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ORIGINAL PAPER

Plant communities on ironstone outcrops: a diverse and endangered Brazilian ecosystem

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Abstract Mountain areas are recognized centres of endemism and diversity on account of their isolation and altitudinal diversity. In tropical regions, mountain tops usually stand as islands of xeric vegetation among mesophytic assemblages. Unlike the vegetation growing on other rock outcrops lithologies, such as inselbergs (granite/gneiss) or *campos rupestres* (quartz/arenite), ironstone outcrop plant communities still lack systematic studies in Brazil. These outcrops (locally known as *canga*) share most of the characteristics of other rock outcrops, such as isolation and edapho-climatic harshness, but differ in that they are the object of opencast mining, and thus subjected to irrecoverable degradation. In addition, they are expected to harbour metal-tolerant and hyperaccumulator plant species. A botanical survey of two ironstone outcrop locations in the most important mining region of southeastern Brazil, the Iron Quadrangle, revealed a high within-site (138 and 160 species per site), and between-site diversity (only 27% of common species), totaling 64 families and 234 species among basal families and eudicots (154 species), monocots (68 species), and ferns (12 species). *Canga* crusts are rich in dicots, several of which play an important role in community structuring, together with the more usual monocot aggregations. Distinct plant communities are found associated to different microhabitats within the iron crust, depending primarily on the amount of soil and moisture retention in the different microtopographies. The environmental uniqueness, high diversity, lack of studies and rapid destruction of these ecosystems pose an immediate challenge for their conservation.

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Introduction

Mountain areas throughout the world play an unquestionable role in promoting regional and global diversity (Burke 2003), because they combine discontinuous distribution with edapho-climatic variations resulting from altitudinal gradients. On account of these characteristics, rock outcrops on mountain tops are recognized worldwide centres of diversity and endemism (Smith and Cleef 1988; Barthlott et al. 1993; Alves and Kolbek 1994; Porembski et al. 1994; Giulietti et al. 1997). These environments usually share a series of stressful characteristics, such as high UV exposure, daily thermal variations, constant winds, high evapotranspiration, low water retention, and overheated, impermeable soils (Scarano 2002; Porembski and Barthlott 2000).

Rock outcrop plant communities are basically edaphically controlled, and in most situations they represent islands of xeric communities rising within a matrix of mesophytic vegetation (Porembski et al. 1994; Porembski et al. 1998). Species show adaptations to over-heating, such as minimal contact with the surface, trichomes or persistent leaf sheaths for isolation, and for water uptake and accumulation, such as succulence, sclerophylly, and desiccation-tolerance (poikilohydry) in the so-called resurrection plants (Gaff 1977, 1987; Porembski and Barthlott 2000).

A substantial amount of information on tropical rock outcrops is available nowadays as a result of botanical, phytogeographical and ecological studies undertaken in several lithologies. Among the best-studied in Africa and South America are granitic/gneissic domes, known as *inselbergs* (Ibisch et al. 1995; Groger and Barthlott 1996; Porembski et al. 1998; Meirelles et al. 1999; Parmentier 2003; Parmentier et al. 2005; Medina et al. 2006). The flora associated with quartz and arenite table-mountains has also received much attention, as is the case of *campos rupestres* (rocky fields) in Brazil (Alves and Kolbek 1994; Meguro et al. 1994; Conceição and Pirani 2005; Pirani et al. 2003).

Comparatively, little is known about plant communities associated with iron-rich outcrops, such as African ferricretes (Porembski et al. 1994, 1997) and *canga* in Brazil (Porto and Silva 1989; Silva 1991). Both are formed basically by processes of weathering/lateritization, but have different physico-chemical characteristics, because they originated from different lithologies (for geological details see Trendall and Morris 1983; Ambrosi and Nahon 1986; Beauvais and Roquin 1996).

The vegetation of ironstone outcrops, besides sharing physiological, morphological and reproductive adaptations typical of *lato sensu* rock outcrops, also exhibits adaptations to living on a substrate rich in heavy metals, and possibly contains metallophytes or at least metal-tolerant species (Porto and Silva 1989). According to Reeves et al. (1999), true metallophytes or hyperaccumulators have a very restricted geographical distribution, and are usually rare or endemic. In Latin America, studies on these species are scarce, and few data on metallophytes are available (Porto and Silva 1989; Silva 1992; Teixeira and Lemos-Filho 1998, 2002; Ginocchio and Baker 2004). In Brazil, these plant communities are associated with large mineral reserves of which the two most important are Serra de Carajás in the Amazon forest and Quadrilátero Ferrífero in the southeast. In these two locations, the intensity of opencast mining poses an immediate threat to these ecosystems, thus eliminating the chance of improving our knowledge of plant tolerance to metals and desiccation, and their potential for sustainable use or for mine degradation recovery (Ginocchio and Baker 2004).

This study represents the first to address floristic and ecological aspects of plant communities associated with ironstone outcrops (*canga*) in SE Brazil, except for unpublished data (e.g. Vincent 2004). These outcrops face an immediate threat because they lie on top of good-quality iron ore deposits of worldwide economic importance, hence the regional name Quadrilátero Ferrífero (Iron Quadrangle). We describe the geographic and geological settings, the main floristic features of two *canga* outcrop sites, characterize the most important habitat types, and discuss the main threats to biodiversity in these systems.

Geographical setting

With an area of approximately 7,200 km^2, the Iron Quadrangle (IQ) is located in southeastern Brazil (19°30′– 20°31′ S, 43°00′–44°30′ W), at the heart of the country's wealthiest region and embracing one of Brazil's largest urban centres represented by the city of Belo Horizonte and surroundings (Fig. 1). Within it, quartzitic, granitic and hematitic outcrops occur interspersed, throughout the mountain tops that compose the southern end of the Espinhaço Range, an orographic formation which runs N–S and has a maximum altitude of ca. 2018 m. The climate is tropical sub-humid and the IQ region, in spite of a mean annual precipitation of 1,500–1,900 mm, may be subjected to water deficit of 5–7 mo (April–October) during winter (Nimer and Brandão 1989). The region harbors the headwaters of important Brazilian watersheds.

Floristically, the Espinhaço Range is one of the leading diversity regions in South America (Giulietti et al. 1997; Rapini et al. 2002). Within it, the IQ lies at the fringe of two major domains, which are the two Brazilian hotspots: the Atlantic Rainforest and the *cerrado* or Brazilian savanna (Mittermeier et al. 2004). This unique setting served as colonization sites for vegetation requiring more xeric conditions, and Austral-Antarctic and temperate *taxa*, during the fluctuating climates of the Late Tertiary and Quaternary (Ledru et al. 1998; Pennington et al. 2004).

The region is also one of the most important mineral provinces in the world (Spier et al. 2003), making Brazil the second largest world producer of iron ore, of which about 75% is extracted from the IQ, where currently about 50 opencast mines are in activity (DNPM 2005). Opencast mining entirely destroys the plant cover, so it is considered a high environmental impact activity (Toy and Griffith 2001; Toy et al. 2001; Teixeira and Lemos-Filho 2002). The Brazilian annual production is expected to increase 3% yearly and reach an annual production of 281 million tons of iron ore by 2010, in order to supply domestic and international demands (DNPM 2005).

