The 'brown line' and the response of bark to fire

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Abstract
Increasingly, eucalypt plantations are being grown for solid wood production throughout the world. With long rotation lengths (15-40 years), these plantations will likely be exposed to wildfire. In order to minimise the damage from wildfire, fuel loads must be managed and prescribed fire is likely to be the most efficient, cost-effective method available. A study in northern New South Wales, Australia, is looking at the effects of prescribed fire on stem (and wood) quality of Dunn's White Gum (*Eucalyptus dunnii*) and Spotted Gum (*Corymbia variegata.*). These species make up two-thirds of the 26,000 hectare eucalypt plantation estate being managed by Forests NSW. The first round of experimental prescribed burns was completed in August 2005. An interesting phenomenon was observed in the bark of trees that were exposed to elevated temperatures. A brown line appeared in the living tissue of the bark of both species and this line appears to be the depth to which cell death from thermal penetration has occurred. Utilising a thermocouple array on selected trees, the brown line depth was modelled against various temperature parameters. It was found that the brown line was best correlated with the duration of temperature exposure at the bark surface above 200^{o}C and that there was no significant difference in the depth of the brown line between the two species.

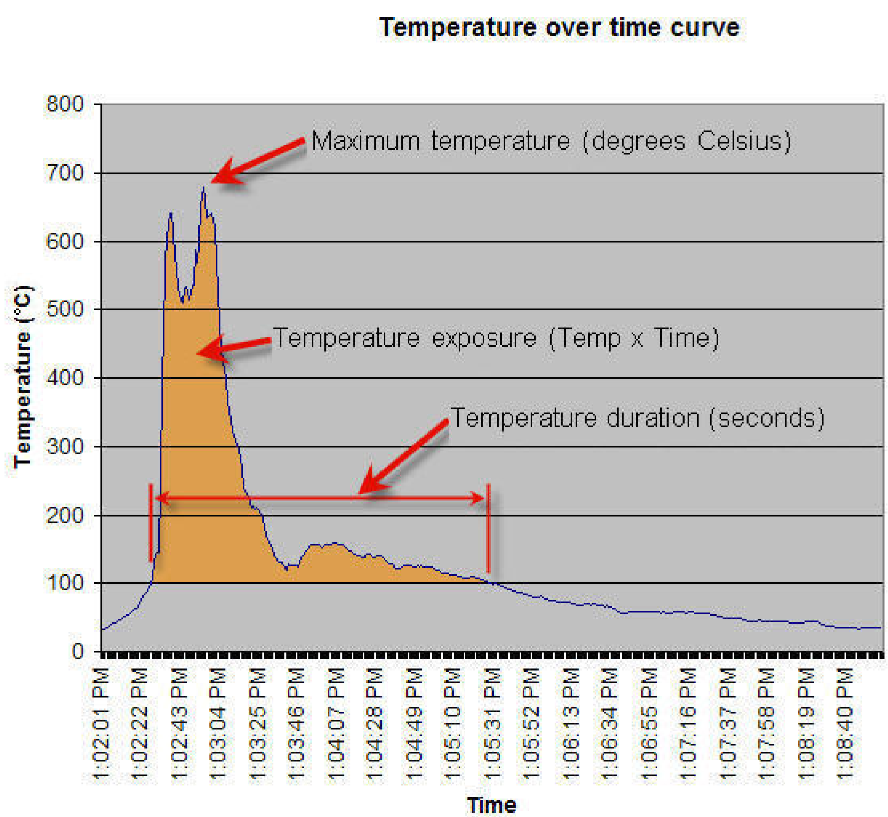
Introduction
The 'brown line' has been personally observed in numerous *Eucalyptus* and *Corymbia* species that have been exposed to higher than ambient temperatures, such as wild and prescribed fire (see Figure 1). The brown line is not apparent in bark that has not been exposed to elevated temperatures so it is reasonable to propose that the brown line appears as a result of bark exposure to elevated temperatures. There have been many papers written about bark responses to fire (e.g. Gill, *et al.* 1986, Chatto *et al.* 2003; Bova & Dickinson 2005), however this phenomenon has never been mentioned. The closest mention of the brown line is by Gill (1974) where he mentions discolouration of the bark of gum-barked eucalypts following fire. However, the brown line has been observed not only in gum-barked eucalypts, but in rough-barked eucalypts as well. Given the lack of information on this phenomenon, it is not known whether this response to elevated temperatures is unique to the bark of *Eucalyptus* and *Corymbia* species.

