Supplementary information

Appendix S1. Methods for studying bark thickness

Measuring bark thickness

Bark thickness varies ontogenetically with tree size (Fig. 4) and thus any measure of bark thickness should be associated with the diameter of the stem where the bark thickness was measured, and also the location on the tree (i.e., height of the bole, or distance to the tip for branches). Ontogenetic variation in bark thickness can be studied by measuring barks in one individual at different ages, but more typically it is studied across individuals of different sizes in a population. In most cases, variability in bark thickness is related to variability in the outer bark (Jackson et al. 1999, Paine et al. 2010), although inner and outer bark thickness are rarely differentiated (see below) and the relative proportion to total bark thickness varies among species. Hereafter, unless otherwise stated, by bark thickness (BT) I refer to total (inner plus outer) bark thickness.

BT can be measured with a standard bark gauge or by inserting a knife or awl and measuring the depth of penetration. The mean of several readings around the stem are usually calculated. In trees with furrowed bark, there is a tendency to measure over the ridges/plates (maximum bark thickness); however, if the ratio of bark ridges to furrow is not constant over the samples (e.g., over the ontogeny, or across the species), then the measurement may overestimate the heat protection in species or individuals with strongly furrowed bark. When comparing species, there may also be some sampling error due to differences in the bark-wood junction depending on the wood hardness and the sharpness of the gauge or knife. However, these errors tend to be small. Extreme cold conditions (frost) may lead to a pronounced shrinking of the bark (Loris et al. 1999). For a more accurate estimation, a portion of the bark can be extracted from the stem with the help of a knife or chisel and the thickness measured with a caliper. Another advantage of this method is that it is possible to differentiate between inner and outer bark thickness. Contour methods (Adams and Jackson 1995, Schwilk et al. 2013) are more time consuming but enable better estimates to be made of the variability in thickness (total, inner, and outer bark thickness) or bark roughness. For saplings or thin branches, BT measurements are typically performed under a dissecting microscope or by using a digital scanner from the stem cross section. Because most studies have measured BT using a bark gauge, knife or awl, they do not differentiate between the inner and the outer bark (for important exceptions see Jackson et al. 1999, Romero et al. 2009, Paine et al. 2010, Graves et al.

submitted).

Bark measurement can be made in different locations of the plant, which complicates comparison across different studies. For trees, it is typically measured at breast height, while for small trees and shrubs, it is measured at the lower parts of the trunk (e.g., 10cm, 50cm), below stem bifurcation. However, because flames in surface-fire regimes are short, trees sometimes have disproportionally thicker bark at the base. Thus, in such ecosystems it may be important to consider the BT at the lower bole (avoiding basal swelling formations). There is some evidence that the rate at which BT tapers height along the bole varies among species (Wiant and Koch. 1974, Odhiambo et al. 2014, Graves et al. *submitted*) and this could determine survival under relatively high-intensity surface fires.

Bark can also be measured in branches or small twigs (e.g., Paine et al. 2010, Baraloto et al. 2010), and this is especially interesting in ecosystems where the full tree is affected by fire (crown-fire ecosystems, see below). These measures in the branches may have the advantage that readings can be standardized by measuring on a given diameter. If the aim of the measurement is not so much the insulation but the allocation to bark, one possibility is to measure the bark in a branch at a fixed distance from the tip of the branch (e.g., Rosell et al. 2014) or at a fixed age (in plants showing a clear annual growth pattern in branches).

Comparing bark thickness

Bark thickness is typically measured for comparing among species or among habitats. The direct BT value (absolute BT) is not always the most useful information as it depends on the tree size. However, it indicates the absolute resistance to fire and thus it is an appropriate measure when searching for thresholds of BT that enable survival (i.e., the safe bark thickness). For instance, Hoffmann et al. (2012) suggest that in the Brazilian cerrado a BT of 5.9 mm is needed to ensure a 50% chance of surviving a low intensity fire (flame length < 2m) and 9.1 mm for a high-intensity fire (flame length > 2m). These thresholds are not general values as they depend on the intensity of fires in each ecosystem. In fact, different authors have studied the BT required for survival using experimental fires in the lab, and the different values obtained reflect the different fire intensities and flame temperatures simulated (see Tables S2 and S3). Absolute BT values have also been used in databases and floras where BT is often given as an 'average' value for adults.