Geomorphology

The IQ lies within a region of geologically very old substrate, with stratigraphic sequences of Archaean (gneiss, granites, basalts, greenstones, and sedimentary rocks) and Paleoproterozoic (chemical sedimentary rocks—banded-iron formations—and

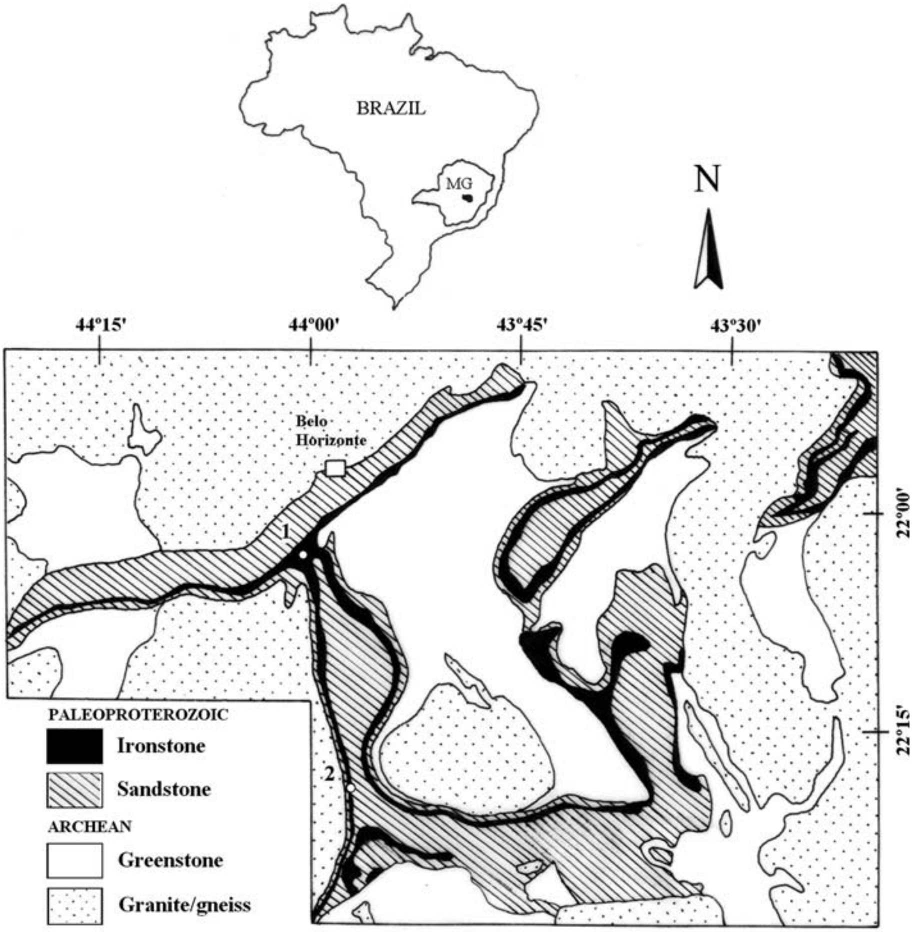

Fig. 1 Geomorphology of the Iron Quadrangle (SE Brazil) and location of study sites 1 and 2 (modified from Alkmim and Marshak 1998). Ironstone outcrops emerge as small isolated areas exclusively over ironstone (in black).

sandstone) origin (Marshak and Alkmim 1989). During the Paleozoic and the beginning of the Mesozoic, extensive erosive processes gave place to the modern landscape (Frakes and Crowell 1969), where banded-iron formations (BIFs) and sandstone were isolated by regressive erosion, and ended as high ridges protruding amidst softer rock terrain (Alkmim and Marshak 1998).

Canga is a Brazilian term for a superficial hematitic deposit. In the IQ, *cangas* form real ironstone islands on the mountaintops formed by BIFs. After intense tectonic events in the Proterozoic, these BIFs were folded and underwent metamorphosis, originating itabirites (metamorphosed iron-formation composed of iron oxides, silica and quartz). Weathering throughout the Paleozoic, Mesozoic and Tertiary made possible the in situ formation of *canga*, by cementing fissures containing itabirite and hematite with other minerals, particularly limonite. Simultaneously, dolomite and quartz were dissolved, increasing the percentage of iron content (Simmons 1963).

Chemical and mineralogical variations during sedimentation processes resulted in different types of BIFs. These gave place to crusts that are highly cohesive, have very low erodibility and permeability, and varying degrees of porosity (Klein 2000; Spier et al. 2003). Therefore, even on local scales, *canga* crusts may reveal different chemical and physical characteristics. Individual crusts may be up to 30 m thick, and extend through an area of 1.75 km^2 (Simmons 1963).

Vegetation

Floristic composition

The total area covered by ironstone outcrops in the IQ is small, estimated in ca. 100 km^2 (Dorr 1964). Considering this, a floristic bimonthly survey of two study sites (Fig. 1) throughout 18 months suggests the existence of a very rich flora in these ecosystems. A total of 234 species of vascular plants was found, distributed among seven fern families and 57 of angiosperms (Table 1). This represents about 26% of all the families that occur in Brazil, recognized as one of the countries with greatest plant diversity.

The sites, distant only 32 km apart, had 138 (Site 1, 1,460 m altitude) and 160 (Site 2, 1,560 m altitude) species each, of which only 27% were common to both. This indicates a high beta diversity for these communities, which is expected for tropical rock outcrops in general, due to their isolation (Burke 2003), and is probably enhanced by local geomorphological traits. The high alpha diversity, however, is a characteristic not shared by all tropical outcrops. Granite outcrops associated with the Brazilian Atlantic forest for example, are far more diverse than similar habitats in Africa, and this difference was attributed to the rich species-pool in the surrounding habitat (Porembski and Barthlott 1997; Porembski et al. 1998). Similarly, both our sites are surrounded by tropical seasonal semi-decidual forests and *cerrado* (savanna) vegetation, two formations with high diversity.

Monocots corresponded to 14 families and 68 species. Compared to the vegetation of granite outcrops (Porembski et al. 1998; Meirelles et al. 1999), ironstone outcrops have more eudicots and basal groups (Magnoliid complex), although most of them are not abundant. Some dominant eudicots, however, like *Mimosa calodendron* and *Lychnophora pinaster*, play an important role in community structuring, providing mesic microenvironments for the establishment of other species. Ironstone outcrops are dominated by phanerophytes, well represented among the eudicots and basal groups. Monocots register a large proportion of chamaephytes and hemicryptophytes. Only four geophytes (*Habranthus irwinianus*, *Sinnigia rupicola*, *S. allagophylla*, *Alstroemeria plantaginea*) and two therophytes (*Sida glaziovii*, *Borreria* cf. *capitata*) were present in our survey. These two life forms are also comparatively underrepresented in other Brazilian outcrops (Meirelles 1999; Ribeiro and Medina 2002; Conceição and Piran 2005).

