**Classification of timber from *Pinus radiata* trees exposed to forest fires**

by

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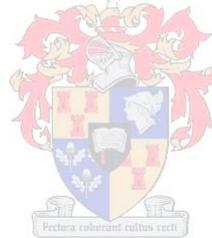
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**Declaration**

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# Abstract

This study aimed to classify wood from trees that were exposed to forest fires with regards to their end use. Exposure to high temperatures over time is known to degrade wood in various ways. This degradation could limit the end use by altering mechanical, chemical and physical properties, leading to difficulty in processing or failing to meet required specifications for various grades.

In this study wood from *Pinus radiata* trees that were exposed to forest fires of different levels of heat intensity was analysed with regards to its anatomical and physical changes. Trees were visually classified into three classes of burn severity. Moisture content measurements were taken from 135 standing trees, divided among the three classes. 30 trees, 10 from each of the three classes, were sampled and used for CT analysis. Samples were taken to include growth from before and after the fire. Two samples were taken from each tree, one from the charred and one from the uncharred side. The CT data was analysed and used to measure properties like growth ring width, cell wall thickness, lumen diameter and cell wall density. The data was used to compare properties from the charred and uncharred sides within a given year, as well as compare properties between years.

The study showed that there were significant differences in the MC between the burnt and unburnt sides of trees from classes 2 and 3. The difference between the MC measurements on the burnt sides of three classes differed significantly from each other. Lightness measurements were taken on samples from classes 2 and 3. These samples showed no significant difference between the burnt and unburnt sides for either of the two classes. The samples from the less exposed class were lighter, but not significantly so.

The macroscopic wood density was determined using core samples. A decrease in wood density was observed with an increase in fire exposure. The mean densities for all three classes however still fulfilled the requirements for structural timber set by the SABS.

Growth ring width, cell wall thickness and lumen diameter analysis gave varied results, with some cases showing a decline in properties while others were seemingly unaffected. For many of the outcomes of this study, results found by previous studies could not be reproduced.

## Opsomming

Hierdie studie het gepoog om bome wat aan plantasiebrande blootgestel is volgens hul eindgebruik te klassifiseer. Dit is bekend dat blootstelling aan hoë tempreature hout in vele maniere afbreuk. Hierdie afbreuking kan die eindgebruik van die hout beperk deur die meganiese, fisiese en chemiese eienskappe sodanig te verander dat dit kan lei tot probleme met verwerking of ongeskiktheid vir sterktegrade.

In hierdie studie is *Pinus radiata* bome wat aan plantasiebrande van verskillende grade blootgestel is ondersoek in terme van hul fisiese en anatomiese veranderinge. Bome is visueel in drie klasse van verskillende brandskade gegroepeer. Voglesings is op 135 staande bome, verdeel tussen die drie klasse, geneem. Monsters is van 30 bome, 10 uit elke klas, geneem vir CT analiese. Monsters is so geneem dat dit groei van voor en na die brand ingesluit het. Daar is twee monsters van elke boom geneem, een van die gebrande en een van die ongebrande kant. Die CT data is geanalieseer en gebruik om eienskappe soos jaarringwydte, selwanddikte, lumendiameter en selwand digtheid te meet. Die data is gebruik om eienskappe tussen die gebrande en ongebrande kante, sowel as tussen jare te vergelyk.

Die studie het gewys dat daar noemenswaardige verskille is tussen die voginhoud van die gebrande en ongebrande kante van bome uit klasse 2 en 3. Die voginhoud van die gebrande kante van al drie klasse verkil ook noemenswaardig van mekaar. Ligtheidmetings is gedoen op monsters van klasse 2 en 3. Die monsters het nie 'n noemenswaardige verskil tussen die gebrande en ongebrande kante getoon nie. Alhoewel die klas 2 monsters ligter vertoon het as die klas 3 monsters, was die verskil nie betekenisvol nie.

Houtdigtheid is bepaal deur fisiese metings op die monsters wat vir die CT skandering gebruik is te doen. 'n Daling in digtheid met 'n toename in blootstelling aan die brand het duidelik na vore gekom. Die digtheid is egter nog hoog genoeg om aan die vereistes vir strukturele hout te voldoen, soos die die SABS bepaal.

Jaarringwydte, selwanddikte en lumen diameter het wisselende resultate opgelewer, met sommige gevalle wat 'n afname in eienskappe wys en ander wat ooglopend onveranderd was. Vir vele van hierdie uitkoms kon die resultate van vorige studies nie bevestig word nie.

## Acknowledgements

Special thanks to the following people:

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# Glossary

| | |
|---|---|
| DBH: | Diameter at Breast height |
| CI: | Confidence interval |
| Crowning: | Fire damage to the canopy where the fire spreads in the canopy |
| CT: | Computed Topography |
| DP: | Degree of polymerization |
| First order fire effects: | Plant mortality resulting directly from fire damage |
| Girdling: | Damage to the cambium right around the tree, resulting in tree death |
| Heat avoidance: source | Materials are shielded from and protected from heat |
| Heat tolerance: | Ability of tissue to resist injury by preventing, repairing tissue or reducing damage |
| Maillard effect: of heat | Chemical reaction that causes browning as a as a result |
| MC: | Moisture Content |
| MOE: | Modulus of Elasticity |
| MOR: | Modulus of Rupture |
| Second order fire effects: | Physiological responses that can have a lethal effect |
| Specific heat: | The amount of heat required per unit mas to raise the object's temperature by 1°C |
| SABS: | South African Bureau of Standards |
| SANS: | South African National Standards |

# 1. Introduction

## 1.1 Research Problem

Fire damage to commercial trees is a big problem in South Africa. Not only is there loss of material as a result of trees dying from exposure to fire, but the surviving trees can potentially lose value, because their mechanical, physical and chemical properties are altered. In many cases burnt wood is not used commercially, because it is not known to which degree it was burnt and therefore to which degree its properties have changed. The pulp & paper industry is also hesitant to use burnt wood, as it would require a modified pulping process due to the introduction of charcoal. This means that substantial amounts of wood that could potentially still be of economic value are not utilised and left for low-value end use, such as fuel wood.

In this project we propose criteria to classify wood from burnt trees into different groups that are initially obtained from visual inspection and later refined depending on its physical and anatomical properties that were determined by various analytical techniques. Wood properties, such as ring structure, density, and anatomical structure will be determined and linked to the different burn classes, in order to determine the effects and extent of the fire damage and to propose potential end-uses for this wood.

## 1.2 Wood production in South Africa

According to a report published by Forest Economic Services, of the 122.3 million hectares of land in South Africa, only 1.04% was covered with commercial plantations in 2011. The total commercial timber plantation area in 2010/2011 was 1 273 357 hectares. Softwood and hardwood species cover 51% and 49% of the area, respectively. The plantation area is divided into 56% for pulp production, 36% for sawlog production, 4% for mining timber and the remaining 4% are used for other purposes. In the year 2010/2011, 10 337 799 t were sold as pulpwood, 4 179 100 m³ as sawlogs and 573 142 t for mining timber.
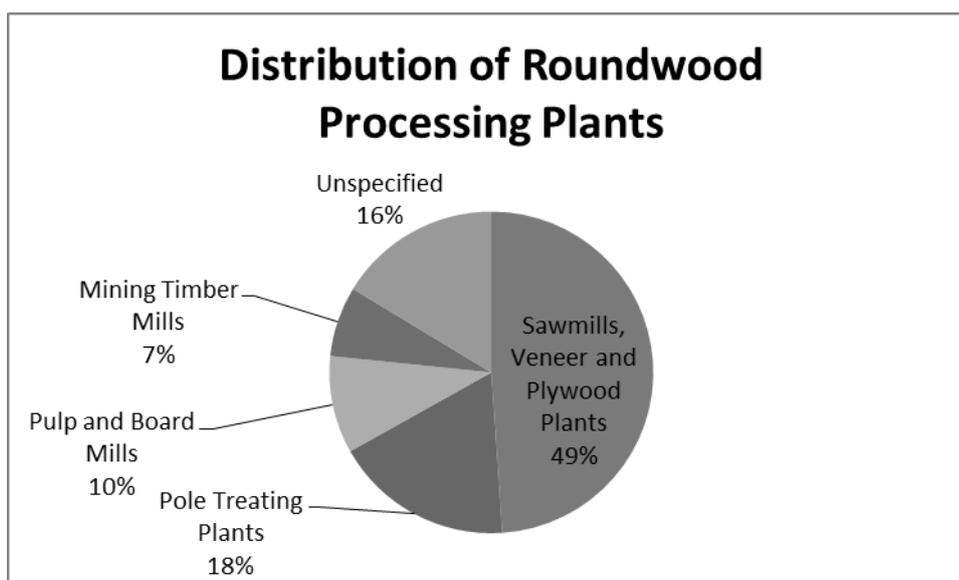


Figure 1: The distribution of roundwood processing plants in South Africa (Forest Economic Services CC 2011)

The total roundwood intake for 2010/2011 was 18 586 532 m$^3$ and the sales value for timber products was R1.67 billion.

Out of the 51% of the area under softwood, *Pinus patula* is most planted, covering 333 686 ha or 51.3% of that area. *Pinus patula* occurs mainly in Mpumalanga, KwaZulu-Natal and the Eastern Cape. *Pinus elliottii* comprises 27.4% of the softwood area and is found in all regions except the Western Cape. *Pinus radiata* on the other hand is confined almost exclusively to the Western Cape, covering an area of 58 999 ha (Forest Economic Services CC 2011).

The forestry industry utilizes only about 1% of the land area in South Africa and contributes about 1.2% to the Gross Domestic Product (GDP). In 2009 the forestry industry employed 201 025 people. The industry was a net exporter in 2010, with goods worth R3.9 billion being exported. Of this, over 99% were value-added products. Having contributed 2.27% to total exports and only 1.61% to total imports, the forestry industry ranks among the top exporting industries in South Africa (van Niekerk 2012).

## 1.3 Forest fires in South Africa

The 2010/2011 survey conducted by Forest Economic Services reported that 40 178 ha were lost or damaged by fire, climatic factors, insects or diseases. 38% of the total area was damaged by fires, of which softwood covered 51%.

In the Western Cape fires accounted for almost all of the sustained damage. Of the 2 585 ha that were damaged in 2010/2011, 2 550 ha were due to fire damage (Forest Economic Services CC 2011).

## 1.4 The nature of Fire

In a broad sense, fire is the opposite chemical reaction to photosynthesis. Plants capture energy from the sun to convert carbon dioxide and water into glucose and release oxygen in the process. Fire reverses this process by oxidizing the glucose into its building blocks and releasing the stored energy as heat and light. A forest, and the trees within it, collect and store energy over many years. All this stored energy can be released in a matter of hours in the case of a large forest fire. In the case of a large high-intensity wildfire, it is said that energy equivalent to that of the Hiroshima atomic bomb is released every 20 minutes (Thomas and Mcalpine 2010).

### 1.4.1 How a fire burns

When heat is applied to a fuel, three distinct phases of combustion are undergone; namely pre-ignition, ignition and combustion.

In the pre-ignition phase the energy applied to a piece of wood will initially be absorbed by the water in the wood. Some of the heat absorbed is conducted into the interior of the fuel and some will raise the surface temperature.  As the temperature rises, the water at the surface of the wood will start to evaporate, keeping the temperature at the surface around 100°C. The water moves into the air and deeper into the wood itself. When the surface is dry, the temperature will start to rise above 100°C and other substances in the wood, such as terpenes, fats, oils and resins will start to evaporate. These evaporated extractives form a cloud of flammable gas over the fuel (Chandler, et al. 1983, Thomas and Mcalpine 2010). When the wood reaches around 130°C it starts to break down chemically, which results in black char and a grey smoke, containing wood alcohol and tar gasses. Cellulose, the thermally most stable compound, is degraded at temperatures above 300°C (Thomas and Mcalpine 2010).

Although oxidization of wood will continue until completion once the wood reaches around 280°C, ignition is usually marked by the appearance of a flame or glow (Chandler, et al. 1983) and from this point on the oxidation process is self-sustaining. The temperature point of un-aided ignition of wood is, depending on the species around 500 - 600°C. At this temperature wood will spontaneously combust and support the combustion process on its own. The gasses formed in the pre-ignition phase can combust at temperatures as low as 320-350°C (Thomas and Mcalpine 2010, Chandler, et al. 1983).

Combustion can be seen as a series of ignitions of progressively deeper layers. Thus, all the variables that influence ignition will also influence combustion (Chandler, et al. 1983). The heat radiating form the combusting wood continually drives the process, evaporating extractives into flammable gasses that add to the flame. As the radiant heat from the flame heats the surrounding wood, it goes through the pre-ignition and ignition phases and will eventually also combust, causing the fire to be self-sustaining (Thomas and Mcalpine 2010).

