sites, the surfaces measured included areas surrounding the iron-rich outcrops.

Concluding Remarks - Conservation of the CRC Endemic Species

The protection of the endemic species from the CRC depends on the increase of the scientific knowledge regarding their accurate range, as well as their morphology, adaptations, population dynamics, demography and genetics. The information presented herein is of value for decision-making and invigilation of the current laws by environmental agencies, providing a sound base for their interaction with the companies that use and transform the land, ensuring sustainable development of this site. International efforts have been made towards improving the sustainability of mining, suggesting strategies to avoid the loss of species (ICMM & IUCN, 2014), for mitigation and compensation (Duke & ten Kate, 2014) and the restoration of post-mining areas (Maron et al., 2012; Giannini et al., 2017). However, for the effective compliance with legal requirements and conservation strategies, it is necessary that biodiversity data is made available and analysed from the scientific point of view, resulting in effective compliance with legal claims, and guiding further strategies to effectively protect or restore biodiversity.

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