The most speciose families in the outcrops were Asteraceae (32 spp.), Orchidaceae (15 spp.), Poaceae (14 spp.), Melastomataceae (12 spp.), Cyperaceae and Myrtaceae (10 spp. each), Fabaceae and Rubiaceae (8 spp. each), Bromeliaceae, Solanaceae and Velloziaceae (7 spp. each). Except for Solanaceae, particularly *Solanum*, typical of ecotone areas like forest edges and Atlantic montane rainforest of

Table 1 Species list from two ironstones outcrops in the Iron Quadrangle, Brazil

Family	Species	Site	Ht
Ferns			
Aspleniaceae	*Asplenium auritum* Sw.	2	TA
Blechnaceae	*Blechnum cordatum* (Desv.)Hieron.	2	TA
Grammitidaceae	*Melpomene* sp.	2	TA
Hymenophyllaceae	*Trichomanes rigidum* Sw.	2	CE
Lomariopsidaceae	*Elaphoglossum* sp.	2	TA
Polypodiaceae	*Microgramma squamulosa (Kaulf.)de la Sota*	1,2	TA
	Phlebodium pseudoaureum Cav.	2	TA
	Pleopeltis macrocarpa (Willd.)Kaulf.	2	TA
	Polypodium minarum Weath.	1	RF
	Polypodium sp.	1,2	TA
Pteridaceae	*Doryopteris ornithopus* (Hook. & Baker)J. Sm.	2	RF
	Doryopteris sp.	2	RF
Magnoliid complex			
Annonaceae	*Guatteria sellowiana* Schltdl.	1	TA
	Guatteria villosissima A.St.-Hil.	2	TA
Aristolochiaceae	*Aristolochia smilacina* Duch.	2	SC
Lauraceae	*Ocotea* cf.*pulchella* Mart.	2	SC
	Ocotea tristis Mart. ex Nees	1,2	TA,SC
	Ocotea sp.	1	TA
Piperaceae	*Peperomia decora* Dahlst.	1	RF,SC
	Peperomia gallioides Kunth	1,2	TA
Monocots			
Amaryllidaceae	*Habranthus irwinianus* Ravenna	1,2	SC,MM
Alstroemeriaceae	*Alstroemeria plantaginea* Mart.	1,2	SC,TA
Araceae	*Anthurium megapetiolatum* E.G.Gonç.	2	TA
	Anthurium minarum Sakuragui & Mayo	1	MM
	Anthurium scandens Engl.	2	TA
Bromeliaceae	*Aechmea bromeliifolia* (Rudge)Baker	1,2	SC,TA
	Aechmea nudicaulis Griseb.	2	SC,TA
	Billbergia minarum L.B.Sm.	1,2	SC,TA
	Cryptanthus schwackeanus Mez	1,2	SC
	Dyckia cf. *simulans* L.B.Sm.	1,2	MM
	Tillandsia geminiflora Brongn.	2	TA
	Vriesea minarum L.B.Sm.	1,2	MM
Commelinaceae	*Commelina erecta* Chapm.	1,2	CE,TA
	Dichorisandra hexandra Standl.	1	TA
Cyperaceae	*Bulbostylis fimbriata* C.B.Clarke	1,2	MM
	Cyperus aggregatus Endl.	2	RF,SC
	Eleocharis minima Kunth	1	EP
	Lagenocarpus rigidus Nees	1,2	MM
	Rhynchospora consanguinea Boeckeler	1	EP
	Rhynchospora exaltata C.B.Clarke	2	SC
	Rhynchospora setigera Boeckeler	1,2	MM
	Rhynchospora tenuis Link	2	MM
	Scleria acanthocarpa Boeckeler	2	SC
	Trilepis lhotzkiana Nees	1,2	MM
Eriocaulaceae	*Eriocaulon* sp.	1	EP
	Paepalanthus sp.	2	CE
Iridaceae	*Neomarica rupestris* (Ravenna)N.S.Chukr	2	SC
	Sisyrinchium sp.	2	SC
	Sisyrinchium vaginatum Spreng.	1	SC
Juncaceae	*Juncus* sp.	1	RP

Table 1 continued

Family	Species	Site	Ht
Orchidaceae	*Acianthera teres* (Lindl.)Borba	1,2	MM
	Bifrenaria sp.	1,2	MM
	Epidendrum secundum Vell.	1,2	SC
	Habenaria sp.	1	SC
	Maxillaria madida Lindl.	2	MM,TA
	Oncidium blanchetii Rchb.f.	1,2	SC
	Oncidium gracile Lindl.	1	SC
	Oncidium warmingii Rchb.f.	1	SC
	Prosthechea vespa (Vell.)W.E.Higgins	1,2	MM
	Sacoila lanceolata (Aubl.)Garay	1	SC
	Sarcoglottis schwackei Schltr.	1	SC
	Sophronitis caulescens (Lindl.)Van den Berg & M.W.Chase	1,2	MM
	Sophronitis crispata (Thunb.)Van den Berg & M.W.Chase	1,2	SC
	Sophronitis liliputana (Pabst)Van den Berg & M.W.Chase	2	MM
	Zygopetalum maculatum (Humb.,Bonpl. & Kunth)Garay	1	TA
Poaceae	*Andropogon bicornis* L.	1	EP
	Andropogon ingratus Hack.	1,2	RF,SC
	Axonopus siccus Kuhlm.	1,2	MM
	Chusquea nutans L.G.Clark	2	SC
	Melinis minutiflora P.Beauv.	1	SC
	Panicum sellowii Nees	1,2	SC,TA
	Paspalum erianthum Nees ex Trin.	2	RF,SC
	Paspalum minarum Hack.	2	RF,SC
	Paspalum polyphyllum Nees ex Trin.	2	RF,SC
	Paspalum scalare Trin.	1,2	MM
	Schizachyrium tenerum Nees	2	RF,SC
	Sporobolus acuminatus Hack.	2	RF,SC
	Sporobolus aeneus Kunth	2	RF,SC
	Sporobolus metallicolus Longhi-Wagner & Boechat	1	RF,SC
Smilacaceae	*Smilax ridida* Russ. ex Steud.	2	SC
Velloziaceae	*Barbacenia tricolor* Mart.	1	MM
	Vellozia caruncularis Mart. ex Seub.	1	MM
	Vellozia compacta Mart.	1,2	MM
	Vellozia crassicaulis Mart. ex Schult. f.	1	MM
	Vellozia graminea Pohl	1	MM
	Vellozia minima Pohl	2	MM
	Vellozia sp.	2	MM
Xyridaceae	*Xyris* sp.	2	MM
Eudicots			
Acantaceae	*Justicia riparia* Kameyama	1	TA
	Ruellia villosa Lindau ex Glaz.	1	SC
	Staurogyne minarum Kuntze	2	TA
Apiaceae	*Eryngium* sp.	2	SC
Apocynaceae	*Ditassa linearis* Mart.	1,2	RF,SC
	Ditassa mucronata Mart.	1,2	RF,SC
	Mandevilla sp.	2	SC,TA
Araliaceae	*Hydrocotyle quinqueloba* Ruiz & Pav.	2	SC
Asteraceae	*Achyrocline chionaea* (DC.)Deble & Marchiori	1	CE
	Ageratum fastigiatum (Gardn.)R.M.King & H.Rob.	1,2	SC,TA
	Ageratum myriadenium R.M.King & H.Rob.	1	SC
	Baccharis pingraea DC.	1,2	SC,TA
	Baccharis reticularia DC.	1,2	SC
	Bidens segetum Mart. ex Colla	1	SC,TA
	Chaptalia cf.*martii* (Baker)Zardini	2	RF,SC
	Chromolaena sp.	1	SC