Glowing combustion, or smouldering, is the dominant process after the volatile components have been removed from the fuel and only the charcoal remains, or if the ash content is high and volatile content is low, so that the combustible gas mixture is not sufficient to maintain the process, or when the density is too low to conduct heat fast enough to evolve the flame gas mixture. Carbon itself glows rather than forming combustible gasses. Glowing combustion takes place at temperatures around 600°C in the presence of insufficient oxygen. In this process carbon monoxide is formed when oxygen that diffuses to the fuel surface binds directly with carbon (Chandler, et al. 1983, Thomas and Mcalpine 2010).

### 1.4.2 Types of forest fires

Fires are often described in terms of their spread rate and intensity (Thomas and Mcalpine 2010). They can be categorised as follows:

- **Smouldering** – burning without flame and barely spreading
- **Creeping** – slowly spreading over the ground with low flames
- **Running** – rapidly spreading
- **Candling** – a running fire with individual trees catching fire
- **Torching** – fire burning into the canopy of standing trees
- **Crowning** – a running fire with the canopy engaged
- **Spotting** – a torching or crowing fire that shoots fire brands ahead of the main fire line.

Forest fires are named after the layer of the forest that they burn in i.e. ground fire, surface fire and crown fire.

**Ground fires** are slow moving fires that creep under the surface through roots, buried logs and decomposing organic matter. Because of the decomposition of the cellulose and extractives, the fuel has a high ash and lignin content and produces low amounts of flammable gas. This leads to glowing combustion. Glowing combustion can take place in environments with oxygen levels as low as 5%, whereas flaming combustion needs 13-15% oxygen to burn. Because of this, glowing combustion can even occur and spread under the ground surface. Temperatures of smouldering fires are lower than those of flaming ones, reaching about 300°C. Ground fires can burn undetected for long periods and when suitable conditions arise, ignite other types of fires (Thomas and Mcalpine 2010).

**Surface fires** burn through the litter on the forest floor. This can range from fallen leaves and other vegetation to branches left behind after pruning operations. A surface fire can generate a lot of heat and can consume dead branch wood several cm in diameter (Thomas and Mcalpine 2010). When investigating forest fires in Brazil, Miranda *et al.* (1993) recorded air temperature of up to 840°C at a height of 60 cm above the ground. The soil temperature 2 cm below the surface rose to a high of 38°C (Miranda, et al. 1993). If the fires burn hot enough and for long enough to combust the bark or wood of standing trees, these trees would also add to the fuel load.

**Crown fires** occur when a fire jumps into the canopy of a tree. It can be a single tree burning or a larger fire moving through the forest canopy with walls of flame spanning from the ground up to 30 meters above the crowns. These fires are usually short-lived, but because they can travel up to $10^{km}/_h$ and reach temperatures of up to 1200 °C, they are extremely dangerous.  Even though a lot of energy is released by crown fires, it is usually only the foliage and small diameter dead wood that is consumed, due to the short impact time. Because of the relatively high moisture content of the living foliage in the canopy, ignition is delayed. The foliage needs to be dry enough and enough heat needs to get into the crown for ignition. Heat is transferred in two ways in the case of a crown fire; convection and radiation. Radiation comes directly from the flames and convection from the surface fire burning under the canopy. As shown in *Figure 2*, the heat from radiation and convection rapidly dissipates as distance from the source increases. Thus it can be assumed that canopy that is closer to the surface fire will more easily catch fire. The rule of thumb is that a gap of more than one and a half (1.5) flame lengths will act as a fire break (Thomas and Mcalpine 2010).

### 1.5 How fire affects trees

Forest fires move through a stand of trees at different speeds and varying intensities, depending on the conditions of the day.  The two main factors influencing the degree of damage a tree sustains during heat exposure are **temperature and exposure time** (Esteves and Pereira 2009). Fengel and Wegener (1983) also list atmospheric conditions, moisture content and the general health of the tree as factors. According to Van Wagner (1972), pine species are more susceptible to death caused by crown scorch than by cambium necrosis. In order to die as a result of damage to the cambium, a tree must be fully girdled (Van Wagner 1972). Girdling refers to the removal of a band of bark entirely around the circumference. This cuts off the flow of nutrients in the phloem and results in the slow death of the tree.

In the case of fire damage, girdling can also refer to cambium necrosis around the entire circumference of the tree (Wilson and White 1986, Odhiambo, Meincken and Seifert 2014). Van Wagner believes that a fire intense enough to fully girdle a tree will also severely scorch the canopy.

The chemical composition of wood changes through thermal degradation when it is heated (Esteves, Domingos and Pereira 2008). Each part of the tree is affected differently, based on its heat transfer mechanism.

Any tree can be roughly divided into three main parts based on the physical differences between the trees parts. The canopy is made up of branches, twigs and leaves. The bole comprises the main part and contains mainly wood and bark. The roots make up the underground part of the tree.

### 1.5.1 Fire effects on different tree parts

There are three mechanisms for heat transfer: Conduction, convection and thermal radiation. All three are present when a fire moves through a stand of trees.

Crown characteristics that affect the tree's resistance to injury by fire include crown height, foliage density and bud size (Ryan and Reinhardt 1988). According to Ryan *et al. (1988)* the best indicator for likely tree mortality is the level of crown damage. Before necrosis sets in, the foliage in the canopy can stand a temperature of 50°C for about ten minutes, but only one minute at 60°C (Van Wagner 1972). This shows again that the temperature and exposure time are both very important factors. The canopy must reach a certain minimum temperature before ignition can occur and the above ground height of the canopy base is an important parameter. As *Figure 2* shows, the heat from the fire tapers outwards as height is gained, making the effects less intense. Because of this, a very intense surface fire is needed to damage a high crown.
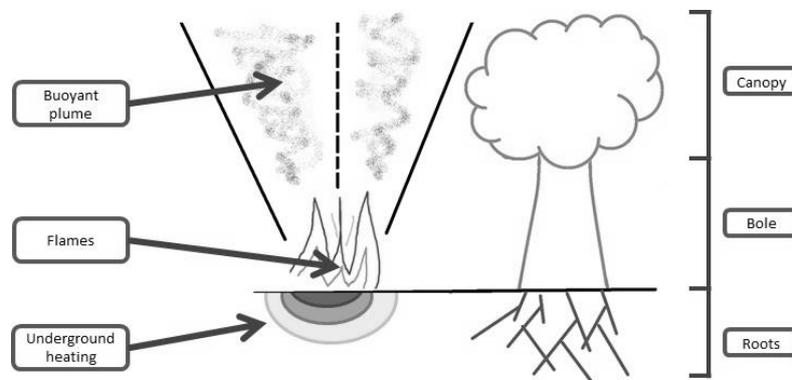


Figure 2: Fire shape and tree parts

The buoyant plume of heat above the fire is wedge shaped, as shown. The buoyant plume consists of columns of hot, low density air that rises above the heat source. As it rises, the plume mixes with the cooler, high density air in the surroundings. As a result of this mixing, the width of the plume increases and the temperature decreases with height (Dickinson and Johnson 2001).

Another obvious parameter that affects crown mortality is the moisture content (MC) of the foliage (Van Wagner 1977). The higher the MC, the more likely the crown is to survive a short, high-intensity fire, as most of the heat is used to evaporate water.

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Raising the temperature in the bole involves all three methods of heat transfer. There is heat transfer by convection and radiation between the flames and the bark surface, as well as conduction through the bark to the wood underneath (Dickinson and Johnson 2001). With an increase in bark thickness the thermal conductivity decreases and the bark offers more protection. The theoretical thermal resistance of bark to cambium damage scales with the square of the bark thickness (Ryan and Reinhardt 1988).

The roots of trees are protected from direct heat exposure by the soil covering it. The MC of the soil also has an effect on the mechanisms that transfer the heat into the soil. In dry soil, heat is transferred by conduction, convection and radiation, because of the porosity. In saturated soil, heat is transferred by conduction alone. In moist soils (wet, but not saturated), heat is transferred by conduction and mass transfer of water in the liquid and vapour phase (Dickinson and Johnson 2001). The latent evaporation of water prevents soil temperatures from going over 95°C until all water has evaporated (Van Wagner 1972). Beadle found that soil temperature drops dramatically with soil depth. In one case where the surface temperature exceeded 250°C, the temperatures under one inch (25 mm) and three inches (75 mm) was measured at 112°C and 55°C respectively (Beadle 1940).

### 1.5.2 First order fire effects

When trees are exposed to heat of sufficient duration or magnitude, plant function can be impaired and death may ensue. Charred bark and stems are visible signs of fire damage that are apparent immediately after the damage has taken place. This can be followed by cambium, bud, and leaf or needle necrosis. Plant mortality resulting directly from fire damage will usually manifest within two to three years after the fire. This kind of injury resulting in mortality is called first order fire effect (Butler and Dickinson 2010). Tree death as a result of crown scorch will be immediate, while death as a result of girdling (cambium necrosis) can take several years (Van Wagner 1972).  Because of unequal heating due to wind, as explained in *Section 1.5.5,* the leeward side may experience cambium necrosis, while the windward side remains unaffected. If the tree survives, the remaining cambial tissue can regenerate and the flow of phloem can be restored. However, a scar will remain (Dickinson and Johnson 2001, Wilson and White 1986).

### 1.5.3 Second order fire effects

Exposure to fire and the subsequent thermal damage leads to a host of physiological responses that can have a lethal effect. These include increased sensitivity to adverse environmental conditions, insect and disease attack and herbivory. These are termed second order fire effects. The trees can also be influenced by changes in soil properties, light resource availability and erosion susceptibility (Dickinson and Johnson 2001).

### 1.5.4 Protection from fires

Tissue survival depends on the location of the tissue and type of heat exposure. It can either be exposed to the heat source directly or shielded. When tissue is protected from direct contact with the heat source by bark, leaves or soil it is termed shielded plant material. Shielded material may resist injury because it is protected from heat flux. This is called heat avoidance.
Heat tolerance is the ability of tissue to resist injury by preventing it, repairing damaged tissue or reducing damage (Stephan, Miller and Dickinson 2010).
The insulating layer of bark is the cambium's main source of protection from heat. The ease with which heat moves through bark decreases with an increase in bark

thickness, density and MC (van Mantgem and Schwartz 2003). There is a linear correlation between bole diameter and bark thickness, resulting in thinner bark for smaller diameter trees. Thus smaller trees often do not survive even low intensity fires, due to insufficient bark material for thermal insulation (Odhiambo, Meincken and Seifert 2014).

### 1.5.5 Fire scars

The use of growth rings to determine the fires experienced by a tree in its past has been named *pyrodendrochronology* by Dietrich (1975). Fire scar analysis was first used by Frederick Clements to reconstruct the history of a burned area. He was able to date 13 fires that occurred between 1707 and 1905. Clements in Dietrich (1975) emphasized the simplicity of fire scar analysis, but also pointed out possible problems, such as errors in dating, as a result of the season the fire occurred. It is also possible that scars from other sources can be mistaken for fire scars.

Fire scars do not form uniformly on trees or across a landscape, thus an understanding of how fire scars form is needed.

When a fire is burning adjacent to a tree, fire scars form in one of two ways: the temperature of the cambium is raised to a lethal level, or the bark, cambium and xylem is consumed by the fire (McBride 1983). The ability of individual plant cells to withstand exposure to high temperatures does not vary significantly between plant species or between plant tissues within a plant. The lethal temperature for mesophytic plants generally ranges from 50 to 55°C (Odhiambo, Meincken and Seifert 2014). A temperature above 60°C is lethal for the cambium. In hardwood species, the bark of an area that has reached the lethal temperature will fall off in one to seven years. This leaves the sapwood exposed to insects and fungal attacks as well as subsequent fires (McBride 1983).

When a portion of the cambium is killed by lethal temperature or consumed by the fire, a rejuvenation process starts at the margins of the wounded area. A callus develops, with a new vascular cambium and a phellogen within the callus tissue. In the case of very shallow scars, or where the cambium was killed by heat, a callus may be restricted or absent (McBride 1983).

Partial healing of the area affected by fire can occur when the fire took place in spring or early summer (the growing season). When a fire occurs after the growing season, the tree does not produce xylem to heal the wounded area until the next growing season. This potential delay can contribute to uncertainty when dating fire scars (McBride 1983).

Many factors influence the occurrence of fire scars, including: fuel conditions, bark thickness, tree diameter, tree species and wind velocity (McBride 1983).

Tree bark of sufficient thickness can insulate the cambium from lethal temperatures. There is a variation in the thickness of the bark and its ability to diffuse heat between different species, as well as within a species, with age. Bark thickness was proven to affect the fire resistance more than the capacity to diffuse heat (McBride 1983). Because there are known differences in the ability of different species to withstand fire, and a general lethal temperature for the cambium across all species, a difference in the insolation abilities of different species is implied (Odhiambo, Meincken and Seifert 2014).