For comparison purposes, it is often more appropriate to use the relative bark thickness (i.e., bark thickness divided by the diameter; BT/D). For instance, while there is no difference in absolute BT values between afrotropical and neotropical savanna plants, the relative BT is clearly different (Fig. 5b; Dantas & Pausas 2013). However, if the relationship between BT and D is nonlinear, the BT/D may also vary with ontogeny, and so a single value for a species may not always be accurate. In such cases, the best approach is to measure BT for a wide range of diameters and thus to have the full distribution of BT with tree size, and compare species or habitats by appropriate statistical methods, such as a covariance-type analysis (Dantas & Pausas 2013) or using the residuals of the BT-D regression (Paine et al. 2010). Performing comparison using only the linear section of the BT-D relationship has also been proposed (Hempson et al. 2014); however, not all species show a clear linear pattern and for some species this method excludes a considerable amount of information.

Bark thickens with tree growth and thus the thickness of the bark is strongly related to tree diameter through a scaling relationship that follows a power (allometric) function: $\mathrm{BT} = A \cdot \mathrm{D}^b$, where BT is the bark thickness, D the diameter, and b the allometric coefficient (also called a scaling factor or allometric scaling). On a log-log scale this power function yields a linear relationship with intercept $\log(A)$ and slope b that can be estimated by a linear regression; because both BT and diameter are subject to error, major axis regression may be a more appropriate fitting approach than standard regression (Warton et al. 2006). The specific coefficients of this relationship reflect different ontogenetic patterns of bark allocation and can be useful for understanding different plant strategies (Jackson et al. 1999, Hoffmann et al. 2003; Higgins et al. 2012; Schwilk et al. 2013; Poorter et al. 2014). Plants may allocate disproportionately greater resources to BT when small ($b < 1$, negative allometry) such as many savanna trees; or when large ($b > 1$, positive allometry) such as in many closed forests (Table 1); yet other plants may show a linear relationship with diameter ($b \sim 1$, isometry; i.e., BT/D is constant). It is important to note that the allometric coefficient indicates the rate at which bark thickens relative to size (ontogenetically) which is not the same as absolute bark thickness because: 1) different species may attain different sizes and reach different BT; and 2) different species may have different allometric patterns of bark thickness (e.g., negative or positive allometry), and thus the BT function in different species may show ontogenetic crossovers (Fig. 4, Schwilk et al. 2013; Poorter et al. 2014).

One difficulty when comparing BT values among species or ecosystems is that none of these measures reveal the bark growth rate (temporal dimension). For two species with similar BT, or similar relative BT, the species growing more quickly or living in more productive environments would achieve a thicker bark sooner, and thus would be better able to survive a short fire interval. For this reason, it would be informative to measure BT together with tree age. In some cases, the age of the bark can be estimated from annual bark rings (e.g., in *Querucs suber*, Sánchez-González et al. 2008, Surový et al. 2009; in *Magnolia*, Shimomura et al. 1988), or from the number of annual shoot growth segments for bark in branches.

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Supplementary information

Table S1. Examples of different bark thickness values (mean, maximum, and relative values) among pine populations (i.e., within species) living in different fire regimes. *P. radiata* is considered a thick-barked species while *P. halepensis* is thin-barked (He et al. 2012). Asterisks (*) indicate the most frequent habitat of the species; BT: bark thickness; D: diameter; variability in BT mean values (var) expressed as standard error in *P. radiata*, and standard deviation in *P. halepensis*.

Species	Inferred fire regime	BT (cm) mean ± var	BT (cm) max	Mean BT/D (mm/cm)
Pinus radiata (1)	No/low frequency fires (never inhabited)	1.4 ± 0.1	4	0.48
	Frequent surface fires (historically inhabited by Native Americans)*	3.3 ± 0.1	6.6	0.85
Pinus halepesis (2)	Frequent crown-fires*	2.34 ± 0.53	3.7	0.09
	No crown-fires (surface fires)	3.14 ± 0.68	5.0	0.11

* (1) Coastal Californian forests (Stephens & Libby 2006); (2) Spanish eastern coast *P. halepensis* forests, elaborated from own data in Hernández-Serrano et al. (2013).

