New Phytologist Supporting Information

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The following Supporting Information is available for this article:

Table S1 Global BBB database

See separate file

A description of the database is given in Notes S1.

Table S2 Carbon reserve compounds in selected BBB species

Examples of carbon reserve compounds recorded for species with different BBB organs. For each species, we include the ecological and biogeographic distribution, plant woodiness (suffrutex refers to plants with herbaceous short-lived shoots from woody bases), and location of the carbon storage reported in the given reference. Note that the energy reserves supporting resprouting are mostly non-structural carbohydrates, usually starch. Nevertheless, many species inhabiting cold or seasonally-dry ecosystems store fructans, particularly Asteraceae and Poaceae (Hendry, 1993; Moraes *et al*., 2016). Fructans not only act as a carbon reserve but also provide resistance to cold, freezing and drought stress (Van den Ende, 2013). Mono- and oligosaccharides might also be present in storage organs, although in many cases they reflect carbohydrate remobilization and utilization (particularly glucose, fructose and sucrose; Martínez-Vilalta *et al*., 2016), rather than carbon storage (but see the raffinose family of oligosaccharides; Van den Ende, 2013). Some monocots store lipids in root tubers (see table). Proteins are also present in some storage organs (particularly root tubers; Pate & Dixon, 1982), but they are essentially a nitrogen reserve, and thus are not in this table. Structural carbohydrates might also contribute to the energy budget supporting resprouting, but evidence is scarce (Braga *et al*., 2006) and so are not considered here. See Notes S1 for the criteria considered in the taxonomic names.

BBB organ	**Species**	**Family**	**Distribution (including realm)**	**Plant woodiness**	**C-storage organ**	**Main C reserve**	**Reference**
Bulb	*Drimia maritima*	Asparagaceae	Mediterranean shrublands – Palearctic	Non-woody	bulb	lipids and polysaccharides	Al-Tardeh *et al*., 2008
Bulb	*Cipura paludosa, C. xanthomelas*	Iridaceae	Several biomes – Neotropics	Non-woody	bulb	starch	Almeida *et al*., 2015
Caudex	*Xanthorrhoea preissii*	Xanthorrhoeaceae	Mediterranean forests to shrublands – Australasia	Non-woody	stem (in desmium)	starch	Lamont *et al*., 2004
Corm	*Stylidium petiolare*	Stylidiaceae	Mediterranean shublands – Australasia	Non-woody	corm	starch	Dixon *et al*., 1983

Corm	*Trimezia cathartica, T. juncifolia*	Trimezieae	Tropical savannas – Neotropics	Non-woody	corm	starch	Almeida *et al*., 2015
Corm-like stem tuber	*Drosera zonaria*	Droseraceae	Mediterranean shrublands – Australasia	Non-woody	stem tuber	starch	Pate & Dixon, 1982
Lignotuber	*Erica arborea, E. scoparia, E. australis*	Ericaceae	Mediterranean shrublands – Paleoarctic & Afrotropics	Woody	lignotuber and root	starch	Canadell & López-Soria, 1998; Cruz & Moreno, 2001; Paula & Ojeda, 2009
Lignotuber	*Eucalyptus obliqua, E. kochii*	Myrtaceae	Temperate and mediterranean woodlands – Australasia	Woody	lignotuber	starch	Carrodus & Blake, 1970; Wildy & Pate, 2002
Non-woody rhizome	*Tussilago farfara*	Asteraceae	Several biomes – Palearctic	Non-woody	rhizome	fructans	Nkurunziza & Streibig, 2011
Non-woody rhizome	*Sasa palmata*	Bambusaceae	Temperate forests – Paleoarctic	Non-woody	rhizome	starch	Magel *et al*., 2005
Non-woody rhizome	*Sisyrinchium vaginatum*	Iridaceae	Tropical forests and savannas – Neotropics	Non-woody	rhizome	raffinose-type oligosaccharides	Almeida *et al*., 2015
Non-woody rhizome	*Echinolaena inflexa*	Poaceae	Tropical savannas – Neotropics	Non-woody	rhizome and root	starch	Souza *et al*., 2010
Non-woody rhizome	*Imperata brasiliensis*	Poaceae	Several biomes – Neoarctic & Neotropics	Non-woody	rhizome	starch	Moraes *et al*., 2013