Davis and Martin measured the difference between temperatures on the leeward and windward sides of longleaf pines (*Pinus palustris*) during ground fires. They found the mean maximum bark temperature of the leeward side to be 638°C, while the corresponding temperature on the windward side was only 376°C. The temperature of the cambium was 82°C and 29°C for leeward and windward sides respectively (Davis and Martin 1961). This temperature pattern would result in death of the cambium and subsequent fire scar formation on the leeward side but not on the windward side.

In fires in the presence of wind, the heating on the leeward (downwind) side is equal or greater than on the windward (upwind) side. The residence time of a standing leeward flame is approximately double that of a free moving flame. If a tree survives a fire, where the heat exposure on the leeward side was sufficient for cambium necrosis, but insufficient on the windward side, a scar will form on the leeward side (Dickinson and Johnson 2001).
 There are four observations to consider when working with fire scars:
1. Fires rise higher on the leeward side
2. Fire scars are only found on the leeward side (In the absence of wind, girdling will take place).
3. Small trees rarely have fire scars
4. Fire scars are mostly shaped triangular, becoming narrower with height.
As air flows around a cylinder, flow is reversed at the leeward side and results in two vortices. This is shown in *Figure 3.* The formation of these vortices is dependent on the upstream wind velocity, cylinder diameter and the kinematic viscosity of the air (Gutsell and Johnson 1996).
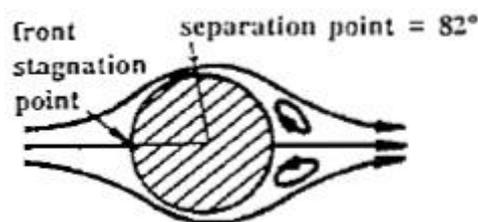


Figure 3: Airflow around the tree bole showing vortices (Gutsell and Johnson 1996).

As a fire moves past a tree, two vortices are formed on the leeward side. The turbulent mixing of gaseous fuel, heat and air in these vortices causes an increase in flame height. The flow of gaseous fuel in the vortices increases the height to which combustion can occur, which results in the triangular shape of the fire scar. Small trees usually do not have fire scars, because the cambium is killed (girdling) or the foliage is destroyed by crown scorch (Gutsell and Johnson 1996). *Figure 4* shows how a fire moves past a tree, illustrating the forming of the vortices described above.
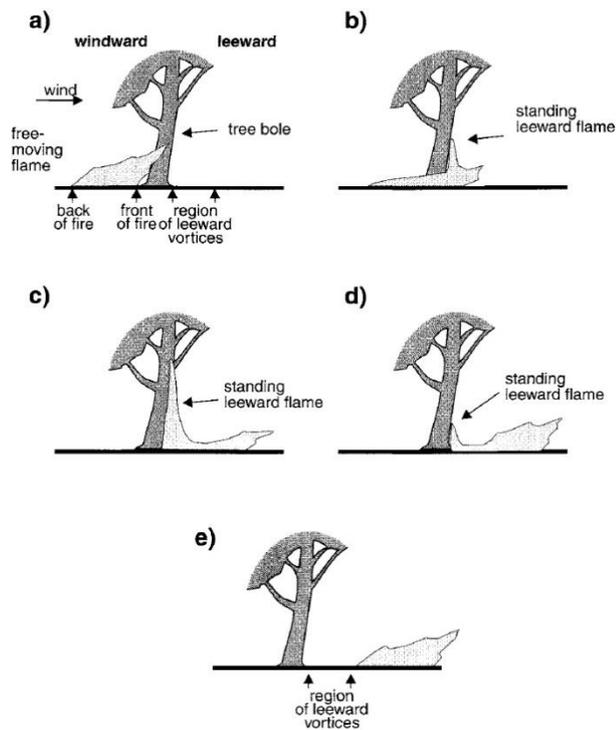
Figure 4: The effect of leeward vortices on a free-moving flame (Dickinson and Johnson 2001)

## 1.6 Wood structure

An understanding of the anatomy of wood is important when defining the characteristics thereof. Because these features affect the characteristics and possibly the end use of the wood, it is important to understand why they are formed and what the effect of exposure to fire will be on them.

*Figure 5* shows a diagram of the different anatomical parts of a tree. Many of these parts are mentioned in the following text.
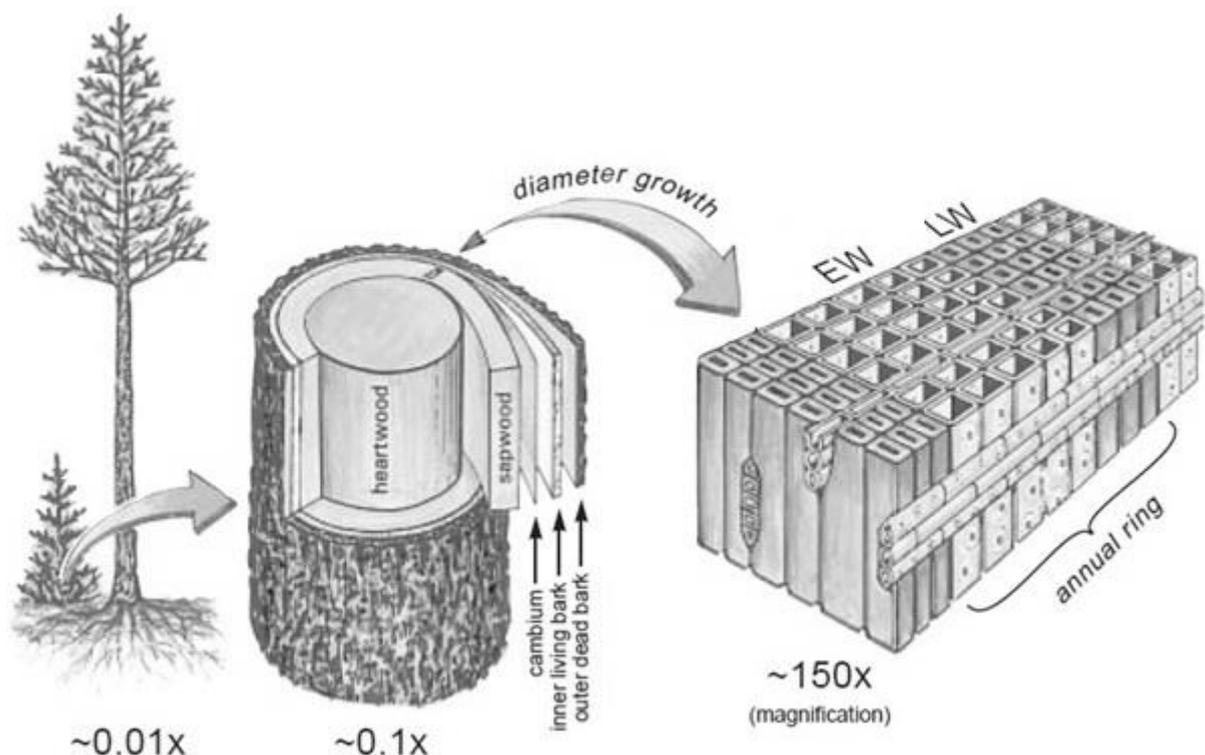
Figure 5: Anatomy of a tree (Jozsa and Middelton 1994)

### 1.6.1 Growth rings

Annual growth rings can be seen in the cross-section and can be used as a chart of growing activity. In spring, when the growing season starts, active cambial division starts. In this period, low density earlywood is produced and ceases when the maturation of new needles takes place at the end of summer. At this time, new foliage starts to produce more photosynthate than it consumes and a reduction on cambial activity follows. This leads to more material being available for cell wall thickening. At the same time, reduced crown activity limits the production of auxin which helps start the production of high density latewood. The production of latewood continues to the end of the growing season (Jozsa and Middelton 1994, Hoadley 2000).

### 1.6.2 Bark

Bark is comprised of two layers: a living inner layer and an outer layer composed of dead cells. The inner layer is made up out of conducting and storage cells for photosynthesis. The primary purpose of the dead outer layer is to protect the living tissue on the inside from drying out (Jozsa and Middelton 1994).

### 1.6.3 Heartwood and Sapwood

Heartwood and sapwood are the two differently coloured divisions in the cross-section. Heartwood is found in the central lower part of a mature stem. Heartwood is formed from sapwood, but it no longer functions physiologically, as it consists of dead cells. Heartwood usually has a darker colour than sapwood because of organic deposits, commonly called extractives. Sapwood is the living layer and performs the physiological activities. It stores food and water and facilitates sap conduction (Jozsa and Middelton 1994, Hoadley 2000).

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## 1.7 Wood properties

### 1.7.1 Density

Basic wood density is given by dividing the green volume by the oven dry weight. It is an important characteristic to describe wood quality and is directly, and mostly linear, related to other wood properties. Basic wood properties such as mechanical, thermal, and acoustic properties, as well as shrinkage and swelling and hygroscopicity are affected by density. Processability, such as drying and sawing are also affected by density (Tsoumis 1991).

Wood density is a measure for the amount of solid material in a given volume of wood, or in other words the amount of cell wall material, which consists of three main components: cellulose, hemicellulose and lignin. They all have similar densities of about 1500 $^{kg}/_{m^3}$. This value is consistent for all wood species. Mechanical properties like strength, heating value, stiffness and pulp yield can be predicted by density (Jozsa and Middelton 1994).

The density of wood can vary greatly within a given species and even within one tree. Depending on tree species and the cambial age of the wood, the minimum density within one growth ring can vary between 250 and 400$^{kg}/_{m^3}$, while the maximum can vary between 600 and 900 $^{kg}/_{m^3}$ (Tsoumis 1991).

*Figure 6* shows the difference in density and ring width between growth rings produced early and later in the life of a tree.
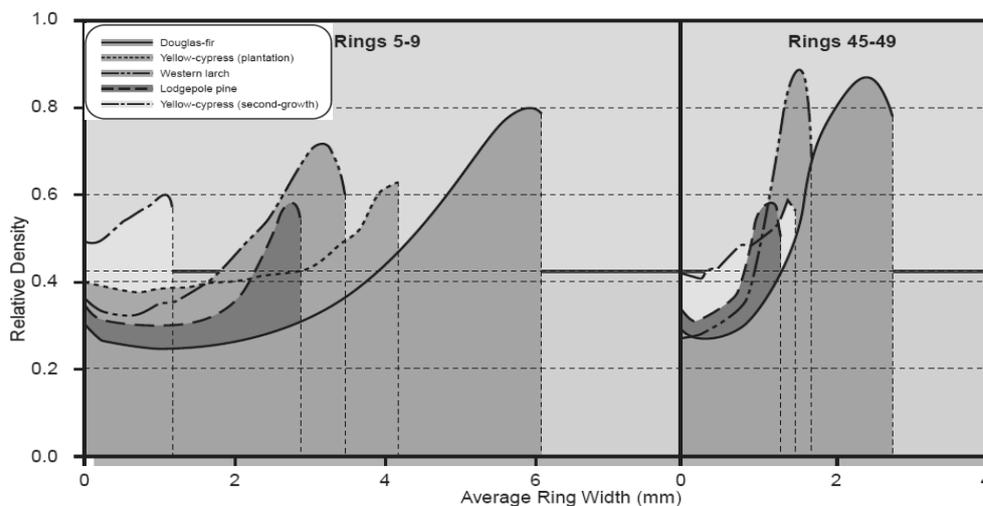


Figure 6: Intra-ring density profiles plotted according to ring width (Jozsa and Middelton 1994).

There is also a variation in density in the tree bole in the longitudinal (base to crown) and radial direction (pith to bark). Usually density decreases with tree height. This can be attributed to both mechanical and biological factors. The weight and the effect of wind on it result in localized stresses in the trunk of the tree, which leads to higher density in this area. The proportion of heartwood is higher in the lower parts of the tree and the extractives impregnating the cell walls add to higher density. Variation in the vertical direction is also influenced by the proportion of juvenile wood. The upper parts of the tree are mostly juvenile wood and have a lower density compared to the mature part of the tree. Taper also has an effect on density variation, with trees with less taper showing more variation (Tsoumis 1991).

Longitudinal and radial density variation is interrelated, with the same mechanical factors that influence variation in both directions. Considering that the density of wood produced in different stages (juvenile, mature and over mature) will differ, the influence of age is clear. In softwoods, density is lowest at the pith, becomes higher with maturity and starts to decrease at an age of around 100 years. For fast growing softwoods like *Pinus radiata*, the distance from the pith has a larger influence on the density than the width of the growth rings (Tsoumis 1991).

When exposed to higher temperatures, the evaporation of volatile degradation products start, causing mass loss and subsequently lower density (Meincken, Smit and Steinmann 2010). Mass loss due to heat-treatment will vary for different species and can be correlated to a decrease in density, which is commonly used as an indicator for wood quality (Esteves and Pereira 2009).