Table S2. Examples of experimental evidence showing the effect of bark thickness (BT, in mm) on the maximum temperature (°C) reached by the cambium, expressed as an equation with BT as an independent variable. BT_{60} shows the predicted bark thickness threshold to protect the cambium from reaching 60°C (given the heat applied).

Heat source	Maximum cambium temperature (°C)	BT_{60} (cm)	Details and reference
Wick fire, ca. 2.35 min	$1 / (0.0106 + 0.00095 \cdot BT)$	0.64	15 species, eastern Amazon, Uhl & Kauffman (1990)
Kerosene-soaked rope attached to the trunk	$103 - 2.3 \cdot BT$ (*)	1.89	11 species, North American hardwoods, Hengst & Dawson (1994)
Kerosene-soaked rope attached to the trunk	255.9·BT^-0.552	1.40	16 species, dry forest in eastern Bolivia, Pinard & Huffman (1997)
Paraffin saturated rope attached to the trunk	$98 - 3 \cdot BT$ (*)	1.27	7 species, northern Australia, Lawes et al. (2011)
Propane torch to the bark, 400°C, 2 min	172.91·BT^-0.4927	0.86	6 species, North America, VanderWeide & Hartnett (2011)

(*) estimated, equation is not reported in original study

Table S3. Examples of experimental evidence showing the effect of bark thickness (BT, in mm) over time (in seconds) for reaching the temperature that kills cambium tissue (T_k), given the applied temperatures to simulate fire. The effect is expressed as an equation with BT as an independent variable.

Applied temperature (°C)	T_k (°C)	Time to T_k (in seconds)	Details and references
500	60	$2.9 \cdot BT^2$	From a physical model, Peterson & Ryan (1986)
215±20	60	$36 \cdot BT^{1.253}$	Heat from a Bunsen burner, 7 species, induced 100% humidity, Bauer et al. (2010)
215±20	60	$9.1 \cdot BT^{1.401}$	Heat from a Bunsen burner, 6 species, induced 0% humidity, Bauer et al. (2010)
--	50	$0.0327 * BT^{1.982}$	Heat form a paraffin saturated rope attached to the trunk. 7 species, Northern Australia, Lawes et al. (2011)
750	60	$7.25 \cdot BT^{1.62}$	Propylene torch 10 cm in front of the trunk, *Eucalyptus microcarpa*, Wesolowski et al. (2014)
750	60	$1.10 \cdot BT^{2.44}$	Propylene torch 10 cm in front of the trunk, *Eucalyptus leucoxylon*, Wesolowski et al. (2014)
750	60	$169.5 + 24.28 \cdot BT$	Propylene torch 10 cm in front of the trunk, *Eucalyptus tricarpa*, Wesolowski et al. (2014)
400	60	$[0, 78] + [5.5, 17] \cdot BT + [-12.7, 0] \cdot Hr$	Disc at 1 cm heated by electric heat gun, 8 species (introduced and native species), South Africa. Shown are the range of coefficient across species [min, max]; Hr: relative height in the stem; Odhiambo et al. (2014)

References (Tables S1, S2 and S3)

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Figure S1. Example of a typical grass-fueled surface-fire ecosystem, in which the trees are tall, with thick basal bark, and with a clear vertical fuel gap that prevents fires to reach the canopy (the *lofty* strategy in Fig 3). Pine forest in Florida (Photo: J.G. Pausas).