Rhizophore	*Smallanthus sonchifolius*	Asteraceae	Montane grasslands – Neotropics	Non-woody	rhizophore	fructans	Machado *et al*., 2004
Rhizophore	*Chrysolaena obovata (=Vernonia herbacea)*	Asteraceae	Tropical forests and savannas – Neotropics	Non-woody	rhizophore	fructans	Machado *et al*., 1997
Rhizophore	*Dioscorea kunthiana*	Dioscoreaceae	Tropical savannas – Neotropics	Non-woody	rhizophore	starch	Rocha & Menezes, 1997
Rhizophore	*Smilax goyazana, S. brasiliensis, S. oblongifolia, S. campestris, S. cissoides*	Smilacaceae	Several biomes – Neotropics	Suffrutex	root	starch	Martins *et al*., 2010
Root crown	*Celmisia pugioniformis*	Asteraceae	Montane grasslands – Australasia	Non-woody	root	fructans	Tolsma *et al*., 2007
Root crown	*Quercus ilex*	Fagaceae	Mediterranean forests – Palearctic	Woody	root	starch	El Omari *et al*., 2003
Root crown	*Clidemia sericea*	Melastomataceae	Tropical forests and savannas – Neotropics	Woody	root	starch	Miyanishi & Kellman, 1986
Root tuber	*Chamaescilla corymbosa*	Asparagaceae	Mediterranean shrublands – Australasia	Non-woody	root tuber	oligosaccharides	Shane & Pate, 2015
Root tuber	*Burchardia congesta*	Colchicaceae	Mediterranean forests – Australia	Non-woody	root tuber	starch and fructans	Pate & Dixon, 1982
Root tuber	*Leptoceras menziesii*	Orchidaceae	Mediterranean and temperate forests –	Non-woody	root tuber	starch	Pate & Dixon, 1982

			Australasia				
Root tuber	*Clematis pubescens*	Ranunculaceae	Mediterranean shrublands – Australasia	Woody	root tuber	starch	Pate & Dixon 1982
Root tuber	*Asphodelus aestivus*	Xanthorrhoeaceae	Mediterranean shublands – Palearctic	Non-woody	root tuber	lipids and polysaccharides	Sawidis *et al.*, 2005
Roots, root crown	*Chresta sphaerocephala*	Asteraceae	Tropical savannas – Neotropics	Woody	root	fructans	Appezzato-da-Glória *et al.*, 2008
Roots, root crown	*Cirsium arvense*	Asteraceae	Several biomes – Palearctic	Non-woody	root	fructans	Nkurunziza & Streibig, 2011
Roots, root crown	*Populus tremuloides*	Salicaceae	Temperate forests – Nearctic	Woody	root	starch	Landhäusser & Lieffers, 2002
Stem tuber	*Trixis nobilis*	Asteraceae	Tropical savannas – Neotropics	Suffrutex	stem tuber	fructans	Appezzato-da-Glória & Cury, 2011
Taproot tuber	*Gyptis lanigera*	Asteraceae	Tropical savannas	Non-woody	taproot tuber	fructans	Appezzato-da-Glória *et al.*, 2008
Xylopodium	*Mandevilla pohliana, M. illustris, M. atroviolacea*	Apocynaceae	Tropical forests and savannas – Neotropics	Suffrutex	xylopodium and root	starch	Appezzato-da-Glória & Estelita, 2000; Lopes-Mattos *et al.*, 2013
Xylopodium	*Pterocaulon alopecuroides*	Asteraceae	Tropical forests and savannas – Neotropics	Non-woody	xylopodium	fructans	Appezzato-da-Glória & Cury, 2011
Xylopodium	*Stenocephalum*	Asteraceae	Tropical forests and	Suffrutex	root	fructans	Appezzato-da-

	(Vernonia) megapotamicum, *Lessingianthus elegans*		savannas – Neotropics				Glória & Cury, 2011

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Table S3 Time of origin of BBB for selected lineages

Oldest time of origin of different types of BBB for selected lineages (see Fig. 3 of the main text), with their vegetation types (all fire-prone) and distribution. We include both stem (origin) and crown (diversification) ages (in Ma) extracted from published phylogenies: the specific origin of the trait for the given lineage should be somewhere at or between these ages. Entries under Lineage in parenthesis is the sister lineage that lacks the trait; in some cases (e.g. *Ceanothus*, *Soroveta*), it is possible that the immediate ancestor had the same condition but knowledge is currently inadequate to determine this (so the age of the BBB is conservative in this regard). References include the source of information for the phylogeny and for the trait. BBB listed alphabetically. Heath = sclerophyllous shrubland to 1 m tall, scrub-heath = sclerophyllous shrubland to 2.5 m tall, savanna = (sub)tropical grassland with scattered trees.