Esteves *et al.* (2009) and Gunduz *et al.* (2010) found that there was an increase in mass loss with increasing temperature and exposure time, as shown in *Figure 7.* The rate of the mass loss was higher in the beginning of heat treatment and then slowed down (Esteves and Pereira 2009, Gunduz, Aydemin and Korkut 2010). Gunduz *et al.* (2009) found that temperature was a more important factor in determining the density loss than duration (Gunduz, Aydemir and Karakas 2009).
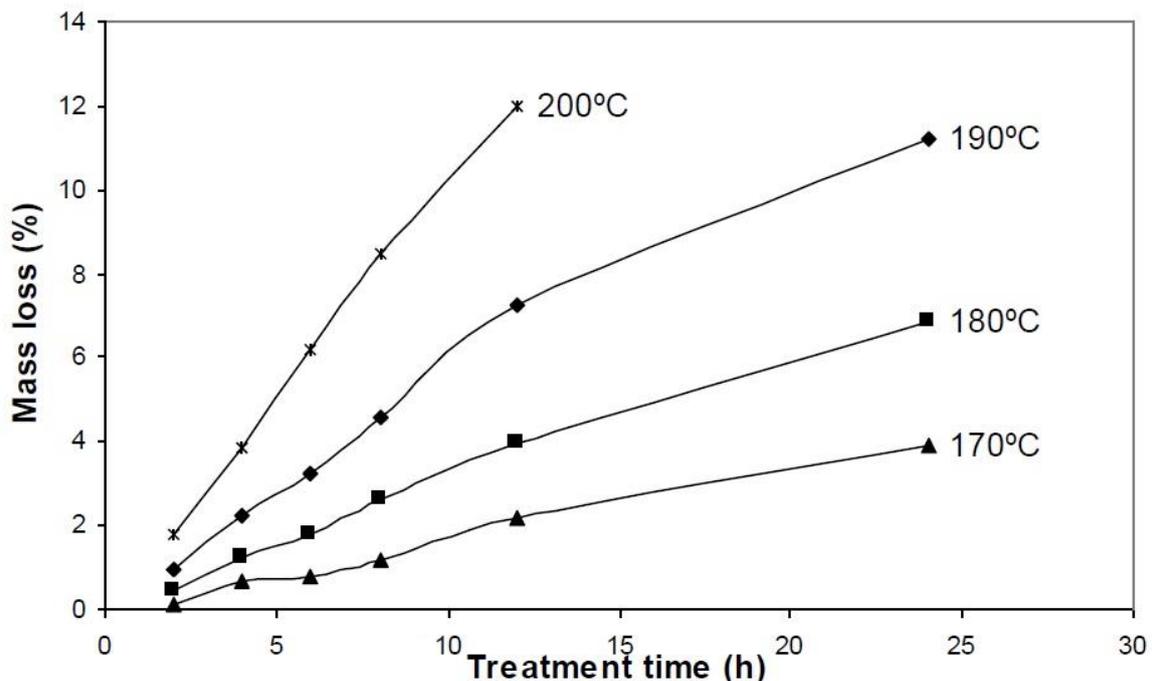


Figure 7: The mass loss of pine with heat treatment (Esteves and Pereira 2009)

When Meincken et al. (2010) compared the density of green, slightly burnt and burnt wood they found the overall density for slightly burnt wood was higher than for green wood. Burnt wood had the lowest density. The higher density in slightly burned wood can be explained by the thickening and densification of cell walls during exposure to moderate temperatures. In another study, Meincken et al. (2013) found that the cell wall thickness increased from temperatures around 150°C up to 220°C, after which material loss prevailed and the cell wall thickness started declining (Meincken and du Plessis 2013).

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### 1.7.2 Thermal properties

Three main factors influence the thermal conductivity of wood: density, MC and temperature. Thermal conductivity generally increases with an increase in any of these three factors. Thermal conductivity is further influenced by the presence of knots and checks, as well as the extractive content (TenWolde, McNatt and Krahn 1988). Loose knots and checks will lower conductivity because of the voids they possess, adding air pockets that do not conduct heat very well. Tight knots and the change in grain direction surrounding them may, however, result in higher density for that area, raising conductivity.

Because of the anisotropic nature of wood, the thermal conductivity along the grain is between 1.5 and 1.8 times higher than across the grain. When a tree is exposed to a forest fire, the different conductivity rates in different directions will cause the heat to be spread up the tree faster than it will penetrate towards the core.

Specific heat is the amount of heat per unit mass needed to raise the temperature of the given mass by 1°C. It is influenced by temperature and MC, but not density, as it is measured per unit mass. As with thermal conductivity, the specific heat rises as the temperature is raised (TenWolde, McNatt and Krahn 1988). Trees with a higher specific heat value need to be exposed to a heat source for longer in order to raise the temperature.

Thermal diffusivity is defined as the ratio of thermal conductivity to specific heat of a material. It is a measure of the ability of the material to conduct thermal energy relative to its ability to store it. Wood's thermal diffusivity is about 100 times lower than that of steel, due to the low thermal conductivity of wood. This means that wood will not diffuse the heat it is exposed to as well as steel and the heating effects remain more localised.

### 1.8 Material properties of burnt timber

When exposed to high temperatures, several wood properties will change. These changes can be divided into two types, namely reversible and irreversible (Stamm 1956). Reversible effects are visible for only short times after wood was heated. If the temperature exposure was short, most wood properties will return to their original value after cooling down. These effects generally appear below 100°C (Kretschmann 2010). Temperatures above 150°C permanently change the chemical and physical properties of wood (Yildiz, Gezer and Yildiz 2006). Irreversible effects result from exposure to high temperatures for longer times. The resulting degradation of wood and the loss of mass and strength is permanent (Kretschmann 2010).

The permanent chemical and physical changes that occur in wood that is exposed to heat are usually the result of the degradation of hemicellulose and lignin. Due to this degradation, the water absorption capabilities of the wood are reduced, leading to more dimensional stability and better resistance to fungal decay. Exposure to heat can also darken the colour; lower the pH and increase thermal insulation properties of wood (Gunduz, Aydemir and Karakas 2009).

Gunduz *et al.* (2009) report that wood exposed to temperatures of 160 and 180°C for durations of 2, 4 and 6 hours improved the physical properties such as swelling due to moisture absorption, biological durability and thermal insulation properties improve. A decrease in mechanical properties such as compression strength, bending strength and MOE was also observed. The changes in physical and mechanical properties are mainly due to depolymerisation reactions. Hemicellulose is more sensitive to heat and the degradation of it is the main reason for the loss of strength properties. (Gunduz, Aydemir and Karakas 2009).

### 1.8.1 Physiological changes

As heat penetrates the wood surface, it causes injury to cells by denaturation of protein and coagulation, membrane destabilization and the accumulation of reactive oxygen. The rate at which injury or necrosis happens has been established as an approximate exponential relationship between temperature and exposure time (Stephan, Miller and Dickinson 2010). Heat affects wood differently over different temperature ranges. As the heat penetrates the wood, the temperature gradually increases, breaking down the different components at different temperatures. Varying temperatures for the decomposition of different components surfaced in reviewing the available literature. It is generally accepted that moisture in the wood is removed at temperatures up to 100°C.

The effect of temperature in the different ranges has been explained by Esteves *et al. (2008).*

Between 20 and 100°C wood dries and water is evaporated, beginning with free water followed by bound water. Between 120 and 250°C chemical degradation of lignin and hemicelluloses starts. At temperatures above 250°C the cellulose is degraded and the carbonization process starts with the formation of $CO_2$ and other pyrolysis products (Brito, et al. 2008, Fengel and Wegener 1983).

Wood exposed to high temperatures becomes less hygroscopic. This can be explained by re-crystallisation of cellulose molecules, as water leaves the system and by the decomposition of hemicelluloses and lignin (Sehlstedt-Persson 1995), which results in fewer available hydroxyl groups to which water could associate.

*Figure 8* shows the weight loss of different wood components as a function of degradation temperature, obtained via Thermo-Gravimetric Analysis (TGA). It can be seen that lignin is one of the first components to start degrading, but it degrades over a wide temperature range and is thus the most thermally stable component. Hemicelluloses is relatively easily hydrolysed and starts to degrade at a temperature of about 180°C. The hemicelluloses is completely degraded at temperatures of 200-230°C (Boonstra and Tjeerdsma 2006). The degradation starts with deacetylation. The released acetic acid acts as a catalyst for the depolymerisation. This further increases the decomposition of polysaccharides (Esteves and Pereira 2009). This acid catalysed degradation leads to the forming of formaldehyde and other aldehydes (Tjeerdsma, et al. 1998). Coincidently, hemicelluloses dehydrates with the decrease in hydroxyl groups (Weiland and Guyonnet 2003). Depending on wood species and the severity of the treatment, the carbohydrate content will also decrease (Esteves and Pereira 2009).

Lignin starts to decompose at temperatures as low as 220°C (Kandem, Pizzi and Jermannaud 2002).

Cellulose is more resistant to thermal degradation than hemicelluloses, because of its crystalline nature. Boonstra and Tjeerdsma (2006) found that cellulose degradeds at temperatures of about 220°C. The crystallinity of cellulose increases as amorphous hemicelluloses degrades, which results in deceased accessibility of hydroxyl groups to water molecules (Boonstra and Tjeerdsma 2006). This explains the lower moisture absorption of wood that has been exposed to high temperatures, as was the case when  Gunduz *et al.* (2009) found that thermally treated wild pear samples absorbed less moisture than the control samples (Gunduz, Aydemir and Karakas 2009).
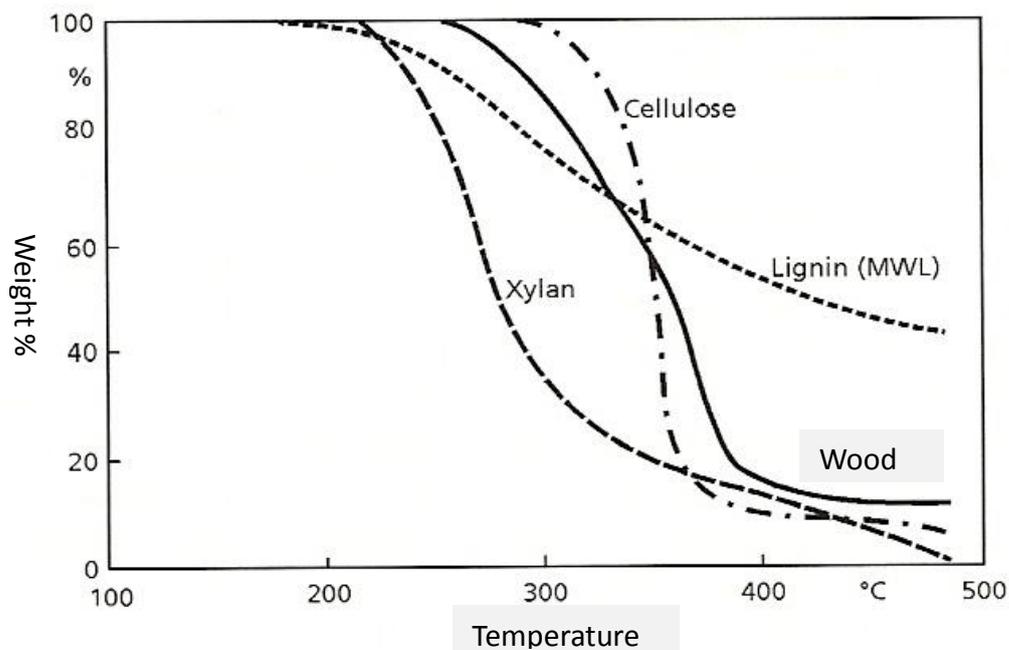
Figure 8: Thermogravimetric diagram of cottonwood (Populus spec.) and its components (Shafizadeh and DeGroot 1976).

### 1.8.2 Colour

When wood is heated its colour darkens. As with most effects of heat-treatment, darkening increases with temperature and exposure time (Esteves, et al. 2008, Gunduz, Aydemir and Karakas 2009). This can be explained by the breakdown of extractives, lignin and hemicellulose and the migration of these breakdown products to the surface, which is called the *Maillard effect* (Meincken, Smit en Steinmann 2010). Yildiz *et al.* (2009) states that colour changes are not an indication of the degree of change in other properties. Many factors influence the change in colour of a piece of wood, such as the method of thermal modification, initial moisture content, atmospheric pressure and the treatment time and temperature (Yildiz, Gezer and Yildiz 2006). The hydrolysis of hemicellulose can also be responsible for the change in colour, as it is degraded to monosaccharides and adds to the discoloration of the wood by reacting with nitrogen compounds (Gunduz, Aydemir and Karakas 2009, Koch, Puls and Bauch 2003).