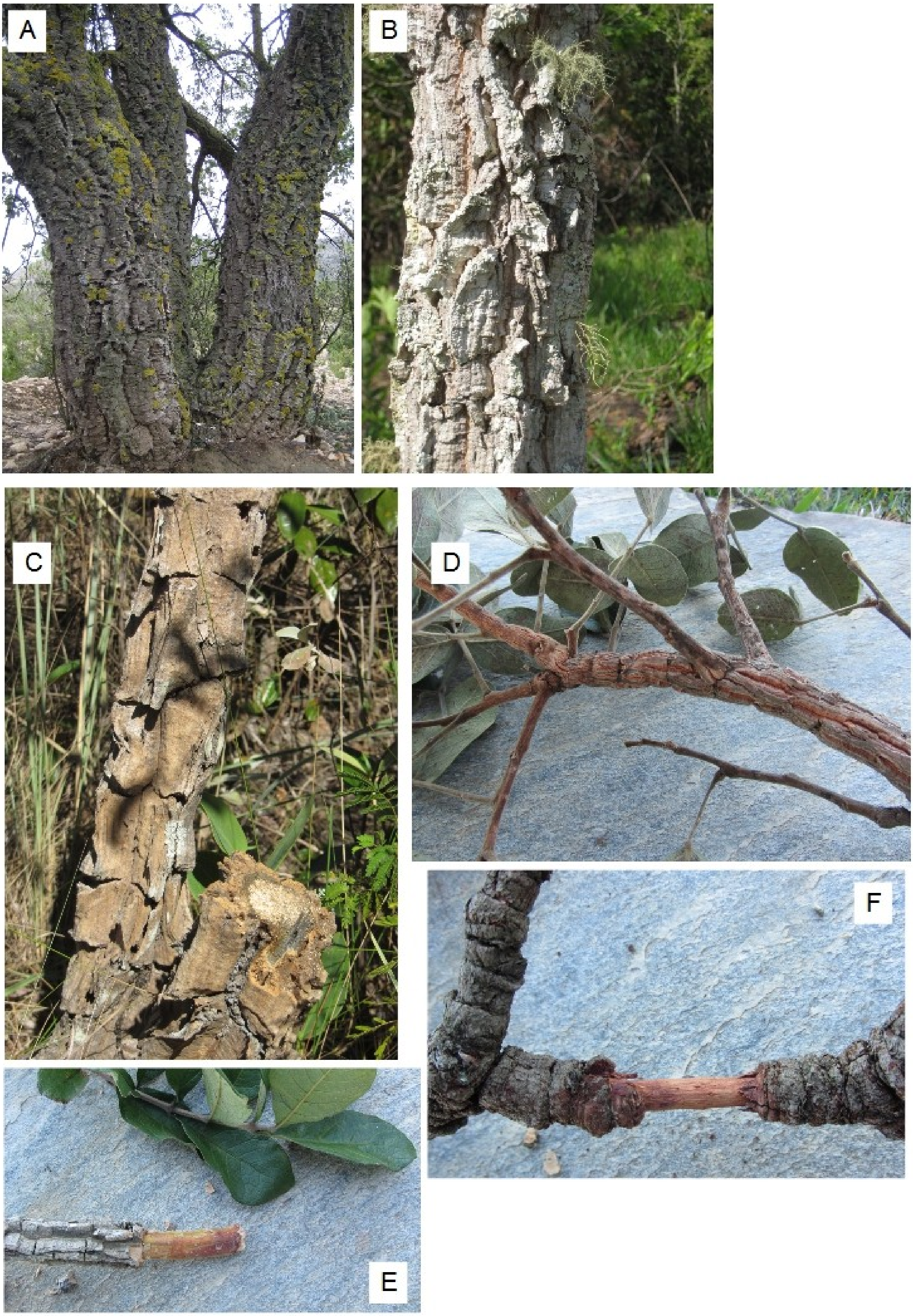

Figure S2. Few examples of trees with strongly suberized corky bark from different lineages (the *corky* strategy in Fig 3). A: *Quercus suber* (Fagaceae), main trunk; B: *Myrcia bella* (Myrtaceae), main trunk; C: *Eremanthus seidelii* (Asteraceae), main trunk with one cutted basal branch; D: *Enterolobium gummiferum* (Fabaceae), small top branch; E: *Aegiphyla lhotzkiana* (Lamiaceae), small top branch with a debarekd section; and F: *Byrsonima verbascifolia* (Malpighiaceae), small top branch with a debarked section. All photographs are from cerrados in Brazil except the first (A) that it is from Spain. Photos by J.G. Pausas, brazilian species determined by R.S. Oliveira.

Figure S3. Example of plants with thin bark living in woody-fueled crown fire ecosystems. The pictures show the plants resprouting from basal bud 6 months after a fire in Valencia (Spain). Left: *Quercus coccifera* resprouting from rizhomes. Right: *Juniperus oxycedrus* resprouting from a lignotuber (Photos: J.G. Pausas).