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Insulation capacity of three bark types of temperate *Eucalyptus* species

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ABSTRACT

Fire plays an increasingly important role in management of native forests and plantations around the world. Thick tree bark represents the most important defence against surface fires, although other bark traits (bark-type, moisture content, density) are also involved. The interplay of bark traits to reduce heat-induced cambium necrosis and related tree death remains poorly understood. Here we introduce a novel method using multiple sensors to accurately measure conductance of heat through the periderm and secondary phloem and to detect how individual bark traits influence the transfer of heat through those tissue types. We employed this method to document the capacity for bark insulation of three *Eucalyptus* species with different bark-type from temperate Australia, simulating a 'worst-case' scenario (750 °C bark surface temperature for 900 s). Thickness of these different bark types ranged from 3 to 65 mm. Our results clearly show the importance of thickness and type of bark for prevention of cambium necrosis due to heat. Coefficients of determination that describe how bark thickness correlates with time to reach lethal temperatures (>60 °C) at the cambium ranged from 0.61 (least effective: *E. tricarpa*, ironbark-type bark, average moisture content = 34%, average bark density = 0.58 g cm^{-3}) to 0.94 (most effective: *E. leucoxylon*, gum-type bark, average moisture content = 54%, average bark density = 0.42 g cm^{-3}) and both followed linear and curvilinear trajectories. The cooling effect of water in the periderm was found to slow conduction of heat towards the cambium. This effect has not previously been documented by empirical measurements and may have significant implications to survival of trees during "cooler" prescribed fires. Our study highlights between-species variation in ability to withstand heat from surface fires. Fire temperatures and duration thus have considerable capacity to change species composition of these Box-Ironbark forests via mortality.

1. Introduction

Fire plays an important role in the dynamics of native and managed forest ecosystems around the world. Both naturally ignited fires as well as fires used as management tools pose risks to tree health. These risks potentially increase under climate change if forests are pre-stressed by high temperatures and shifts in seasonal patterns of precipitation (Golding and Betts, 2008; Nepstad et al., 2008; van Mantgem et al., 2013). Unsurprisingly, these combined risks to tree health highlight the importance of ecosystem-specific knowledge.

Low-intensity management fires, also termed 'prescribed fires', are commonly used in natural forested ecosystems of South (e.g. Kennard and Putz, 2005; Pivello and Norton, 1996) and North America (e.g. Ryan et al., 2013), Europe (e.g. Fernandes et al., 2013) and Australia (e.g. Burrows and McCaw, 2013; Penman et al., 2008). The use of prescribed fire is not limited to native forests and is an increasingly important part of contemporary management of plantations (e.g. de Ronde et al., 1990; Fernandez et al., 2011) where it is used to minimise the risk of catastrophic loss of capital.

Regardless of geography and the type of fire or forest, tree bark is a key protection against heat-related damage. Thickness of bark has long been identified as the trait most readily describing the capacity of a given tree species to avoid cambium necrosis during fires (e.g. Gill and Ashton, 1968; van Mantgem and Schwartz, 2003). Tree bark usually has low thermal conductivity due to its characteristics in heat transfer, including porosity, density and proportion of stored water. Hence, the insulation capacity of bark increases with bark thickness. The vascular cambium, a layer of meristematic cells underneath the periderm, is responsible for the production of secondary phloem and xylem and dies when exposed to lethal temperatures. Studies investigating fire-induced cambium necrosis have reported that temperature ⩾60 °C is the 'instant' lethal temperature (ILT), although exposure to temperatures below 60 °C for long periods can also result in death of the entire cambium (Dickinson and Johnson, 2004; Hare, 1961; Jones

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Nomenclature

Symbol	Description
α_T	rate of increase in temperature (°C s^{-1})
D_b	thickness of bark (mm)
D_b I, II, III	thickness of bark in classes I, II, III (mm)
DBH	stem diameter at breast height (cm)
ILT	instant lethal temperature at cambium ($\geqslant$60 °C)
ρ_b	density of bark (g cm^{-3})
ρ_{bs}	density of secondary phloem (g cm^{-3})
ρ_{bp}	density of periderm (g cm^{-3})
T_{bs}	temperature at the bark surface (°C)
T_c	temperature at the cambium (°C)
$T_{c\ ambient}$	temperature at the cambium prior to heating (°C)
τ_{60}	time required to reach 60 °C at the cambium (s)
τ_{lag}	lag-phase after flame ignition before T_c ambient increases more than 0.5 °C within 5 s
MC_b	moisture content of bark (%)
MC_{bs}	moisture content of secondary phloem (%)
MC_{bp}	moisture content of periderm (%)
MC_{b50}, MC_{b75}	moisture content of bark reduced to 50% and 75% of fresh bark

et al., 2006; Kayll, 1963). Tree bark provides protection to the vascular cambium by mitigating the effects of radiant heat. Death of the vascular cambium can be a direct cause of tree mortality as can complete or near-complete scorch of the tree canopy, but indirect effects, such as post-fire diseases, infections, excessive heating of roots or loss of hydraulic conductivity in xylem are also important (Michaletz et al., 2012; Michaletz and Johnson, 2008; Varner et al., 2009).