Table 1 continued

Family	Species	Site	Ht
	Dasyphyllum candolleanum (Gardner)Cabrera	1,2	SC,TA
	Eremanthus elaeagnus Sch.Bip.	2	SC,TA
	Eremanthus cf. *glomerulatus* Less.	1	TA
	Eremanthus erythropappus (DC.)N.F.F.MacLeish	2	SC,TA
	Eupatorium sp. 1	1	TA
	Eupatorium sp. 2	1	SC
	Hololepis pedunculata DC.	2	SC
	Koanophyllon adamantium (Gardn.)R.M.King & H.Rob.	1	SC,TA
	Lychnophora pinaster Mart.	1,2	SC
	Lychnophora cf.*reticulata* Gardner	2	SC
	Lychnophora sp.	2	SC
	Mikania cf.*microphylla* Sch.Bip. ex Baker	2	SC
	Mikania sp.	2	SC
	Pseudobrickelia brasiliensis (Spreng.)R.M.King & H.Rob.	1	SC
	Senecio adamantinus Bang.	2	SC
	Senecio pohlii Sch. Bip. ex Baker	2	SC
	Senecio sp.	2	SC
	Stevia sp.	2	SC
	Symphyopappus brasiliensis (Gardner)R.M.King & H.Rob.	1,2	SC,TA
	Trichogonia sp.	1	SC
	Trixis vauthieri DC.	1	SC
	Trixis sp.	2	SC
	Vernonia buddleiifolia Mart. ex DC.	2	SC
	Vernonia sp.	2	SC
Begoniaceae	*Begonia rufa* Thunb.	1,2	SC,CE
	Begonia sp.	1	CE
Bignoniaceae	*Arrabidea* sp.	1	SC
	Pyrostegia venusta (Ker-Gawl.)Miers	2	SC
Cactaceae	*Arthrocereus glaziovii* (K.Schum.)N.P.Taylor & D.C.Zappi	1,2	RF,SC
Celastraceae	*Maytenus gonoclada* Mart.	1	TA
Campanulaceae	*Lobelia camporum* Pohl	2	SC
	Siphocampylus sp.	2	CE
Clusiaceae	*Clusia arrudae* Planchon & Triana	1	SC,TA
Hypericaceae	*Vismia parviflora* Cham. & Schltdl.	2	TA
Convolvulaceae	*Evolvulus filipes* Mart.	1	RF
	Evolvulus sp.	2	RF,SC
	Ipomoea sp. 1	1	SC
	Ipomoea sp. 2	2	SC
	Jacquemontia sp.	1	SC
Ericaceae	*Agarista* cf.*oleifolia* G.Don	2	SC
	Agarista coriifolia (Sleumer)W.S.Judd	1	SC
Euphorbiaceae	*Alchornea triplinervia* (Spreng.)Müll.Arg.	1,2	TA
	Chamaesyce sp.	2	SC
	Croton serratoideus Radcl.-Sm. & Govaerts	1	SC
	Croton sp. 1	2	SC
	Croton sp. 2	2	SC
	Sebastiania glandulosa (Mart.)Pax	1,2	SC
Gentianaceae	*Calolisianthus pendulus* Gilg.	2	SC
Gesneriaceae	*Nematanthus strigillosus* (Mart.)H.E.Moore	2	CE
	Paliavana sericiflora Benth.	1,2	CE
	Sinningia allagophylla (Mart.)Wiehler	2	SC
	Sinnigia rupicola (Mart.)Wiehler	1,2	CE,SC,TA

Table 1 continued

Family	Species	Site	Ht
Fabaceae	*Bauhinia rufa* R.Grah.	1	SC,TA
	Copaifera langsdorffii Desf.	1	TA
	Galactia martii DC.	2	SC
	Macroptilium sp.	2	SC
	Mimosa calodendron Mart.	1	SC
	Mimosa sp.	2	SC
	Periandra mediterranea (Vell.)Taub.	1	SC
	Senna macranthera (Collad.)H.S.Irwin & Barneby	1	TA
Lamiaceae	*Aegiphila verticillata* Vell.	1	TA
	Eriope macrostachya Mart. ex Benth.	1	SC
	Hyptis sp.1	2	SC
	Hyptis sp.2	2	SC
	Vitex sellowiana Cham.	1	TA
Loganiaceae	*Spigelia* sp.1	1	SC
	Spigelia sp.2	2	SC
Loranthaceae	*Struthanthus flexicaulis* (Mart.)Mart.	1	RF,SC,TA
	Tripodanthus acutifolius Tiegh.	1	RF,SC,TA
Lythraceae	*Cuphea thymoides* Cham. & Schltdl.	1	SC
Malvaceae	*Sida glaziovii* K.Schum.	1	SC
Melastomataceae	*Cambessedesia* sp.	2	SC
	Leandra australis (Cham.)Cogn.	1,2	SC,TA
	Marcetia taxifolia DC.	2	SC
	Miconia corallina Spring ex Mart.	1,2	SC
	Miconia cf. *sellowiana* Naudin	2	TA
	Microlicia crenulata Mart.	2	SC
	Microlicia sp.1	2	SC
	Microlicia sp.2	1	SC
	Tibouchina cordifolia Cogn.	2	SC
	Tibouchina multiflora Cogn.	1,2	SC
	Tibouchina sp.	1	SC
	Trembleya parviflora Cogn.	2	SC
Malpighiaceae	*Byrsonima variabilis* A.Juss.	1,2	SC
	Heteropteris campestris A.Juss.	1	SC
	Heteropteris sp.	2	SC
	Peixotoa tomentosa A.Juss.	1,2	SC
Meliaceae	*Cabralea canjerana* (Vell.)Mart.	1	TA
Myrsinaceae	*Myrsine coriacea* Sieber ex DC.	1,2	TA
	Myrsine umbellata Mart.	2	TA
Myrtaceae	*Eugenia cavalcanteana* Mattos	2	TA
	Eugenia sonderiana O.Berg	1,2	TA
	Myrceugenia alpigena (DC.)Landrum	2	SC,TA
	Myrcia eriocalyx DC.	1	SC,TA
	Myrcia mutabilis (O.Berg)N.J.E.Silveira	1,2	TA
	Myrcia obovata Nied.	1,2	TA
	Myrcia splendens DC.	1,2	TA
	Myrcia subcordata DC.	2	TA
	Psidium sp.	2	TA
	Siphoneugena densiflora O.Berg	1,2	TA
Nyctaginaceae	*Guapira opposita* (Vell.)Reitz	1,2	TA
Ochnaceae	*Ouratea semiserrata* Engl.	1,2	SC,TA
Onagraceae	*Fuchsia* cf.*regia* (Vell.)Munz	2	TA
Orobanchaceae	*Esterhazya splendida* Mikan	2	SC
Passifloraceae	*Passiflora villosa* Vell.	2	SC,TA