BBB	**Family – subfamily**	**Lineage (sister lineage)**	**Stem age** (Ma)	**Crown age** (Ma)	**Vegetation type**	**Current location**	**References**
Belowground caudex	Asphodelaceae – Xanthorrhoeoideae	*Xanthorrhoea* (Asphodeloideae)	59.5	22	Heath, scrub-heath, woodland, forest	Australia	Crisp *et al*., 2014; caudex diagnostic for entire genus
Corm	Iridaceae	*Gladiolus-Melasphaerula* (*Iris*)	~30	26	Heath, scrub-heath	Cape, Mediterranean Basin	Valente *et al*., 2011; corm diagnostic for entire lineage
Lignotuber	Proteaceae – Proteoideae	*Franklandia* (*Isopogon*-Adenanthinae)	81.5 (fossils to 75 Ma)	74	Heath, scrub-heath, woodland	SW Australia	Sauquet *et al*., 2009; He *et al*., 2016b; T. He (unpublished) https://florabase.dpaw.wa.gov.au/
Lignotuber	Myrtaceae – Leptospermoideae	*Melaleuca s.l.* (*Osbornia*)	50	35	Heath, scrub-heath, woodland	Australia	Crisp *et al*., 2011; M. Crisp, pers. comm.
Lignotuber	Rhamnaceae	*Ceanothus* subg. *Ceanothus* (subg. *Cerastes*)	23	12	Heath, scrub-heath, woodland	California	Onstein & Linder, 2016; P. Rundel, pers. comm.
Non-woody	Haemodoraceae	*Haemodoraceae*	89.5	79	Heath, scrub-heath,	S Hemisphere,	He *et al*., 2016a; He &

rhizome		(Pontederiaceae)			woodland, forest	SE USA	Lamont unpubl.
Non-woody rhizome	Ecdeiocoleaceae	*Ecdeiocolea-Georgeantha* (Poaceae)	73.5	59	Heath	SW Australia	Bremer, 2002; https://florabase.dpaw.wa.gov.au/
Non-woody rhizome	Asphodelaceae – Hemerocallidoideae	*Pasithea caerulea* (*Phormium* sub-clade)	56	?	Shrubland, woodland	Peru, Chile	Crisp *et al*., 2014; He & Lamont unpubl.; https://florabase.dpaw.wa.gov.au/
Non-woody rhizome	Asphodelaceae – Hemerocallidoideae	*Agrostocrinum-Dianella-Stypand*	46	42	Shrubland, woodland	SW/SE Australia	Crisp *et al*., 2014; He & Lamont unpubl.
Non-woody rhizome	Restionaceae	*Soroveta ambigua* (*Restio-Elegia* subclade)	31.5	?	Scrub-heath	S Africa	Litsios *et al*., 2014
Non-woody rhizome	Anarthriaceae	*Anarthria-Lyginia-Hopkinsia* (Restionaceae)	91	50	Heath, scrub-heath, woodland	SW Australia	Bremer, 2002; https://florabase.dpaw.wa.gov.au/
Root	Proteaceae	*Banksia elegans* (*B. ilicifolia* lineage)	15.5	?	Scrub-heath	SW Australia	He *et al*., 2011; Lamont *et al*., 2011
Root crown (epicormic*)	Myrtaceae – Leptospermoideae	*Syncarpia-Eucalyptus s.l.* (Leptospermeae-Chamelaucieae)	60.5	60.0	Scrub-heath, woodland, forest	Australia	Crisp *et al*., 2011; M. Crisp, pers. comm.
Root crown	Asphodelaceae – Hemerocallidoideae	*Corynotheca* (*Caesia-Johnsonia*)	46.5	6	Heath, scrub-heath, woodland	SW, NW, C Australia	Crisp *et al*., 2014; https://florabase.dpaw.wa.gov.au/
Root crown (epicormic*)	Proteaceae – Grevillioideae	Lambertinae (*Floydia-Darlingia*)	45.5	35	Scrub-heath, forest	SW, E Australia	Sauquet *et al*., 2009; He & Lamont unpubl.