Figure 1: Illustration of the 'brown line'

This brown line seems to show the depth to which cell death from thermal penetration has occurred. The bark within the brown line (on the cambial side) is moist to touch, whereas the bark on the outside of this line appears dry. There may be some relationship between the depth of this line and the temperature reached within the bark. Typically, living plant cells cannot survive temperatures above 60°C (Alexandrov 1964), so there may be a correlation between temperatures above 60°C and the depth of the brown line. Since there is a noticeable moisture content difference on either side of this line, there may be a correlation between the depth of the brown line and temperatures above 100°C (i.e. the boiling point of water). If water is driven off on the outer layers of the bark, subsequent increases in bark temperature are likely, resulting in a 'desiccation front' that moves deeper into the bark (Jones *et al.* 2004). Further heating following initial drying (desiccation) causes volatile gases to be driven out of the bark in a process known as devolatilization, or pyrolysis (Tillman *et al.* 1981). As part of developing a stem heating model, Jones *et al.* (2004) used 200°C as the temperature in which devolatilization occurs. The brown line may be more closely related to this devolatilization temperature.

Temperatures in this study were obtained using an array of thermocouples as described in the Materials and Methods section of this paper. Each thermocouple reading enables the development of a temperature-time curve and a number of temperature parameters can be obtained from these. Maximum temperature, temperature duration and temperature exposure above specific temperatures are the parameters of interest in this study. Temperature exposure is determined by calculating the total area of the curve above a specified temperature. See Figure 2 for a graphical representation of these parameters.

Figure 2: Graphical representation of temperature parameters (temperature duration and temperature exposure are for 100°C in this example)



There are a wide range of bark types within the genus *Eucalyptus*. *Corymbia* species have smooth bark. Although the occurrence of a brown line is a common reaction to elevated temperatures for observed species in these genera, the depth of this brown line may vary depending on bark type. This study focuses on Dunn's White Gum (*Eucalyptus dunnii*), which has rough bark, and Spotted Gum (*Corymbia variegata*), which has smooth bark.

Materials and Methods

Plots established for fire behaviour experimental burns were utilised for this experiment. These plots were located on two sites of different age classes (planted in 1997 and 2000) with 30m x 30m plots established in both Dunn's White Gum and Spotted Gum. The sites are located west of Casino, northern New South Wales. There were three plots at each site/species combination and these were ignited in the morning, midday, and afternoon with the aim of varying the fire intensity.

Within each plot, four trees were selected to ensure that they were subjected to the head fire rather than a lower intensity backing fire. Thermocouples were installed on the morning and afternoon plots for each species and site combination. Midday plots were not used for this experiment due to time constraints. Four thermocouples were attached to each tree 50cm above ground level; one upslope, one downslope, and two perpendicular to these. The thermocouples were held to the tree using wire and the tip of the thermocouple was bent away from the tree so that the sensor was generally about 10-15mm away from the bark. Four adjacent trees per experiment (two trees in one row and two trees in the next row) were set up in this way. Thermocouples were connected to an in-ground data-logger that recorded temperature at one second intervals. Temperature data following each burn were downloaded in the field to a notebook computer.