### 1.8.3 Moisture content

When testing the moisture content of boards obtained from fresh, slightly burnt and severely burnt trees, Meincken *et al.* (2010) found that moisture content decreased with an increase in fire exposure. It was also found that the moisture content varied more as fire exposure increased. After drying the boards it was found that the boards from all three categories had similar MC values. There was however, a larger standard deviation in the slightly and severely burnt boards. Almost no variance was found for the MC measured in individual unburnt boards, while a significant variance was found within individual boards that were slightly and severely burnt. This could be explained by chemical and structural modification of the wood cells by the high temperatures, like densification of plastification of the cells. The flow of moisture could also have been decreased by pits being blocked, slowing down the drying process (Meincken, Smit en Steinmann 2010).

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### 1.8.4 Mechanical properties

The effects of heat exposure on mechanical properties of wood are largely caused by the degradation of hemicellulose. As hemicellulose degrades, acetic acid is formed, which reduces the degree of polymerization of glucose, by breaking glycosidic bonds. This leads to reduced mechanical strength in wood (Sinha 2013).

Compression strength perpendicular to the grain in *Abies bornmulleriana* (uludag fir) was found to decrease with heat treatment. Higher temperature and longer exposure times lead to higher loss in strength. Hardness, in all three main planes, was also fond to decrease with heat-treatment (Gunduz, Aydemin and Korkut 2010). Yildiz *et al.* (2006) found similar results when testing spruce (Yildiz, Gezer and Yildiz 2006).

The Modulus of Elasticity (MOE) as well as bending strength for heat–treated pine decreases with mass loss. The reduction of bending strength can be attributed to the degradation of hemicellulose (Esteves, Domingos and Pereira 2008).
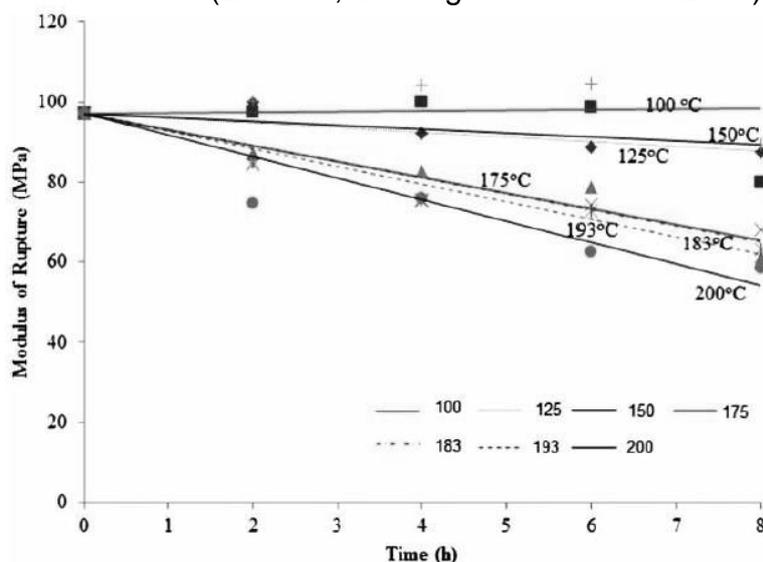


Figure 9: Bending strength as a function of exposure time and temperature (Sinha 2013)

When heating wood to different temperatures at various exposure times, Sinha (2013) found a steady decrease in Modulus of Rupture (MOR), as shown in *Figure 9.* Little to no effect was recorded for the samples exposed to 100°C.

In slightly burnt wood, Meincken, *et al. (2010)* found that the MOE initially increased. For wood exposed to higher temperatures, however, the MOE decreased. The higher MOE of slightly exposed wood can be explained by the thickening of cell walls, an initial degree of polymerisation and subsequent decrease in lumen diameter.

A known disadvantage of heat-exposed wood is its mechanical brittleness, which causes a higher MOE and a lower MOR. The MOR decreases with an increase in temperature, which can be attributed to the degradation of lignin. The decrease of strength of pine is directly proportional to the mass loss (Meincken, Smit and Steinmann 2010).

In another study by Berger and Meincken (2013) small pieces of *Pinus radiata* were subjected to different temperatures for different times and their MOE and MOR values were determined subsequently

In *Figure 10*, the MOR of samples exposed to different temperatures for different lengths of time is shown. Initially a small increase in MOR could be detected, which was more pronounced for longer exposure times. For temperatures exceeding 200°C the MOR started to decline.
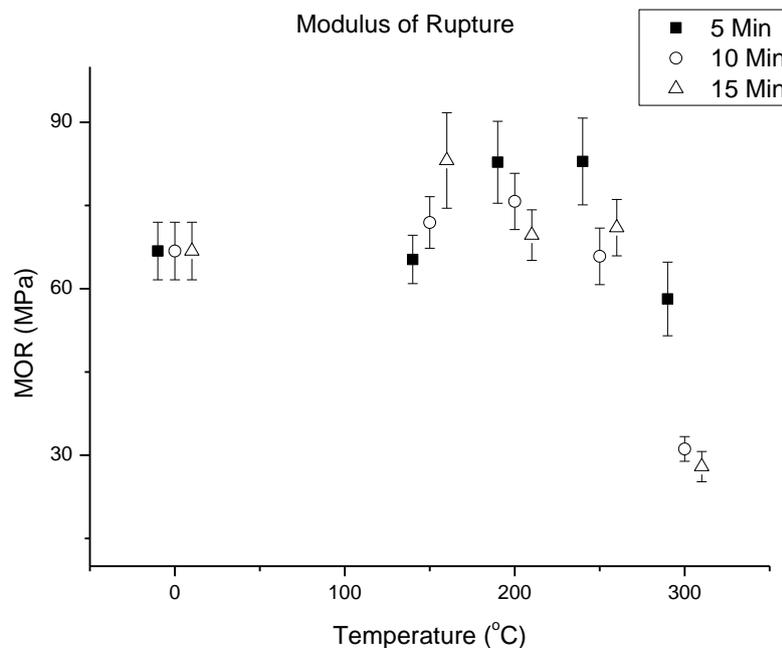
Figure 10: MOR values for different temperatures and exposure times

## 1.9 Minimum requirements for different timber uses

Timber has many different uses. It can be graded visually or destructively graded for its strength properties to determine the end use.

### 1.9.1 Structural grade timber

The South African Bureau of Standards published the first specification for graded timber in South Africa (SABS 5-1948) in 1948. The Department of Forestry later implemented compulsory grading of structural timber and the task of applying these regulations was given to the SABS (York timbers n.d.).

As density is a good indicator for strength, it is often used in conjunction with other grading methods to classify structural timber.

The minimum required density for visually stress graded timber according to SANS 1783-2 is given in Table 1.

Table 1: Structural timber requirements (South African National Standards 2005)

| Grade | S5 | S7 | S10 |
|---|---|---|---|
| Density ($^{kg}/_{m^3}$) | 360 | 425 | 475 |
| MOE (MPa) | 7800 | 9600 | 1200 |

The standard also states that timber intended for structural use should be free of insect damage and should not have more than half of the area covered by medium discoloration, of more than a quarter of the area covered by heavy discoloration. In the case of trees that died as a result of a forest fire, insect and fungal damage can occur if the trees are not harvested quickly enough.

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### 1.9.2 Industrial grade

Industrial grade timber can be used for a variety of applications, ranging from furniture to shelving and flooring. It is divided into six visual grades that give an indication of the end use:

- **Clear grade:** suitable for the manufacturing of high quality furniture and mouldings;
- **Semi-clear grade:** suitable for furniture and joinery;
- **Cutting grade:** suitable for recovering clear pieces for remanufacturing purposes;
- **Appearance grade:** suitable for the manufacture of furniture, flooring and shelving   and for joinery;
- **Utility grade:** suitable for manufacture of products where appearance is not important;
- **Packaging grade:** suitable for manufacture of packing products like pallets and crates

Table 2: Industrial grade density requirements (South African National Standards 2010)

| Grade | Clear Semi-clear Appearance | Cutting Utility Packaging |
|---|---|---|
| Density ($^{kg}/_{m^3}$) | 400 | 350 |

*Table 2* shows the density requirements for the different grades of industrial timber. The timber is graded visually, therefore timber will be graded with regards to knots and defects inherently present in the wood regardless if it was exposed to a forest fire or not. The deciding factor will be the wood density, as SANS does not prescribe MOE requirements for industrial timber.

### 1.9.3 Furniture

For furniture manufacturing strength is less important than visual appearance. There are generally three visual grades of wood used for furniture i.e. Clear, Select/Appearance and Industrial grade. Clear grade timber is normally used for high quality furniture and mouldings. Select grade timber is used furniture, shelving and flooring. Industrial grade timber is used in furniture where it is possible to hide the visually unappealing wood, like in upholstered furniture (York timbers s.j.).

Unless the wood was charred, the visual classification should be the same as for trees that were not affected by fire, though discoloration may occur.

### 1.9.4 Pulp

Pulp mills normally have a zero tolerance for charcoal, as charcoal contamination can spoil a large volume of pulp. Carbon particles are inert to the chemicals used in pulping and are of a similar density as the cooked pulp. Therefore they are not destroyed and very hard to remove. According to Watson and Potter (2004), due to the relative scarcity of wood, some pulp mills in Canada were forced to use trees that were damaged in forest fires. The trees were separated according to MC at the harvesting site to ensure that the trees taken into the mill had the desired MC. By adjusting settings on the debarking machines, some mills were able to limit the charcoal contamination to only 0.03% when using logs that sustained fire damage to the wood. The pulping recipe should be adjusted when chips from burnt trees are added. Watson and Potter explained that when sulphite pulping was used to pulp spruce trees that died as a result of a forest fire, the cooking conditions proved to be too harsh, which resulted in lower strength and bleachability.

Another concern for pulp mills is the moisture content of the wood they use. Chips with low MC have to be steamed to raise the MC before pulping, resulting in higher costs.  When using a mix of burnt and fresh wood, some Canadian pulp mills experienced paper with higher tear and burst strengths, but lower brightness and tensile strength. This suggests that the thermally degraded chips had started to decay. It was concluded by Watson and Potter (2004) that timber affected by forest fires can be used for pulp and paper, as long as the trees are harvested as soon as possible, to retain as much moisture as possible, and all charcoal is removed by debarking (Watson and Potter 2004).

## 2. Materials and Methods

### 2.1  Sample collection
Samples were collected and measurements were taken on various visits in the plantation. The collection of samples was complicated due to the harvesting team not having any fixed cutting schedules. Harvesting operations were further complicated by heavy rains during the winter months, which made the collection of samples temporarily impossible.

### 2.1.1 Site
The samples originate from a private plantation, named Topcliff Farm, on the slopes of the Helderberg in Somerset-West in the Western Cape, South Africa. Only *Pinus radiata* samples were collected. In April 2011 a planned fire that got out of control burnt through the plantation, thereby damaging or killing more than 50% of the trees. The fire was reportedly started on a nearby golf estate to reinvigorate old fynbos, before it spread over to the plantation. A near gale force south easterly wind was blowing, driving the fire at a high speed around the mountain (Lewis and Williams 2011). *Figure 11* shows a map of the location of the plantation relative to the town of Somerset West.
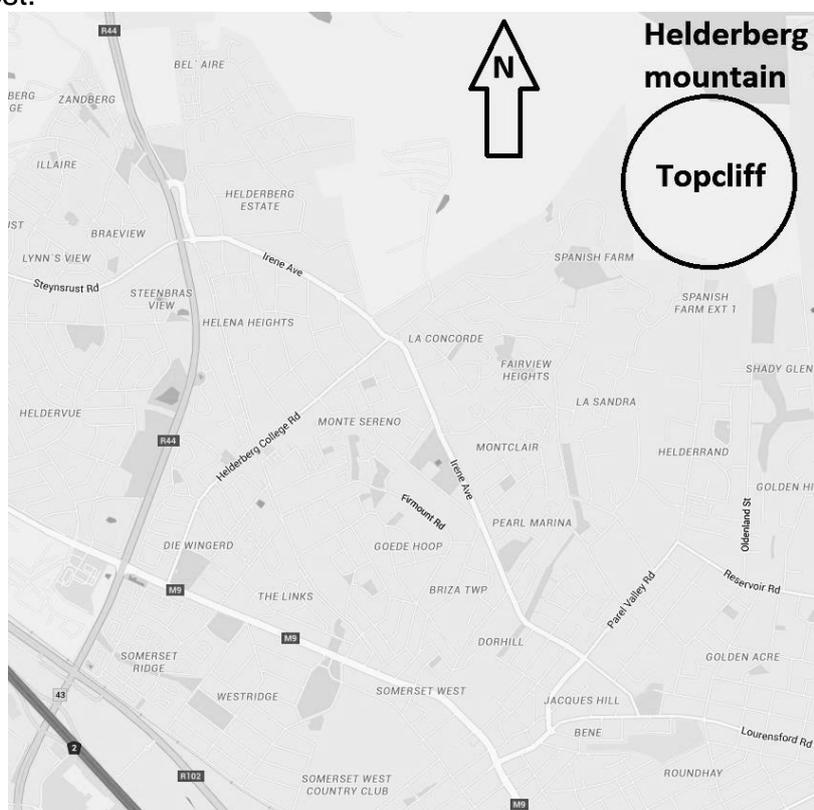


Figure 11: Location of the plantation

Because of the many different aspects of the slopes, the fire moved simultaneously in various directions through the plantation causing the burnt sides to face in different directions. Compass direction does not have an effect on the fire resistance of the bark, and therefore will be ignored in this study (Odhiambo, Meincken and Seifert 2014). Thus, the side that had the most char was marked as the burnt side, while the opposing side was marked the unburnt side.