Root tuber - adventitious	Orchidaceae	Orchidoideae (Epidendroideae)	58	48	Heath, scrub-heath	Cape, SE Africa, Med Basin, Australia	Gustafsson *et al*., 2010; Givnish *et al*., 2015; Lamont & He, 2017
Root tuber - adventitious	Asphodelaceae – Hemerocallidoideae	*Caesia* (*Johnsonia*)	35	?	Heath, scrub-heath, woodland	SW, E Australia, Cape, Madagascar	Crisp *et al*., 2014; https://florabase.dpaw.wa.gov.au/
Root tuber - taproot	Caricaceae	*Jarilla* (*Horovitzia*)	18.3	7.1	Savanna	México, Guatemala	Carvalho & Renner, 2012; Olson, 2002
Stem tuber	Haemodoraceae	*Tribonanthes* (Conostyloideae)	41.8	11.7	Heath, wetland	SW Australia	Pate & Dixon, 1982; He *et al*. , 2016a
Woody rhizome	Proteaceae	Prostrate *Banksia* lineage (shrubby *B. baueri* lineage)	17	12	Heath, scrub-heath, woodland	SW Australia	He *et al*., 2011; Lamont & He 2017
Woody rhizome	Fabaceae – Faboideae	*Millettia makoudensis* (*M.* spp. non-savanna)	12.4	12	Savanna	SW Africa	Maurin *et al*., 2014; Lamont *et al.*, 2017
Xylopodium	Melastomataceae	Microlicieae (*Rhynchanthera)*	17.2	9.8	Savanna (Cerrado)	Brazil	Simon *et al*., 2009 – Fig. S2d

*All species are lignotuberous at the juvenile stage but many outgrow this stage to become epicormic or root-crown resprouters from a main trunk; thus, these lineages can be used to estimate the origin of root-crown resprouting.

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Notes S1 Description of the BBB database

The aim of the BBB database (Table S1) is to provide examples of structures that support belowground bud banks (BBBs) of plants in different ecosystems and regions of the world. The emphasis is on plants indigenous to fire-prone ecosystems (but not exclusively); information on BBBs for non-woody plants in temperate environments is given in Klimešová et al. (2017). The database is largely based on published work, although personal observations of the authors (and collaborators) are also included. However, there is a lot of confusion in the literature about the terminology and definitions of the different BBBs. For instance, there are authors who call any basal resprouter lignotuberous without checking whether the plant actually has a lignotuber or another type of BBB; and various authors use the term rhizome and sobole in different ways. This database reflects our interpretations based on our literature review, and we have provided, for each species, the references on which we have based our interpretation, although the term used in the reference may differ from that accepted in the database. Where we are unsure of the BBB, we use a question mark (?). We discarded references that mentioned a BBB, but the actual BBB was unclear to us. We also avoided including generalizations of some species groups; for instance, most terrestrial orchids have adventitious root tubers, but we only included those for which we have specific references. Thus, the emphasis is on data quality rather than on quantity.

The current version of the BBB database (BBBdb_2017.11) includes 2115 species in 737 genera and 173 families. The database is provided in a spreadsheet (xls format; see Table S1), and includes 2 sheets: *Data*, *References*. The *Data* sheet is explained below, the *Reference* sheet provides the full references to the reference codes mentioned in the *Data* sheet.

The *Data* sheet includes a matrix with species in rows (2115 species + 1 header = 2116 rows) and the following information for each species in columns:

· **Family**: taxonomic family
· **Taxon**: taxonomic binomial name. In general, we used accepted names following the Taxonomic Name Resolution Service (Boyle et al., 2013). For Brazil, we used a local flora (Brazilian Flora, 2020), and for Western Australia the https://florabase.dpaw.wa.gov.au.
· **Woodiness**: presence and distribution of wood in the plant using the following five categories:

Woodiness	Definition
Woody	Woody plant
Herb	Non-woody plant, typically herbaceous
Suffrutex	Subshrub with herbaceous short-lived (or fire-killed) shoots arising from a woody base

Fibrous	Some plants, such as tree-like monocots, tree ferns, cycads, graminoids and bamboos, have a fibrous stem consistency that is neither woody nor herbaceous
Variable	Plant that shows variability or limited information

· **BBB**: belowground bud bank organ; 15 types, see table below for the categories considered and a short definition; for more details see the main text, Box 1, Fig. 1 and Notes S2. Some species may have several BBBs.