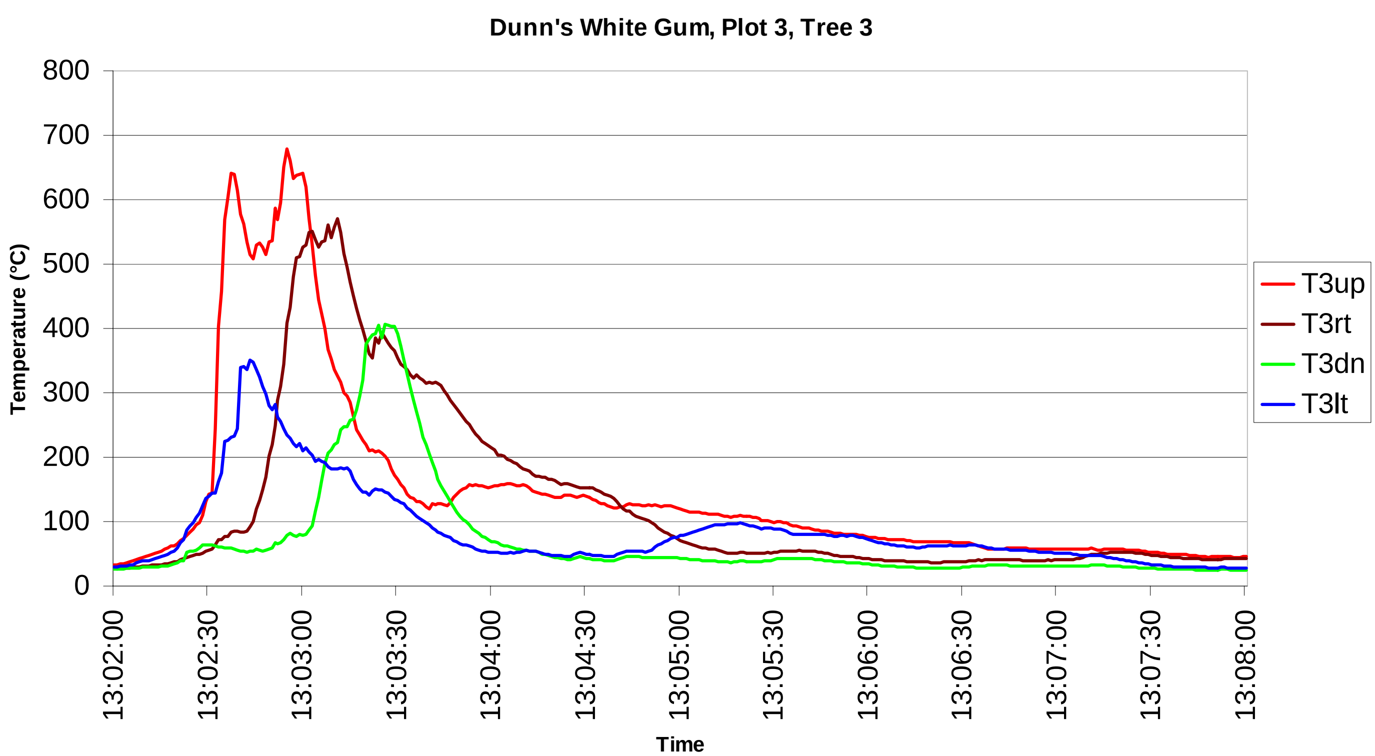
The sensors were positioned a small distance off the bark in order to reduce the impact of bark insulation on the temperature readings. By positioning the sensors like this, a better representation of the heat flux from the fire could be achieved without the influence of the bark absorbing part of the heat.

Two months after the experimental burns, bark thickness and depth of the brown line was measured adjacent to each thermocouple. Bark thickness was measured using the bark probe described by Gill *et al* (1982). Brown line depth was measured by cutting into the bark at the same point where the thermocouples were attached and measuring, using vernier callipers, the distance from the outer bark to the visible brown line.

Results

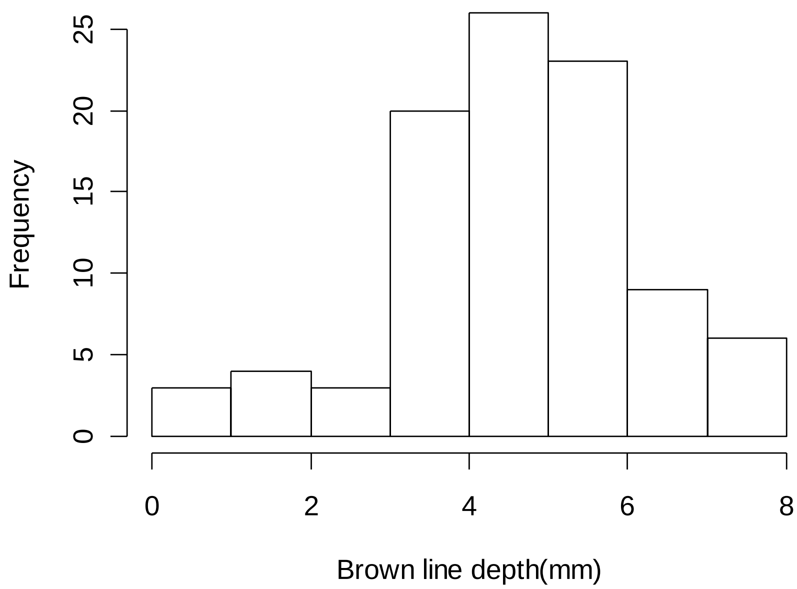
A typical temperature versus time graph is shown in Figure 3. It can be seen from this graph that each tree can be subjected to differing exposures of temperature around the circumference of the stem.

Figure 3: Typical temperature-time graph showing tree number and location of thermocouple on tree (up-slope, right, down-slope, left)



Measured brown line depths ranged from 0.3mm to 8mm. The distribution of brown line depths can be seen in Figure 4.