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Additional severely burnt trees were also sampled from Jonkershoek in Stellenbosch. The fire broke out in the beginning of March 2015 and burned down about 5000ha of Fynbos, plantation trees and alien vegetation (Malgas 2015).

### 2.1.2 Visual classification

After the first visit to the source plantation, the trees were grouped in three classes (*Figure 12* and *Figure 13*) based on the amount of fire damage sustained:

**Class 1:** Trees that sustained fire damage to the bole, but are seemingly unaffeted. These trees have charred bark, but no canopy damage
**Class 2:** Trees that sustained fire damage to the bole and canopy.
**Class 3:** Trees that sustained damage to the bole and canopy and died as a result of the fire damage



Figure 12: Class 1 tree
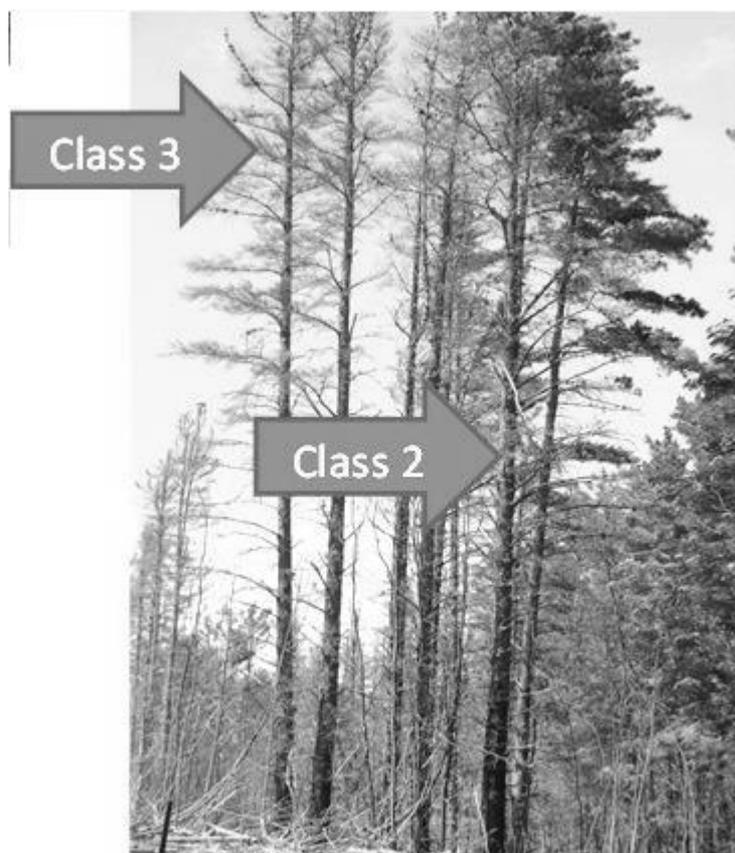
Figure 13: Trees from classes 2 and 3

### 2.1.3 Sample selection and collection

Sample collection was spread out over a long time, due to the harvesting operations very erratic and slow. Furthermore, harvesting operations ceased and the plantation was closed off in the wet winter months, making sample collection impossible.

At first 23 disks sawn from sawlogs after felling were collected from the plantation in Somerset West. These disks comprised of 15 disks from class 2 trees and 8 from class 3. The disks proved difficult to visually classify, as the trees were delimbed before being dragged to the roadside, where the disks were cut. This added to the slow rate of collection, as samples were not taken from trees that could not be classified.

The disks were cut from the bottom log and the burnt and unburnt sides were identified and marked. The disks were used to prepare samples for CT scanning, as well as lightness measurements. Only samples from class 2 trees were used for the CT analysis. As explained below, more samples from class 3 trees were collected from the plantation in Jonkershoek. In order to get results that were relatable within the class, it was decided not to mix the samples from different origins.

Samples from classes 1 and 3 were collected with an increment borer. Samples from class 1 trees were obtained from the plantation in Somerset West, while samples from class 3 trees came from Jonkershoek in Stellenbosch. The reason for this was, that by the time sampling started in Somerset West most trees from class 3 were already removed and hence samples were sourced from Jonkershoek.

### 2.1.4 MC measurements

The Moisture Content (MC) was measured on 135 standing trees from each class with a Bollmann resistance moisture meter. MC was measured at breast height on the burnt and the unburnt side.

### 2.1.5 Lightness measurements

Lightness measurements were taken on the cross-sections of logs stacked at roadside using a hand held photo spectrometer. The lightness (L) was determined on the burnt and unburnt side. The measurements were however, complicated by the rough surface of the logs and the presence of dirt and resin and were therefore not included for analysis.

Subsequently lightness measurements were repeated under laboratory conditions. The small blocks described in *Section 3.3* were dried and sanded and three lightness measurements were obtained as close to the surface under the bark as possible, to include the wood affected by the fire.

## 2.2 CT analysis

A computerized tomography (CT) scanner takes a series of x-ray images from different angles and, using computer software combines these images to yield cross sectional images of the scanned object.

All collected samples were kept in a conditioning room until they were processed. The conditioning room is kept at 20°C and 65% relative humidity. Prior to CT analysis the samples were oven-dried.

Two sets of samples were analysed with CT scans. Small samples cut from the 23 disks were scanned in the General Electric VTomex L240 CT scanner and analysed. The VTomex L240 is a large machine capable of scanning samples with diameters of up to 300mm. At the time the first set of samples were scanned, it was the only scanner available. With the resolution obtained the width and grey values for early and latewood band of the growth rings were measured. These samples were mounted on a small plastic cylinder with a density of $1200^{kg}/_{m^3}$. This plastic cylinder was used to relate the grey values to a density value. These scans unfortunately did not yield high enough resolutions and was not used further for this study. *Figure 14* shows an image obtained from this set of scans.
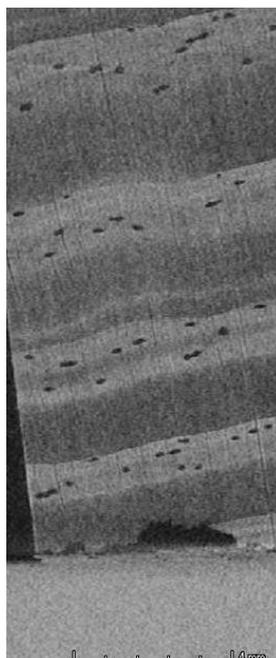
Figure 14: Image obtained from the first set of CT scans

The second set of samples comprised of specimens from 10 trees form each of the three classes. These samples were scanned with the General Electric Nanotom S, which allowed much higher image resolution. The Nanotom S is smaller than the VTomex L240 and can obtain higher resolutions. From these scans the growth ring width, grey value, cell wall thickness, lumen diameter and percentage of solid material was measured for the early and latewood bands of the growth rings.

*Figure 15* shows two images obtained from CT scanning. These images were analysed using Volume Graphics VGStudioMax 2.2 to obtain the measurements mentioned above.
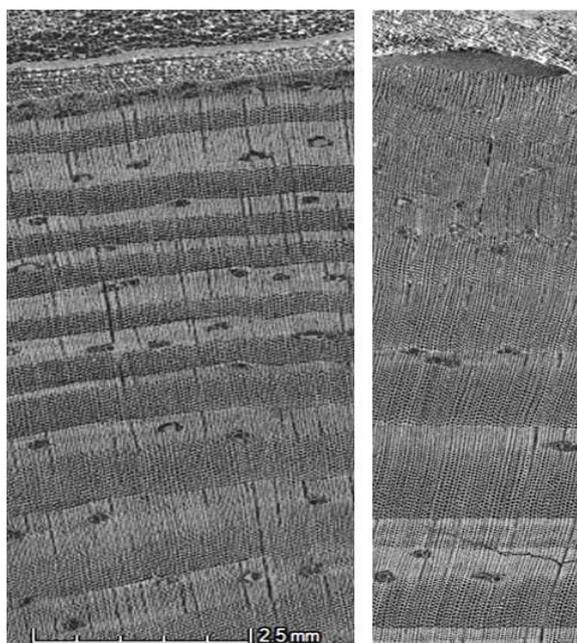


Figure 15: Images obtained from second set of CT scans

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The test samples were taken from the burnt and unburnt sides of the sample trees. For classes 1 and 2, the test samples were taken to include growth rings for two years prior to the fire, the year of the fire and two years after the fire. For samples from trees in class 3, the samples included growth rings for 4 years prior to the fire and the year of the fire, as there was no growth after the fire. Samples for class 1 had more growth after the fire, as they were taken later than the ones for class 2. This was taken into account when growth rings were identified and measurements were taken.

Samples were for classes 1 and 3 were collected with an increment borer, while the samples for class 2 were sawn out of disks taken from felled trees.

## 2.3 Statistical analysis

### 2.3.1 Hypotheses

The hypotheses were set so that the means of different measured characteristics of the burnt and unburnt sides of the trees could be compared. When comparing independent samples the hypotheses would look like the following:

The Null-hypotheses is:     $H_0: \mu_1 = \mu_2$ There was no difference between the two sample means

Alternative hypotheses is:     $H_A : \mu_1 \neq \mu_2$ There was a significant difference between the two sample means

However, the samples used in this study were dependant. To test if there is a difference in the means of paired samples, the difference between the two measured variables for each sample were determined and used as a new variable. The hypotheses then changed to:

The Null-hypotheses is:     $H_0: \mu_D = 0$ There was no difference between the two sample means

Alternative hypotheses is:     $H_A : \mu_D \neq 0$ There was a significant difference between the two sample means

With $\mu_D$ = the mean of the difference between the burnt and unburnt samples.

With the hypotheses set as above, a two tailed test, a significance level of 0.05 was performed.

### 2.3.2 Analysis Plan

The first analysis done was to test whether the data was normally distributed or not. The outcome determined which test could be used to compare the means. A paired T-test was used to test the hypotheses of normality. In order for the data to qualify for a Paired T-test, it must meet the following conditions:

- The sampling method must be random
- The samples must be dependant
- The sampling distribution is approximately normal

For data that was not normally distributed, a Wilcoxon Signed Rank test was used. In order for the data to qualify for the Wilcoxon Signed Rank test it must meet the following conditions:

- The sampling method must be random
- The samples must be dependant
- The measured data must be on an ordinal scale

All samples were obtained from random trees and came from opposing (burnt and unburnt) sides of the individual trees. Therefore the first two conditions for both the tests were met and the presence of normally distributed data was the deciding factor for which test was used. The Shapiro-Wilk test was used to test for normality, as the sample number is smaller than 2000.

# 3. Results and discussion

The main aim of this study was to determine if there are notable differences between the burnt and unburnt sides for trees from different damage classes and if the severity of anatomical/physical changes differed for the different burn classes. Age differences within trees were also investigated to determine if the fire had an effect on properties like cell wall thickness, lumen diameter and density.

## 3.1 DBH measurements

Standing tree MC and DBH values were taken from 135 trees from all three classes. The DBH values were used to ensure that the trees were normally distributed. *Figure 16* shows the DBH distribution of these 135 trees. It can be seen that the DBH-values for the entire sample of trees, were distributed normally.
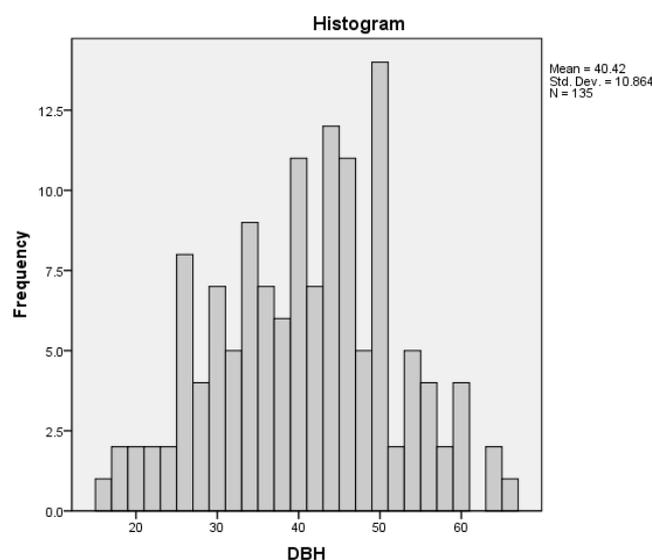


Figure 16: Histogram of the DBH values of all 135 trees measured for MC

The DBH values for classes 1, 2 and 3 were also normally distributed with p-values of 0.710, 0.595 and 0.171 respectively. These values are all higher than 0.05 and thus there is not enough evidence to reject $H_0$ in any of the cases. It is therefore concluded that the DBH values of the trees in all three classes are normally distributed.