BBB type	**Location of the buds**
Root	Lateral roots that give rise to buds ('gemmiferous roots')
Root crown	Root-shoot transition, typically not thickened.
(Thickened) Root crown	Root-shoot transition, often thickened after multiple resprouting events (i.e., burls of secondary origin). Thickened root crowns are often termed 'lignotubers' by many authors, but theses swellings are not present at a young age.
Lignotuber	Basal woody burl (at the root-shoot transition) of shrubs, mallees and small trees much wider than the taproot. They appear when young (burls of ontogenetic origin) and develop at the cotyledonary axils.
Xylopodium	Basal woody burl of some subshrubs that originates from the hypocotyl or the upper part of the main root provided not swollen, or from both, and can also include the base of the stems. Only marginally wider than the taproot.
Basal burl	Basal woody burl of unknown origin. It could refer to a lignotuber, a xylopodium or to enlarged thickened root crown, but we do not have enough information to know which.
Rhizome	Non-woody rhizome, i.e., a subterranean non-woody stem that usually grows horizontally
Rhizophore	Non-woody subterranean stem with downward-facing shoots that produces roots
Woody rhizome	A subterranean woody stem that grows horizontally ('sobole')
Bulb	A globose stem structure composed of outer dry and inner fleshy scales
Corm	Compressed swollen stem that lacks fleshy scales
Stem tuber	Tuber of stem origin
Adventitious root tuber	Swollen, soft, lateral roots of adventitious origin that produce buds
Taproot tuber	Solitary tuber originating from the primary root that produces buds

Belowground caudex	Belowground caudex (non-woody trunk of some palm-like plants)

· **References**: Code for the references that are used to support the BBB type.
· **Biome**: Biogeographical biome where the species occurs, based on Olson *et al*. (2001). The 14 biomes are termed as follows: TrMoist (tropical & subtropical moist broadleaved forests), TrDry (tropical & subtropical dry broadleaved forests), TrConif (tropical & subtropical coniferous forests), TempBroad (temperate broadleaved & mixed forests), TempConif (temperate conifer forests), Taiga (boreal forests), TrGrass (tropical & subtropical grasslands, savannas & shrublands), TempGrass (temperate grasslands, savannas & shrublands), FlGrass (flooded grasslands & savannas), MontGrass (montane grasslands & shrublands), Tundra, Med (mediterranean forests, woodlands & scrub), Desert (deserts & xeric shrublands), Mangrove, several. This is indicative only, and it may be based on details in the references or from other sources; some species may occur in other biomes and this is not fully accounted for here; this column does not aim to be comprehensive but indicative.
· **Realm**: Biogeographic realm as follows: Afrotropic, Antarctic, Australasia, Indo-Malay, Nearctic, Neotropic, Oceania, Palearctic, and Cosmopolitan.
· **Comments**: some comments are included here.

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Notes S2 Types of fleshy underground swellings

Bulb: A globose stem structure with extremely short internodes and composed of outer dry and inner fleshy scales (non-chlorophyllous leaf structures) with a bud at the apex of the compressed stem core. Because the bud is located in the center, it is not only protected by the soil but also by the scales. Bulbs mainly occur among herbaceous monocots (and in a few dicots, Table S1), and are present in many ecosystems, where the bud is protected against many environmental constraints, such as cold, frost, and fire. They are abundant in many fire-prone ecosystems, with some remarkable examples of species with fire-stimulated flowering (e.g. *Rhodophiala advena* (Amaryllidaceae) in Chile; Keeley, 1993; Lamont & Downes, 2011).

Corm: Of the stem origin, this is morphologically similar to the bulb but it lacks fleshy scales and the swollen is compressed. It may possess axillary buds as well as the dominant apical bud as with stem tubers. Corms mainly occur among herbaceous monocots (Table S1). Many cormous species display fire-stimulated flowering (e.g. *Moraea*; Lamont & Downes, 2011).