Figure 4: Histogram of brown line depth



Analysis

The relationship between the depth of the brown line and the following temperature parameters was analysed:

- Maximum temperature
- Temperature duration (i.e. time above 60 ^oC, 100 ^oC, 200 ^oC and 300 ^oC), and
- Temperature exposure (i.e. area of temperature-time curve above 60 ^oC, 100 ^oC, 200 ^oC and 300 ^oC)

Analysis of each parameter involved plotting the parameter against brown line depth and distinguishing between species and sites. Following this, two analyses of covariance were conducted to test whether there was a significant difference in response between sites (i.e. age classes) or a significant difference in response between species. In all cases, except for temperature exposure above 300^{o}C, there was no significant difference in response (i.e. brown line depth) between sites or species. With this result, all analyses considered site and species together, except for temperature exposure above 300^{o}C.

The model used for the regressions was:

$$D = \alpha + \beta \log T + \varepsilon$$

Where:
D = brown line depth (mm)
T = temperature parameter (either temperature duration in seconds, or temperature exposure in ^{o}C×sec)

The model used for maximum temperature was as above, but without the log transformation of the temperature variable.

Figure 5 shows a comparison of all model regressions. It can be seen from this figure that the temperature parameter that shows greatest correlation with brown line depth is log temperature duration above 200^{o}C (r^2 = 0.529). Figure 6 shows a plot of these variables.

Figure 5: Regression comparison for all models

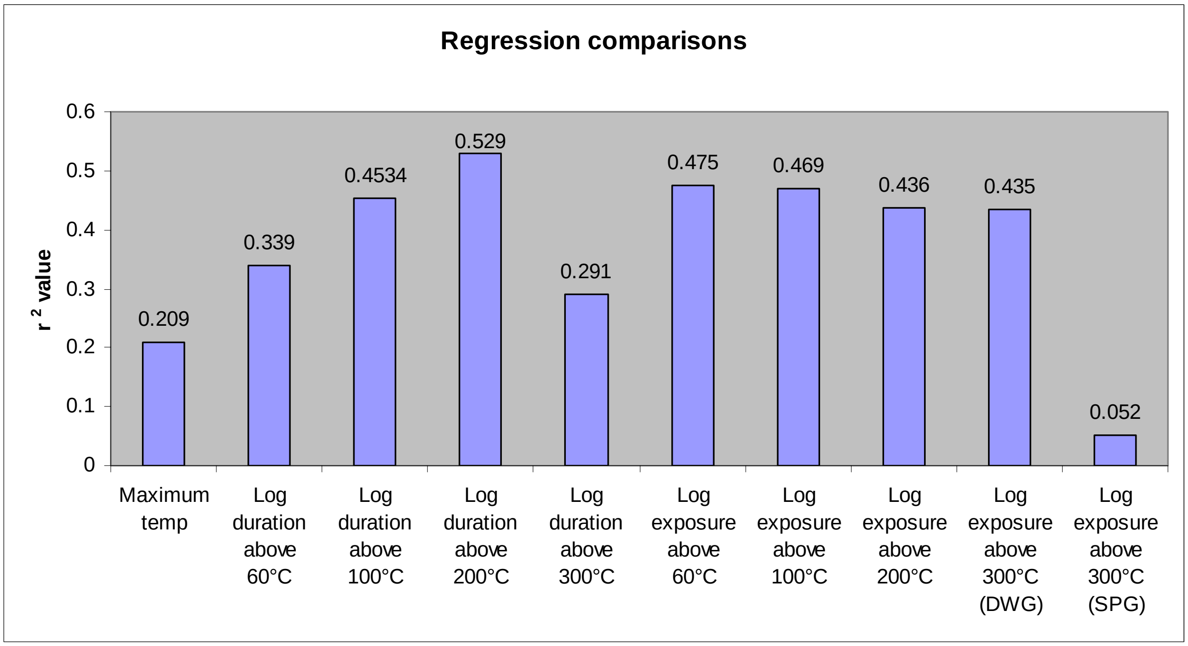
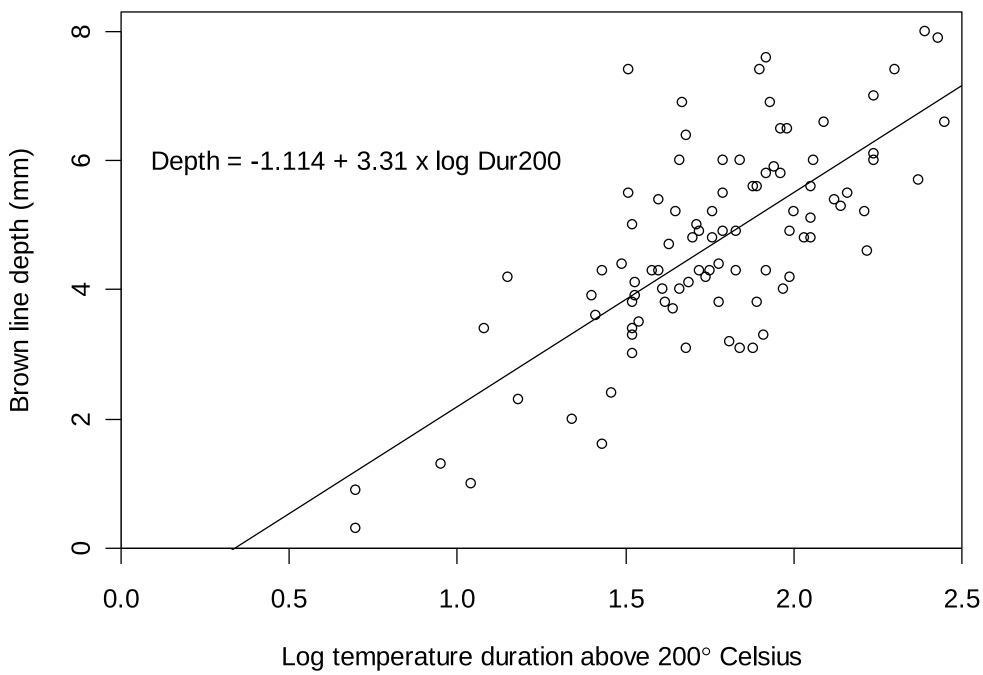