Table 1 continued

Family	Species	Site	Ht
Phyllanthaceae	*Phyllanthus submarginatus* Müll.Arg.	2	CE
Portulacaceae	*Portulaca hirsutissima* Cambess.	1	SC
Rubiaceae	*Borreria* cf. *capitata* (Ruiz & Pav.)DC.	1,2	SC
	Coccocypselum aureum Cham. & Schltdl.	1	TA
	Coccocypselum lanceolatum Person	1,2	TA
	Cordiera concolor Cham.)Kuntze	1,2	SC,TA
	Diodia sp.	2	TA
	Galianthe sp.	2	SC
	Psychotria vellosiana Benth.	1,2	TA
	Psychotria sp.	1	TA
Sapindaceae	*Matayba mollis* Radlk.	1,2	TA
	Paullinia carpopoda Cambess.	1	TA
	Serjania gracilis Radlk.	1,2	TA
Solanaceae	*Brunfelsia brasiliensis* (Spreng.)L.B.Sm. & Downs	1	TA
	Solanum cladotrichum Dunal	1,2	TA
	Solanum didymum Dunal	1	TA
	Solanum isodynamum Sendtn.	2	TA
	Solanum refractifolium Sendtn.	1	TA
	Solanum stenandrum Dunal	1,2	SC
	Solanum subumbellatum Vell.	1	TA
Verbenaceae	*Lantana camara* L.	1,2	SC,TA
	Lippia gracilis Phil.	1	SC
	Lippia sp.	2	SC
	Stachytarpheta confertifolia Moldenke	2	SC
	Stachytarpheta glabra Cham.	1	SC

Ht = habitat types. CE = crust edges and cave entrances; EP = ephemeral small ponds; MM = Monocotyledonous mats; RF = rock fissures; SC = soil-filled depressions, steps and crevices; TA = tree associations. See Fig. 1 for site locations

SE Brazil (Oliveira-Filho and Fontes 2000), all the other families of this shortlist are among the most characteristic *taxa* of the Espinhaço Range *cerrado* and quartzitic *campos rupestres* (Giulietti et al. 1987, 1997).

The most common species were the shrubs *Baccharis reticularia*, *Lychnophora pinaster*, *Tibouchina multiflora*, the orchids *Acianthera teres* and *Sophronitis caulescens*, the grasses *Andropogon ingratus* and *Paspalum scalare*, and the sedges *Bulbostylis fimbriata* and *Lagenocarpus rigidus*.

Surviving on ironstone outcrops

Plant species of ironstone outcrops, like those of other geological typologies of rock outcrops, are subjected to stressful environmental factors. Overall, they are compact, hard substrates with thin soils that are poor in nutrients, highly acidic, and with low water content (Giulietti et al. 1997). Soils of ironstone outcrops have an additional stress factor, represented by high levels of heavy metals (Porto and Silva 1989; Silva 1992; Teixeira and Lemos-Filho 2002; Vincent 2004). Moreover, climatic features also impose stressful conditions to plant establishment, such as high UV incidence, high daily temperature amplitude, winds, and low relative humidity of air. Additionally, the IQ undergoes a severe dry season, eased only by mist and dew in higher altitudes (Giulietti et al. 1997).

Plants growing on rock outcrops show morphological and physiological adaptations to these environmental constraints. Some xeromorphic characters that provide protection against water loss are coriaceous, thickened, waxy, or hairy leaves, protected stomata, strong imbricate insertion of leaves, and the presence of water-storing parenchymatous tissues (Giulietti et al. 1987, 1997). Increased water uptake is promoted by special roots with velamen and pseudobulbs in orchids, water tanks, scales and trichomes in bromeliads, and velamen, adventitious roots between the stem, and a layer of remnant leaf-sheaths in pseudostems of Veloziaceae (Giulietti et al. 1997). Waxy or hairy leaves also help to avoid over-heating.

Physiological adaptations to water deficits include control of stomata activity, CAM strategy, and poikilohydry—the ability to survive to almost complete desiccation (Gaff 1977, 1987). During the dry season, some species of *canga* lose partially (chamaephytes and hemicryptophytes) or totally (geophytes) their aboveground portion, maintaining only belowground organs, such as bulbs, xylopods, and tuberous roots. East Brazilian rock outcrops, mainly in the Minas Gerais state, are a diversity centre of poikilohydric vascular plants (Gaff 1987). These ‘resurrection plants’ represent one of the most characteristic life-strategies on granitic outcrops (Porembski et al. 1998). In *canga* outcrops, this adaptation is found in mosses, the fern *Polypodium minarum*, the Cyperaceae *Trilepis lhotzkiana*, and most probably in all *Vellozia*.

Crassulacean acid metabolism (CAM) is characteristically a stress-resistance mechanism that optimizes water-use efficiency in plants (Scarano 2002). This adaptation occurs in the bromeliads *Aechmea bromeliifolia* and *A. nudicaulis* (Sayed 2001), which are epiphytes in rainforests and epilithic on *canga* outcrops. *Clusia*, the only true dicotyledonous tree (Lüttge 2004), with 12 species reported to exhibit CAM (Sayed 2001), is an important nurse plant in stressful sandy habitats at the periphery of the Atlantic rainforest complex (Scarano 2002), and also plays this role in ironstone outcrops, together with bromeliads. It is worth noting that CAM is not a common feature of granite outcrop plants (Scarano et al. 2001), where the main nurse plants are bromeliads, Velloziaceae and mosses. In *canga* outcrops, not only these plants but also several eudicots such as *Mimosa calodendron*, *Microlicia crenulata*, and *Lychnophora pinaster* provide germination sites underneath them, where their own litter promotes pileup of organic matter and moisture retention.

High metal concentrations are toxic, probably causing dwarfness in plants (Porto and Silva 1989). Metal accumulation was recorded in leaves and roots of several savanna trees and shrubs in IQ *cangas* (Teixeira and Lemos-Filho 1998) and in Carajás, northern Brazil (Silva 1992). Leaves of *Eremanthus erythropappus and E. glomerulatus* (Asteraceae), *Microlicia crenulata and Trembleya laniflora* (Melastomataceae) growing on nearby ironstone soils (about 5 km from Site 2) exhibited accumulation of Zn, Fe, Mn, and Cu (Teixeira and Lemos-Filho 1998). Species of *Vellozia* were classified as metal accumulators (Antonovics et al. 1971; Brooks 1998), suggesting adaptations to high metal concentrations in Velloziaceae. These examples and the high metal concentrations in ironstone soils (Teixeira and Lemos-Filho 2002; Vincent 2004) suggest the occurrence of many metallophytes in *cangas*, or at least metal-tolerant species. Adaptations to high metal concentration have evolved independently many times in different phylogenetic lineages, as both ancient and recent processes (Broadley et al. 2001).