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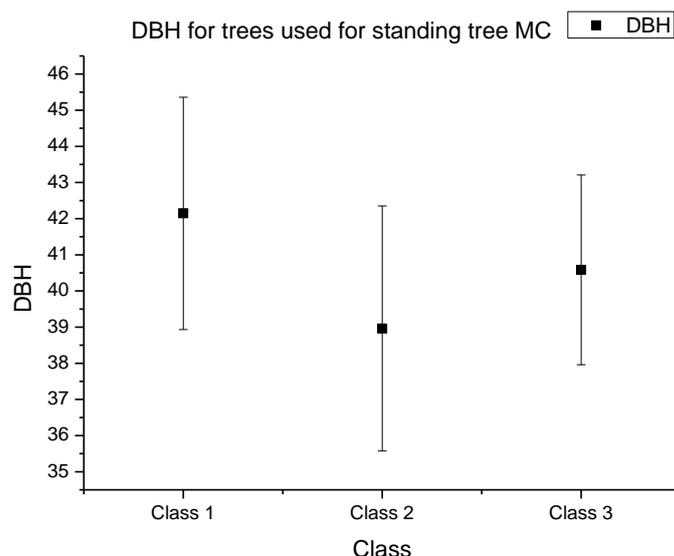
Figure 17: Means and 95%CI of DBH for standing trees used for MC measurements

*Figure 17* shows the distribution and standard deviation of the DBH values of the trees used for the standing tree MC measurements. No significant difference was found between the DBH values for the different classes.

The DBH values of the trees selected for CT analysis were tested and found to all be normally distributed within the tree classes (p-values of 0.92, 0.59 and 0.19 for classes 1, 2 and 3 respectively). Independent samples T-test was used to determine if there was a difference between the DBH values for the different classes. No significant difference was found between classes 1 and 2, with p = 0.49.
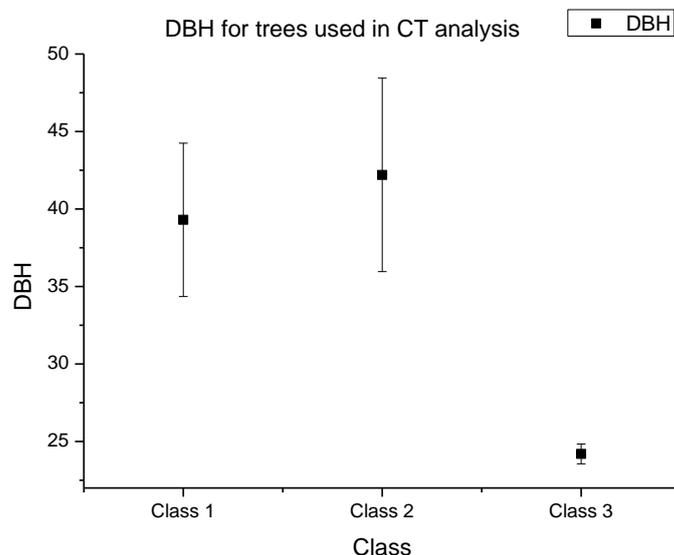


Figure 18: DBH and 95%CI for trees used for CT analysis

A significant difference was found between classes 1 and 3 (p = 0.01) and classes 2 and 3 (p = 0.01), as illustrated in *Figure 18.*

Since the sample trees for classes 1 and 2 came from one plantation (Topcliff Farm , Somerset West) and the trees from class 3 came from another (Jonkershoek, Stellenbosch), this is could be expected.

## 3.2 MC measurements on standing trees

MC measurements were obtained from standing trees, about two years after the fire occurred. Trees that had little to no needles left were marked as class 3 trees. *Figure 19* shows the average MC of the burnt and unburnt side of tress from class 1, 2 and 3. For classes 1 and 2, the difference in MC between the burnt and unburnt sides is normally distributed, with p-values of 0.229 and 0.051 respectively. The difference in MC for class 3 however is not normally distributed, with a p-value of 0.004
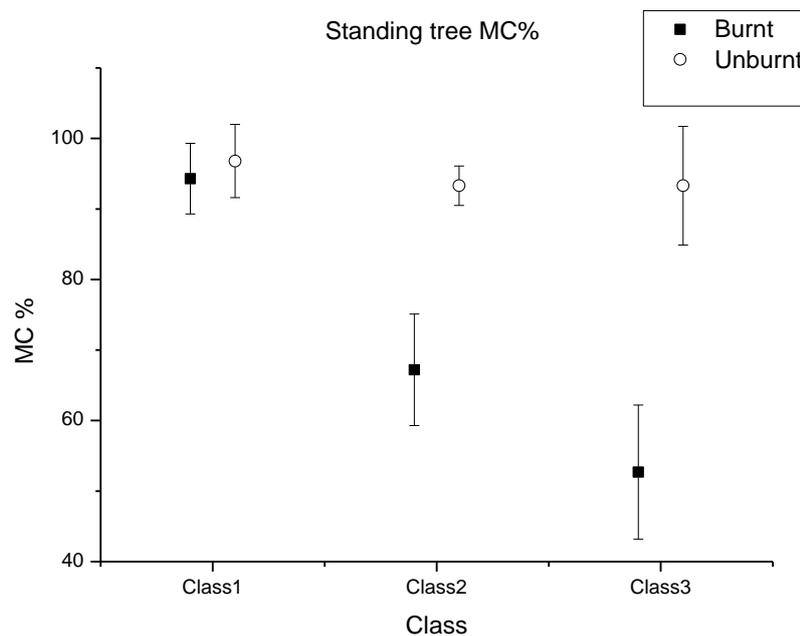


Figure 19: Means and 95% CI for MC values for different classes

For classes 1 and 2, the paired T-test was used to determine a significant difference between the MC of the burnt and unburnt sides, while for class 3 the Wilcoxon Signed Rank test was be used.

**Class 1**
A statistically significant difference between the MC values for the burnt and unburnt sides of trees from class 1 could be determined with p=0.044 at 95% CI.
**Class 2**
A highly significant difference between the MC values for the burnt and unburnt sides for trees from class 2 was determined with p<0.0001 at 95% CI.

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**Class 3**
A highly significant difference between the MC values for the burnt and unburnt sides for trees from class 3 was determined with $p<0.0001$ at 95% CI.

The difference between the burnt and unburnt sides for class 1 is, though significant, not as large as for classes 2 and 3. It is clear that the fire severity has a large effect on the standing MC.

As can be seen in *Figure 19*, the MC on the burnt sides of trees from classes 2 and 3 is significantly lower than that of the unburnt sides and this effect increases with the severity of the fire exposure. This most probably results from the evaporation of water from the tree. It can be further influenced by the wood becoming less hygroscopic, because of the degradation of hemicelluloses, as explained in *Section 1.8.1*. This will result in a permanent reduction in hygroscopicity of the wood affected by the fire. As the degradation of hemicelluloses already starts at temperatures as low as 120°C, the hygroscopicity can be expected to decrease from the same temperature threshold.
This will affect further processing and drying of the wood. Timber exposed to high temperatures has been found to take longer to dry, and have larger variation in the MC within boards, which could lead to warping and twisting and is most likely as a result of pits being blocked, as explained in *Section 1.8.3* (Meincken, Smit and Steinmann 2010).
Saw logs that have different MC values on opposing sides may also pose problems. Saws will cut through the wet and dry material and wear out at different rates which could slow down production.
Trees with different MC values on opposing sides will have a smaller impact on the pulping process, but will have to be treated differently compared to healthy trees. The chips from the wetter and dryer sides of trees will mix in the chipping process, resulting in the need to steam them before pulping. This will incur more costs for the mill.
As exposure to fire already degrades some of the wood components, the pulping process would have to be adjusted. The reduction in extractives, hemicelluloses and lignin may result in the standard pulping recipe for fresh chips to be too harsh, resulting in lower strength pulp, as explained in *Section 1.9.4*.

**3.3 Lightness**
Disks cut from 23 felled trees were used to cut smaller samples to determine the lightness values. 15 Samples were obtained from trees from class 2 and 8 from class 3 trees. The samples were oven-dried before 3 measurements were taken from each of the burnt and unburnt sides.
The lightness values of the samples from class 2 showed no significant difference between the burnt and unburnt sides ($p = 0.061$) and the lightness values of the samples from class 3 showed an even less significant difference between the different sides ($p = 0.446$).
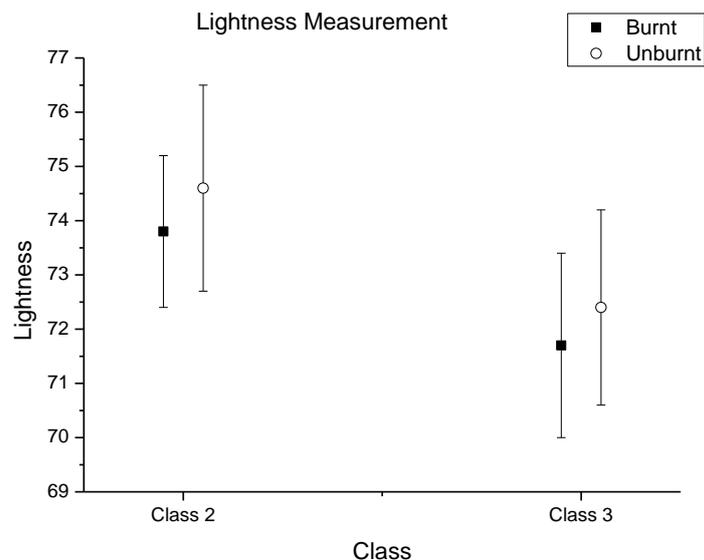
Figure 20: Lightness values and 95% CI for trees from classes 2 and 3

*Figure 20* shows the means and 95% CI of the obtained lightness values. It can be seen that for both classes the unburnt sides were slightly lighter in colour than the burnt sides. The difference is however not significant. It is also notable that the samples from class 3 were somewhat darker than the ones from class 2, although this difference is also not significant. The differences in lightness may be the result of extractive degradation and migration to the surface.

### 3.4 Cell wall density
The percentage of material in a given volume of wood was determined by CT analysis and used to calculate the cell wall density values for early and latewood bands individually. The density of cell wall material is typically around $1500^{kg}/_{m^3}$, as mentioned in Section 1.7.1.

### Class 1 Earlywood
Values for 2009 and 2010 were not normally distributed, while the values for 2011, 2012 and 2013 were. There was a significant difference between burnt and unburnt samples for 2009 and 2010 but no significant difference for years 2011, 2012 and 2013 (p-values of 0.04, 0.01, 0.33, 0.80 and 0.21 for years 2009 to 2013 respectively). The difference in density between the burnt and unburnt sides for the years prior to the fire may be as a result of mass loss due to the fire, as discussed in Section 1.7.1. Although they are not all significant, the density on the unburnt side is generally higher than on the burnt side in all years, including the years before the fire, which means that the density was affected by thermal degradation. This effect is most notable in the year directly before the fire year and decreases towards the pith of the tree. The density difference is smallest in the year following the fire (2012), indicating that the fire may have affected both sides, but had a smaller effect on the unburnt side.
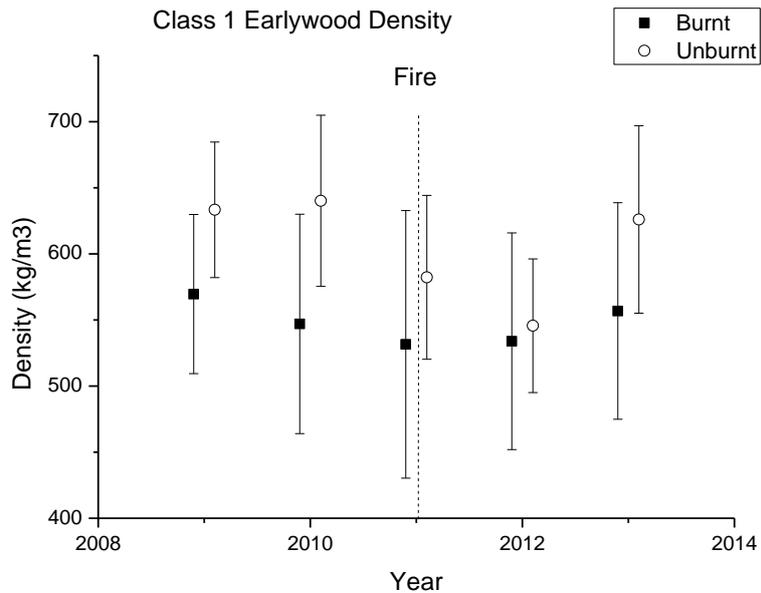
Figure 21: Class 1 Earlywood ring density and 95% CI