Figure 6: Brown line depth versus log temperature duration above 200°C with regression line



Discussion

Analysis of the data clearly shows that there is a relationship between elevated temperatures and the depth of the brown line. This relationship is consistent across the two sites and the two species. Although one plantation has a higher site quality (e.g. higher rainfall, more fertile soils) than the other, this is not unexpected. Regardless of site quality, the inherent properties of bark are likely to be the same for each of the species, so one would expect bark from the same species to respond to elevated temperatures in a very similar manner.

An unexpected result is that, although the bark types of the two species are different, they respond to elevated temperatures in the same fashion. That is, there is no significant difference in brown line depth between the two species. This result may be misleading however, because bark thickness prior to the burning experiments was not measured. Although there is unlikely to be any bark loss from fire in Spotted Gum, there was obvious charring on Dunn's White Gum and it would be expected that some of the bark was consumed during the fires. This initial loss of bark may be a factor when analysing the brown line and should be taken into account in any further experiments of this nature. On the other hand, if measurements of the brown line can be used as an aid to predicting stem damage, it is only the post fire measurements that are important.

There was a considerable time lapse (two months) after the fires before bark measurements were made. During this time, there was shrinkage of the decorticating bark in Spotted Gum as seen by cracks appearing in the bark. This shrinkage may not have been so great with Dunn's White Gum due to the fibrous nature of this bark. This may have also contributed to the finding that there was no significant difference between the two species.

Moisture content affects density, heat capacity and thermal conductivity (Jones *et al.* 2004). Bark thickness, bark moisture content, and the duration of heat input at the bark surface will determine the amount of heat received at the cambial zone (Vines 1960). This experiment did not measure bark moisture content. It is recommended that future experiments measure bark moisture content.

Conclusions

The formation of a brown line within the bark of eucalypts is a response to elevated temperatures. This response is most correlated with the duration of bark surface temperature above 200^{o}C.

Future measurements, observations of the plots and destructive sampling of selected trees in this experiment will provide stem damage data. The ultimate aim of this will be to determine if scarring or internal wood damage (i.e. the formation of kino veins) can be related to a ratio of brown line depth and bark thickness.

The potential of this work is that forest managers who have a stand of trees exposed to wildfire will be able to use a simple ratio of brown line depth to bark thickness to determine if that stand is worth retaining or if it should be salvaged immediately and the process of re-establishment begun. The usefulness of such an aid is that this decision can be made very soon after the fire, i.e. one does not need to wait until fire scars appear many months (or years) later; they may be able to utilise a sampling method that will give them the answer within weeks of the fire. This would minimise the area of unproductive plantation land within the forest manager’s estate.

Acknowledgements

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