Vegetative reproduction is an advantage in stressful and unpredictable habitats. Clonal growth was observed in 48 species (about 21% of the total and 70% of the monocots). The production of ramets (identically genetic modules that may become independent, Cook 1983) allows to distribute resources among them, and grants a high reproductive success in these habitats.

Habitat types

Ironstone outcrops are a mosaic of smooth surfaces, fissures, holes, depressions and boulders, usually on flat or smoothly inclined terrain on top of ridges, and interrupted abruptly at the edges. Each of these microhabitats is occupied by a distinct plant community, distributed according to microtopography, substrate characteristics, and soil structure, depth, and moisture (Fig. 2). The most common habitat types in our study sites are described below, and illustrated with representative species. We followed a fairly established categorization for rock outcrop habitat types (Barthlott et al. 1993, Porembski et al. 1994, Porembski and Barthlott 2000), with some adaptations.

Exposed rock surfaces: are flat, smooth surfaces exposed to intense radiation. They are usually covered only by lichens and cyanobacteria (e.g. *Cyanothece aeruginosa* (Nägeli) Komárek).

Rock pools: these small permanent pools (1–2 m^2) have a diversity of Euglenophyta (*Trachelomonas*, *Phacus*, *Euglena*), unicellular (*Closterium*) and filamentous (*Oedogonium*) Chlorophyta, Cryptophyta (*Cryptomonas*) and cyanobacteria.

Ephemeral small ponds: are formed during the wet season (3–4 months) in shallow depressions and where the crust is less porous. The substrate is completely covered with *Eriocaulon*. *Evolvulus*, *Rhynchospora*, and*Xyris* occur on the borders.

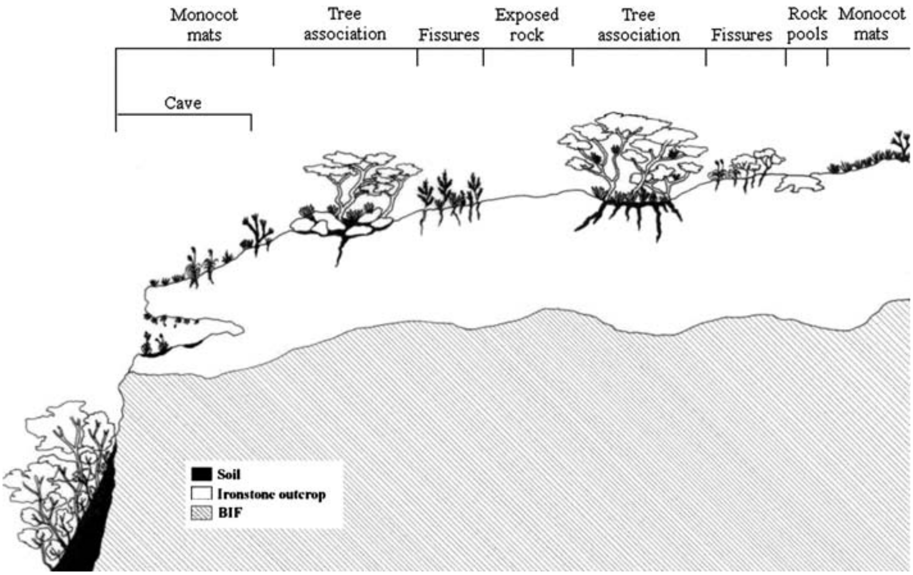

Fig. 2 Schematic representation of the main habitat types on ironstone outcrops in the Iron Quadrangle

Rock fissures: several species of grasses and sedges (e.g. *Andropogon*, *Paspalum*, *Rhynchospora* and *Bulbostylis*) occur in narrow (0.5–1.0 cm width), shallow-soil crevices and fissures. Also common are *Ditassa* and *Evolvulus*.

Soil-filled depressions, steps and crevices: Different kinds of terrain irregularities promote organic matter and moisture retention in shallow (5 cm) soils, where a more robust root system can develop. *Lychnophora pinaster*, *Baccharis reticularia*, *Epidendrum secundum*, *Oncidium blanchetii*, *Mimosa calodendron*, and *Stachytarpheta* thrive in these microhabitats. In turn, several of these species—notably eudicots—act as nurse plants, facilitating germination and seedling survival in a wetter and richer soil.

Monocotyledonous mats: small to very large mats are typical rock outcrop structures. Mats usually start around a fissure or crevice but may then spread clonally over very smooth surfaces. Twenty-five mat-forming species were identified. The most important representatives are *Anthurium minarum*, *Trilepis lhotzkiana*, *Acianthera teres*, *Vellozia graminea*, *Vellozia caruncularis*, and *Xyris*. This number is slightly higher than the one found by Porembski et al. (1998) in East Brazilian inselbergs, considered high and attributed to a large species-pool.

Tree associations: where there is soil accumulation in large amounts (depressions, crevices, termite mounds, or barriers formed by boulder aggregations), small islands of arborescent vegetation occur, usually composed of nearby savanna elements, such as *Eremanthus*, *Myrcia*, *Guateria*, *Alchornea triplinervia* and *Copaifera langsdorffi*. These moist, shaded sites harbor many bryophytes and ferns. *Dichorisandra*, *Tillandsia*, *Coccosypselum*, *Peperomia gallioides* and *Serjania* are only found associated with these islands. Isolated trees such as *Clusia arrudea* and *Myrcia subcordata* also form a mesophytic microhabitat under whose shadow more delicate, forest components like *Anthurium*, *Aechmea*, *Leandra australis*, *Sinningia*, and *Billbergia* are regularly found.

Crust edges and cave entrances: Microhabitats (negative walls or small caves) underneath the border of crusts receive water that seeps from the crust above. Walls are covered by mosses, whereas fissures and small depressions harbor *Paepalanthus*, *Phyllanthus*, and *Paliavana sericiflora*. *Commelina* and *Begonia* are common on the floor. The occurrence of small caves in *canga* edges is fairly frequent (Simmons 1963; Ferreira 2005), but has not been mentioned associated with other rock outcrops.

Endangered ecosystems

Unlike inselbergs in Brazilian Atlantic rainforests, which are of little economic interest and therefore have been reasonably well preserved (Porembski et al. 1998), ironstone outcrops withstand an increasing mining demand. Strip mining removes the top soil, and, after extraction, hardening and impoverishment of the substrate hampers revegetation processes, whether natural or artificial (Teixeira and Lemos-Filho 2002). This is certainly the single most devastating threat to ironstone outcrops in SE Brazil.