Stem tuber: This is a localized, swollen, underground shoot that bears nodes, each subtending one or a few buds ('eyes') that may give rise to new, non-swollen shoots. Sometimes, the scars of the primordial leaves (cataphylls) are visible at these nodes. The presence of nodes distinguishes a stem tuber from a root tuber (Box 1). They often terminate non-swollen, horizontally-aligned rhizomes of indefinite length, as in *Solanum* (dicot). In some species, stem tubers are associated with rhizophores (see main text). The BBB organs in *Drosera* behave functionally like corms but are anatomically stem tubers, and thus have been termed pseudocorms or corm-like stem tubers (Conran, 2008). Some droseras produce rhizomes from their tuber (called 'droppers'), especially after fire, that bend down at their tips to produce new organs and can create clones by this process (Dixon & Pate, 1978). Stem tubers are produced annually as overwintering structures in some herbaceous plants of temperate ecosystems. The only stem-tuberous species with fire-stimulated flowering recorded by Lamont & Downes (2011) were droseras, suggesting that this structural type is rare in fire-prone systems.

Root tuber: There are two well-defined types:

Adventitious root tuber: Swollen lateral root of adventitious origin from stem bases that looks similar to a stem tuber but lacks nodes or leaf scars. Usually a plant has multiple tubers at any time whereas others are solitary but are replaced annually (Pate and Dixon 1982). They do not have secondary xylem; they have one or a few buds at their apex that produce a single stem or are stemless above ground. It occurs among monocots in particular and a few dicots. Typical examples include most terrestrial orchids (Table S1), many of which display fire-stimulated flowering (Lamont & He, 2017).

Taproot tuber: Taproot of primary origin, swollen at its base that looks similar to a xylopodium but is soft-wooded at best. Thus it is a solitary (very rarely 2–3), globose or carrot-shaped swelling, sometimes very large in relation to the rest of the plant (e.g. Venter, 2009). One or a few, often ephemeral, stems arise from the apex of the tuber. It is restricted to dicots. Taproot tubers may be non-woody or soft-wooded, i.e., with some secondary xylem (e.g. *Moringa* tuberous shrubs in Olson & Carlquist, 2001), but all are formed almost entirely of axial parenchyma. They are often associated with semiarid as well fire-prone ecosystems, and one of their functions is storing water. They are present in African and South American savannas (Table S1), and have previously been grouped with the subshrub geoxyles (White, 1977; Maurin *et al*., 2014), though they are not woody. While often cultivated for their ornamental basal swellings, it is not appreciated that these are usually located underground in the wild (e.g. *Fockea edulis*, Apocynaceae). Their secondary shoots are usually deciduous (or destroyed by fire) and replaced from a few buds located in the upper part of the swelling.

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Notes S3 Some special cases

Many species have one of the BBB structures described in the main text; however, there are many cases of combinations of different bud-bearing organs. For instance, there are plants that generate an initial burl when young, but later they develop woody rhizomes and knots that connect different rhizomes, as is the case for many geoxyles in savannas (Fig. 2F in the main text), in temperate ecosystems (*Quercus gambelii*; Tiedemann et al., 1987), and in various Australian Myrtaceae species (Lacey, 1974; Lacey & Whelan, 1976). Similarly, the combination of lignotubers and bud-bearing roots that sucker after fire is present in some *Banksia* and *Erica* species (Table S1). Some species with rhizophores also produce stem tubers. We distinguish the non-woody, non-fleshy (wiry) rhizomes typical of graminoids and ferns from the woody rhizomes of some dicots. An exception is the dicotyledonous tree-mistletoe, *Nuytsia floribunda*, that produces long spongy rhizomes (>100 m) from a stem tuber that may exceed 1 m in diameter, and forms clones that may cover several thousand m^2 and is widespread in SW Australia (Lamont & Downes, 2011). Layering involves procumbent or stoloniferous stems that form roots from nodes that touch the ground, sometimes forming fire-resistant knots from which roots and ramets arise (Fig. 1), as in *Poikilacanthus humilis* (Acanthaceae) in the Brazilian savannas (Rachid, 1947).

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