A number of empirical models have been developed to predict cambium necrosis and tree mortality by fire. These models have been developed for a range of tree species (e.g. Bennett 1992; Costa et al., 1991; Dickinson, 2002; Gill et al., 1986; Jones et al., 2006; Michaletz and Johnson, 2008; Ryan and Reinhardt, 1988). There are, however, difficulties that prevent universal application of these models to all tree species. For example, there is conflicting evidence about the influence of moisture content on the thermal insulation properties of bark (e.g. Bova and Dickinson, 2005; Jones et al., 2004). Water contained within bark helps to prevent combustion of bark fibres. However, the same water can increase conduction and storage of heat in bark during a fire. As a result, high moisture content of bark may result in reduced fire resistance (Agee, 1993; Lawes et al., 2011; VanderWeide and Hartnett, 2011). Other deviances from model predictions can be caused by factors related to the environment (e.g. nutrient or water availability) of a given species, leading to either thinner or thicker bark that in turn affects the capacity to survive a fire event. The interrelationships of fire characteristics (e.g. frequency and intensity), traits related to bark (e.g. thickness, moisture content and density), and tree architecture (e.g. tree height, location of buds) are sufficiently complex that the causes of tree mortality during fires are not yet fully understood (Michaletz and Johnson 2007).

For *Eucalyptus* species that dominate forests and woodlands of temperate Australia, we have remarkably poor knowledge of the insulation capacity of bark. Many eucalypt-dominated ecosystems are highly flammable and over the past decade fires have burnt through millions of hectares of eucalypt forest, often at high intensity (Adams and Attiwill, 2011). Fire is of such significance that it is now listed as a threatening process for many eucalypt ecosystems (Adams and Attiwill, 2011).

We have focused on developing a simple and effective method that allows establishment of species-specific relationships to describe the impact of selected bark traits (i.e. thickness, moisture content, density) on insulation capacity. To test our method, we selected three species of *Eucalyptus* with different bark types (gum bark, box bark, ironbark) as it has previously been shown that bark type could have a profound effect on fire resistance of trees (Gill and Ashton, 1968). We specifically tested the hypotheses that: (1) bark thickness of *Eucalyptus* species from temperate Australia is a key trait for preventing cambium necrosis and (2) our novel method accurately captures differences in conduction of heat through the radial profile of a variety of bark types. Such information will allow us to better understand how water influences the insulation properties of tree bark during fire.

2. Material and methods

2.1. Site description

Bark samples were collected from three common overstorey species in Box-Ironbark forest in central Victoria, Australia (36°45′S, 145°00′E), namely *Eucalyptus microcarpa* Maiden (grey box), *E. leucoxylon* subsp. *pruinosa* F. Muell. ex. Miq (yellow gum) and *E. tricarpa* L.A.A. Johnson and K.D. Hill (red ironbark). The climate of this region is temperate with mean annual maximum temperatures of 21 °C and mean annual minimum temperatures of 8 °C. Mean annual rainfall is 487 mm (Australian Bureau of Meteorology). The site was 171 m above sea level. The study forest had a fire history typical of much of the Box-Ironbark forest, being dominated by prescribed fires at intervals of 10+ years. The study forest had not been burnt for at least ten years at the time of the study. Wildfires in these forests are often small in size.

2.2. Bark characteristics

The species selected represented three different bark types (Fig. 1). The periderm of *E. microcarpa* is a typical 'box-type' where long, persistent bast fibres form an open surface structure that

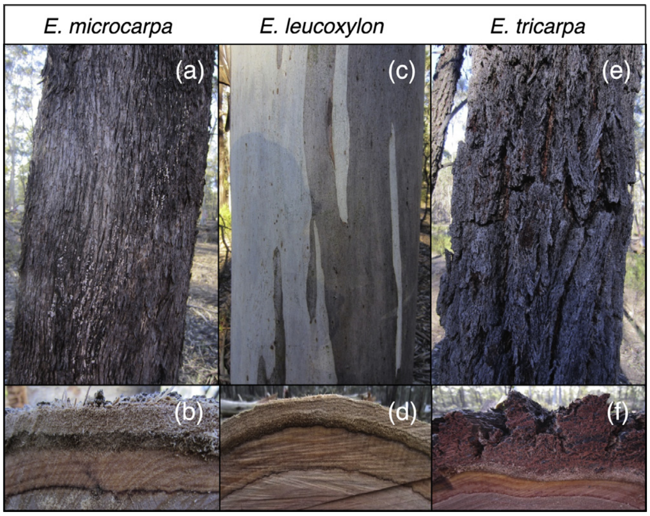

Fig. 1. View of stem (top panels) and transverse plane (bottom panels) of bark types: 'box-type' with persistent bast fibres (a and b), 'gum-type' with smooth surface (c and d), 'ironbark-type' with deeply furrowed periderm (e and f). The sequence of periderm, secondary phloem, sapwood and heartwood can be distinguished in bottom panels.