Several of the most important community-structuring species are of economic interest and collected illegally, even within public conservation units. Among these, ornamentals like orchids and bromeliads, and medicinal plants like *Lychnophora pinaster*. The IQ region is a heavily populated area, and most ironstone outcrops are close to urban centres, and thus are subjected to the risks of degradation, fire and vandalism. In addition, impacts caused by the proximity of highly populated areas, increasing ecotourism, and mountaineering may encourage the establishment of invasive weeds. The exotic grass *Melinis minutiflora* has already made its way in Site 1 of our study, as well as in other rock outcrops (Porembski et al. 1998; Meirelles et al. 1999; Vincent 2004).

Typical ironstone-restricted species are the cactus *Arthrocereus glaziovii* (Taylor and Zappi 2004) and the bromeliads *Aechmea maculata*, *Dyckia consimilis*, *D. schwakeana*, found only in the IQ (Versieux 2005). The bromeliad *Vriesea minarum* is also endemic to the IQ, and grows over both quartzitic and *canga* outcrops. There are probably many more endemic species yet to be discovered, because these ecosystems, like other tropical outcrops, are of difficult access and still need extensive surveys. Unfortunately, these regions are undergoing tremendous habitat loss leading to species extinction. *Ditassa monocoronata* Rapini (Apocynaceae), discovered in 2001, is an example of this situation. Rapini et al. (2002) believe that this species, found exclusively on two small ridges in the IQ, is on the verge of extinction due to mining activities. It is also certain that further studies will confirm the expectation of a number of metallophytes, but the challenge is overwhelming because, as stressed by Ginocchio and Baker (2004), chances are high that unknown species go extinct before they are ever identified. International concern for the conservation and use of metallophytes in ecological restoration is recent. Among the most promising global initiatives stands the Mining, Minerals and Sustainable Development (MMSD) Project (Whiting et al. 2004).

In view of its distinctive characteristics, notably high alpha and beta diversity, endemism, anthropic pressure, and unique ecosystems such as the one described, the IQ was recently declared officially an area of extreme biological importance (Drummond et al. 2005). Regrettably, economic pressing interests resulting from a growing iron ore market, and few conservation units in the region make a much-needed geobotanical and ecological exploration a challenging endeavor in the immediate future.

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References

Alkmim FF, Marshak S (1998) Transamazonian orogeny in the southern São Francisco Craton Region, Minas Gerais, Brazil: evidence for paleoproterozoic collision and collapse in the Quadrilátero Ferrífero. Precambrian Res 90:29–58

Alves RJV, Kolbek J (1994) Plant species endemism in savanna vegetation on table mountais (Campo Rupestre) in Brazil. Vegetatio 113:125–139

Ambrosi JP, Nahon D (1986) Petrological and geochemical differentiation of lateritic iron crust profiles. Chem Geol 57:371–393

Antonovics J, Bradshaw AD, Turner RG (1971) Heavy metal tolerance in plants. Adv Ecol Res 7:1–85

Barthlott W, Groger A, Porembski S (1993) Some remarks on the vegetation of tropical inselbergs: diversity and ecological differentiation. Biogeographica 69:105–124

Beauvais A, Roquin C (1996) Petrological differentiation patterns and geomorphic distribution of ferricretes in Central Africa. Geoderma 73:63–82

Broadley MR, Willey NJ., Wilkins JC, Baker AJM, Mead A, White PJ (2001) Phylogenetic variation in heavy metal accumulation in angiosperms. New Phytol 152:9–27

Brooks RR (1998) Geobotany and hyperaccumulators. In: Brooks RR (ed) Plants that hyperaccumulate heavy metals: their role in phytoremediation, microbiology, archaeology, mineral exploration and phytomining. CAB International, Cambridge, 384 pp

Burke A (2003) Inselbergs in a changing world – global trends. Divers Distrib 9:375–383

Conceição AA, Pirani JR (2005) Delimitação de habitats em campos rupestres na Chapada Diamantina, Bahia: substratos, composição florística e aspectos estruturais. Bol Bot Univ São Paulo 23(1):85–111

Cook RE (1983) Clonal plant populations. Am Sci 71:244–253

DNPM – Departamento Nacional de Produção Mineral (2005) Ferro. Ministério de Minas e Energia, Brasília

Dorr JN (1964) Supergene iron ores of Minas Gerais, Brazil. Econ Geol 59:1203–1240

Drummond GM, Martins CS, Machado ABM, Sebaio FA, Antonini Y (eds) (2005) Biodiversidade em Minas Gerais: um atlas para sua conservação, 2nd edn. Fundação Biodiversitas, Belo Horizonte, 222 pp

Ferreira RL (2005) A vida subterrânea nos campos ferruginosos. O Carste 17:106–115

Frakes LA, Crowell JC (1969) Late Paleozoic glaciations: I – South America. Geol Soc Am Bull 80:1007–1042

Gaff DF (1977) Desiccation tolerant vascular plants of Southern Africa. Oecologia 31:95–109

Gaff DF (1987) Desiccation tolerant plants in South America. Oecologia 74:133–136

Ginocchio R, Baker AJM (2004) Metallophytes in Latin America: a remarkable biological and genetic resource scarcely known and studied in the region. Rev Chil Hist Nat 77:185–194

Giulietti AM, Menezes NL, Pirani JR, Meguro M, Wanderley MGL (1987) Flora da Serra do Cipó, Minas Gerais: caracterização e lista de espécies. Bol Bot Univ São Paulo 9:1–151

Giulietti AM, Pirani JR, Harley RM (1997) Espinhaço Range region – Eastern Brazil. In: Davis SD, Heywood VH, Herrera-MacBryde O, Villa-Lobos J, Hamilton AC (eds) Centres of plant diversity: a guide and strategy for their conservation, vol 3. The Americas. WWF/IUCN Publications Unit., Cambridge, pp 397–404

Groger A, Barthlott W (1996) Biogeography and diversity of the inselberg (laja) vegetation of southern Venezuela. Biodiv Lett 3:165–179

Ibisch PL, Rauer G, Rudolph D, Barthlott W (1995) Floristic, biogeographical, and vegetational aspects of pre-cambrian rock outcrops (inselbergs) in eastern Bolivia. Flora 190:299–314

Klein C (2000) Geochemistry and petrology of some Proterozoic banded iron-formations of the Quadrilátero Ferrífero, Minas Gerais, Brazil. Econ Geol Bull Soc Econ Geol 95:405–428

Ledru M-P, Salgado-Labouriau ML, Lorsscheitter ML (1998) Vegetation dynamics in southern and central Brazil during the last 10 000 yr B.P. Rev Palaeobot. Palynology 99:131–142

Lüttge U (2004) Ecophysiology of Crassulacean acid metabolism (CAM). Ann Bot 93:629–652

Marshak S, Alkmim FF (1989) Proterozoic contraction/extension tectonics of the Southern São Francisco Region, Minas Gerais, Brazil. Tectonics 8:555–571

Medina BMO, Ribeiro KT, Scarano FR (2006) Plant–plant and plant–topography interactions on a rock outcrop at high altitude in Southeastern Brazil. Biotropica 38:27–37

Meguro M, Pirani JR, Giulietti AM, Mello-Silva R (1994) Phytophysiognomy and composition of the vegetation of Serra do Ambrósio, Minas Gerais, Brazil. Rev Brasil Bot 17:149–166

Meirelles ST, Pivello VR, Joly CA (1999) The vegetation of granite rock outcrops in Rio de Janeiro, Brazil, and the need for its protection. Environ Conserv 26:10–20

Mittermeier RA, Gil PR, Hoffmann M, Pilgrim J, Brooks T, Mittermeier CG, Lamoreux J, Fonseca GAB (eds) (2004) Hotspots revisited. Earth's biologically richest and most endangered terrestrial ecoregions. CEMEX, Mexico

Nimer E, Brandão AMPM (1989) Balanço hídrico e clima da região dos Cerrados. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, 166 pp

Oliveira-Filho AT, Fontes MAL (2000) Patterns of floristic differentiation among Atlantic forests in Southeastern Brazil and the influence of climate. Biotropica 32:793–810

Parmentier I (2003) Study of the vegetation composition in three inselbergs from continental Equatorial Guinea (Western Central Africa): effects of site, soil factors and position relative to forest fringe. Belg J Bot 136:63–72

Parmentier I, Stévart T, Hardy OJ (2005) The inselberg flora of Atlantic Central Africa. I. Determinants of species assemblages. J Biogeogr 32:685–696

Pennington RT, Lavin M, Prado DE, Pendry CA, Pell SK, Butterworth CA (2004) Historical climate change and speciation: neotropical seasonally dry forest plants show patterns of both Tertiary and Quaternary diversification. Phil Trans Royal Soc Lond B 359:515–537

Pirani JR, Mello-Silva R, Giulietti AM (2003) Flora de Grão-Mogol, Minas Gerais, Brasil. Bol Bot Univ São Paulo 21:1–24

Porembski S, Barthlott W (1997) Inselberg vegetation and the biodiversity of granite outcrops. J Royal Soc W Australia 80:193–199

Porembski S, Barthlott W (2000) Granitic and gneissic outcrop (inselbergs) as centers of diversity for desiccation-tolerant vascular plants. Plant Ecol 151:19–28

Porembski S, Fisher E, Biedinger N (1997) Vegetation of inselbergs, quartzitic outcrops and ferricretes in Rwanda and eastern Zaïre (Kivu). Bull Jard Bot Nat Belg 66:81–99

Porembski S, Martinelli R, Ohlemüller R, Barthlott W (1994) Vegetation of rock outcrops in Guinea: granite inselbergs, sandstone table mountains, and ferricretes – remarks on species numbers and endemism. Flora 189:315–326

Porembski S, Martinelli R, Ohlemüller R, Barthlott W (1998) Diversity and ecology of saxicolous vegetation mats on inselbergs in the Brazilian Atlantic rainforest. Divers Distrib 4:107–119

Porto ML, Silva MFF (1989) Tipos de vegetação metalófila em áreas da Serra de Carajás e de Minas Gerais. Acta bot Bras 3:13–21

Rapini A, Mello-Silva R, Kawasaki ML (2002) Richness and endemism in Asclepiadoideae (Apocynaceae) from the Espinhaço Range of Minas Gerais, Brazil – a conservationist view. Biodivers Conserv 11:1733–1746

Reeves RD, Baker AJM, Borhidi A, Berazaín R (1999) Nickel hyperaccumulation in the serpentine flora of Cuba. Ann Bot 83:29–38

Ribeiro KT, Medina BMO (2002) Estrutura, dinâmica e biogeografia das ilhas de vegetação sobre rocha do Planalto do Itatiaia, RJ. Boletim do Parque Nacional do Itatiaia 10:11–82

Sayed OH (2001) Crassulacean acid metabolism 1975–2000, a check list. Photosynthetica 39:339–352

Scarano FR (2002) Structure, function and floristic relationships of plant communities in stressful habitats marginal to the Brazilian Atlantic Rainforest. Ann Bot 90:517–524

Scarano FR, Duarte HM, Ribeiro KT, Rodrigues PJFP, Barcellos EMB, Franco AC, Brulfert J, Deléens E, Lüttge U (2001) Four sites with contrasting environmental stress in southeastern Brazil: relations of species, life form diversity, and geographical distribution to ecophysiological parameters. Bot J Linnean Soc 136:345–364

Silva MFF (1991) Análise florística da vegetação que se cresce sobre canga hematítica em Carajás-PA (Brasil). Bol Mus Para Emílio Goeldi – Ser Bot 7:79–108

Silva MFF (1992) Distribuição de metais pesados na vegetação metalófila de Carajás. Acta bot Bras 6:107–122

Simmons GC (1963) Canga caves in the Quadrilátero Ferrífero, Minas Gerais, Brazil. Nat Speleol Soc Bull 25:66–72

Smith JMB, Cleef AM (1988) Composition and origins of the world's tropicalpine floras. J Biogeogr 15:631–645

Spier CA, Barros SM, Rosière CA (2003) Geology and geochemistry of the Águas Claras and Pico Iron Mines, Quadrilátero Ferrífero, Minas Gerais, Brazil. Miner Depos 38:751–774

Taylor N, Zappi D (2004) Cacti of eastern Brazil. The Royal Botanic Gardens, Kew, pp 499

Teixeira WA, Lemos-Filho JP (1998) Metais pesados em folhas de espécies lenhosas colonizadoras de uma área de mineração de ferro em Itabirito, Minas Gerais. Rev Árvore 22:381–388

Teixeira WA, Lemos-Filho JP (2002) Fatores edáficos e a colonização de espécies lenhosas em uma cava de mineração de ferro em Itabirito, Minas Gerais. Rev Árvore 26:25–33

Toy TJ, Griffith JJ (2001) Changing surface-mine reclamation practices in Minas Gerais, Brazil. Int J Surf Mining Reclam Environ 15:33–51

Toy TJ, Griffith JJ, Ribeiro CAA (2001) Planejamento a longo prazo da revegetação para o fechamento de minas a céu aberto no Brasil Rev. Árvore 25:487–499

Trendall AF, Morris RC (1983) Iron-formation: facts and problems. Elsevier, Amsterdam, 559 pp

Vincent RC (2004) Florística, fitossociologia e relações entre a vegetação e o solo em áreas de campos ferruginosos no Quadrilátero Ferrífero, Minas Gerais. Ph.D. Thesis, Universidade de São Paulo, Brazil

Versieux LM (2005) Bromeliáceas de Minas Gerais: catálogo, distribuição geográfica e conservação. M. Sc. Thesis, Universidade Federal do Rio de Janeiro, Brazil

Whiting SN, Reeves RD, Richards D, Johnson MS, Cooke JA, Malaisse F, Paton A, Smith JAC, Angle JS, Chaney RL, Ginocchio R, Jaffré T, Johns R, McIntyre T, Purvis OW, Salt DE, Zhao FJ, Baker AJM (2004) Research priorities for conservation of metallophyte biodiversity and their potential for restoration and site remediation. Restor Ecol 12:106–116