**Class 1 Latewood**

Values for 2009, 2010 and 2013 were normally distributed, while the values for 2011 and 2012 were not normally distributed. No significant difference was found for any given year (p-values of 0.61, 0.44, 0.17, 0.05 and 0.54 for years 2009 to 2013 respectively).
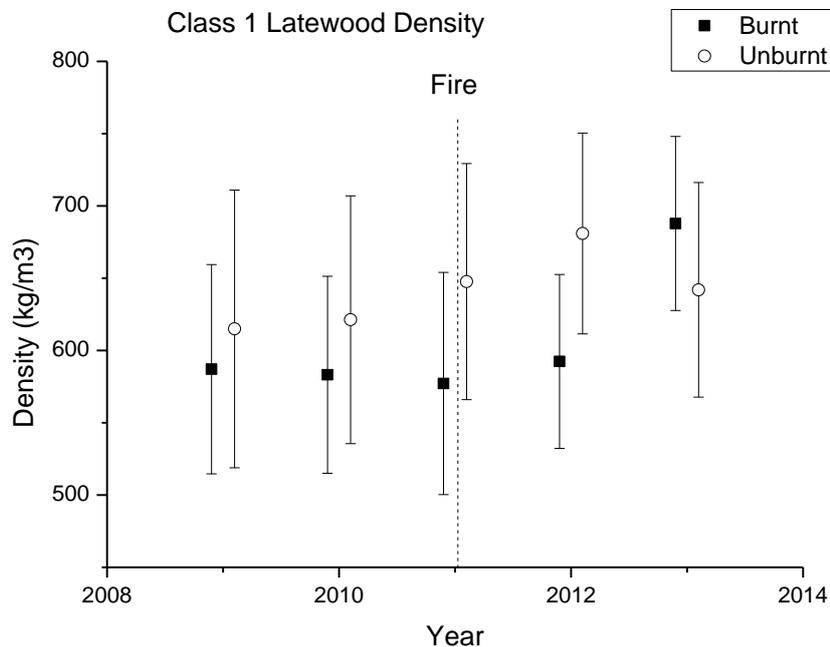


Figure 22: Class 1 Latewood ring density and 95% CI

*Figure 22* shows that the density increased on both sides after the fire, which can be translated into slower growth. This was somewhat more pronounced on the unburnt side. A significant difference between the densities of 2012 and 2013 on the burnt side (p-value = 0.04) could be observed. Generally the differences in density are less pronounced than in the earlywood.

**Class 2 Earlywood**

Values for 2009 and 2013 were not normally distributed, while the values for 2010, 2011 and 2012 were. No significant difference was found for any given year (p-values of 0.12, 0.59, 0.47, 0.61 and 0.45 for years 2009 to 2013 respectively).
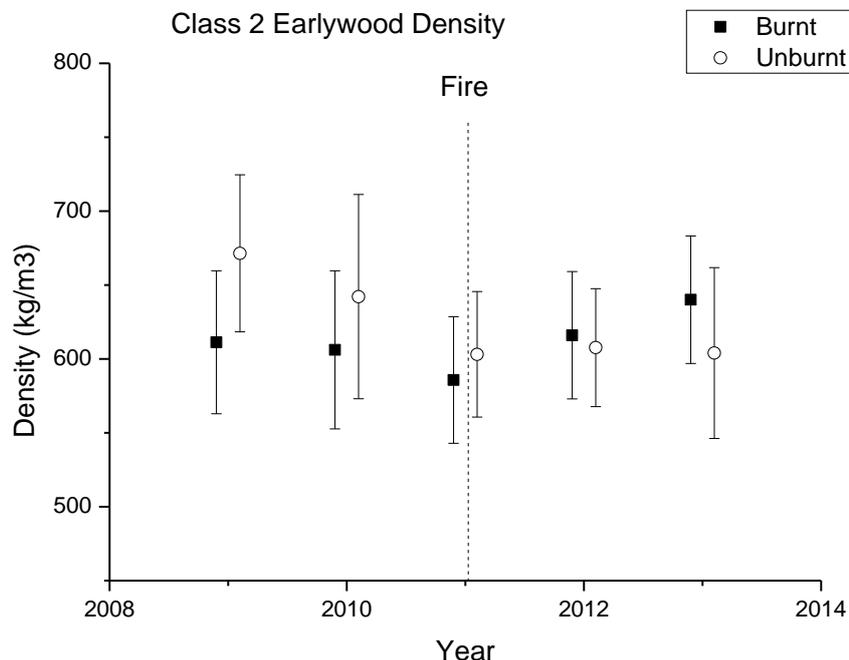


Figure 23: Class 2 Earlywood ring density and 95% CI

*Figure 23* shows that there were downward trends for both the burnt and unburnt sides in the years leading up to the fire. In the years after the fire the densities for both sides increased again. In the years leading up to the fire the unburnt side's density was higher, while after the fire, the burnt side seemed to recover more quickly and had higher densities that the unburnt side.

**Class 2 Latewood**

Values for 2009 and 2010 were not normally distributed, while the values for 2011, 2012 and 2013 were. No significant difference was found for any given year (p-values of 0.33, 0.68, 0.18, 0.75 and 0.19 for years 2009 to 2013 respectively).
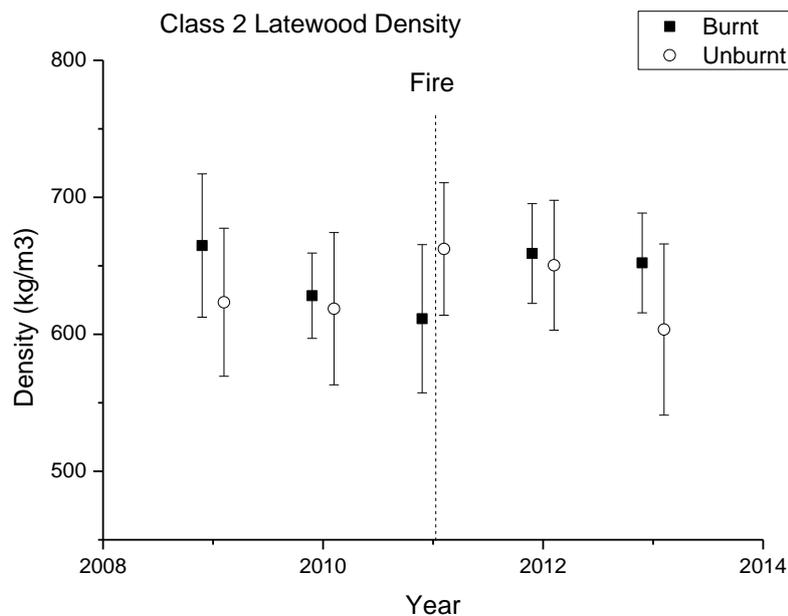
Figure 24: Class 2 Latewood ring density and 95% CI

*Figure 24* shows a decrease in density on the burnt side for the years leading up to the fire and a rise in the years thereafter. The density on the unburnt side remained fairly constant in the years prior to the fire, raised during the year of the fire and sloped downward again thereafter. There was a significant difference between the densities of 2010 and 2011 on the unburnt side (p-value = 0.21). The higher density for 2011 may be as a result of growth taking place after the fire occurred, or the densification as discussed in *Section 1.7.1.* A significant difference was also found on the burnt side densities of 2011 and 2012 (p-value = 0.1).  The density increased from 2011 to 2012 and then remained similar for 2013.

**Class 3 Earlywood**
Only values for 2015 were normally distributed, while the rest were not. No significant difference was found for any given year (p-values of 0.66, 0.25, 0.52 and 0.81 for years 2012 to 2015 respectively).
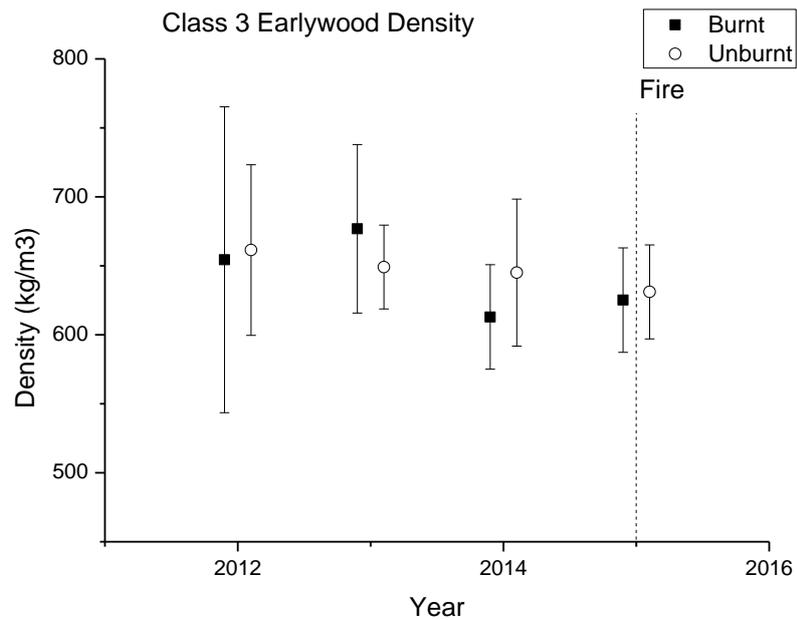
Figure 25: Class 3 Earlywood ring density and 95% CI

*Figure 25* shows a notable, but not significant, decrease in the years leading up to the fire for the burnt side. There is a decrease in the unburnt side as well, but not as pronounced as on the burnt side. This may be an indication that mass was lost due to exposure to the fire.

Class 3 Latewood

None of the values were distributed normally. No significant difference was found for any given year (p-values of 0.59, 0.35, 0.20 and 0.08 for years 2012 to 2015 respectively).
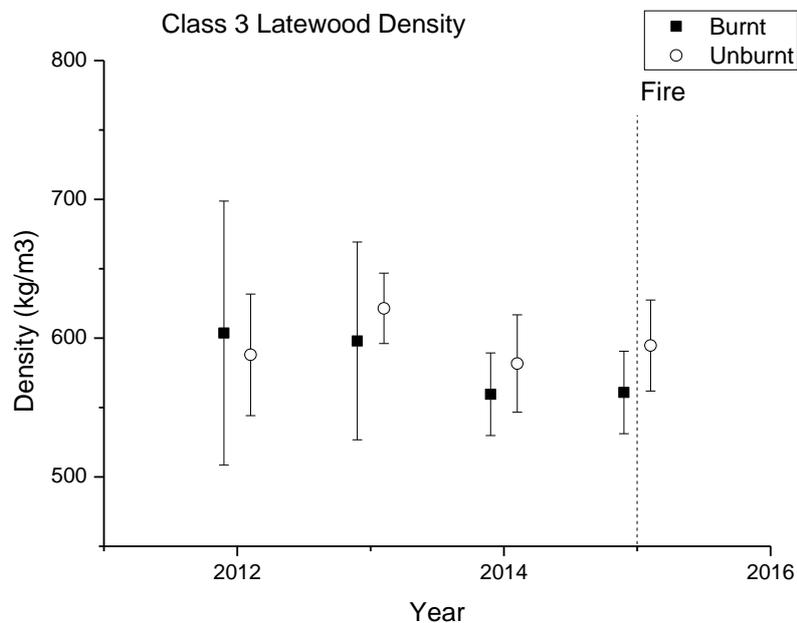


Figure 26: Class 3 Latewood ring density and 95% CI

*Figure 26* shows a notable decrease in the density of both the burnt and unburnt sides.

The reduction in density in the years leading up to the fire is likely due to the loss of mass, as described in Section 1.7.1. An increase in density for years following the fire is likely a sign of growth patterns returning to normal.

## 3.5 Wood density

The macroscopic basic density of the core samples was measured at a MC of 7%. The values were adjusted to represent oven dry density.



Figure 27: Wood density determined by physical measurements, showing the density requirements to achieve S10 grade

Figure 27 shows that the wood density is clearly affected to different degrees depending on the thermal exposure. The wood density of the class 3 trees may be lower than classes 1 and 2, regardless of the fire, as the trees were younger and came from a different site.  However, all sample means fulfil the density requirements for structural wood to be graded S10. There are however a few samples that lay between the S5 and S7 grades. This shows that the wood density is high enough to fulfil the density requirements for industrial and structural timber as given in Sections 1.9.1 and 1.9.2.

## 3.6 Growth ring width

Unless material is physically removed from the tree, growth rings already present will not be influenced by any stressful event in the trees life, such as a forest fire. Thus the width of growth rings present before a fire occurs will not be altered. The growth ring width was analysed statistically to determine if there were any differences between the ring width before and after the fire occurred. The growth ring widths were measured by analysing images from the CT scanner.

## 3.6.1 Growth ring width analysis

The growth ring width values were tested for normality, and later tested to determine if there was a difference between burnt and unburnt sides for each given year.

**Class 1 Earlywood**

For the trees from class 1, the ring width values for earlywood bands were not distributed normally. The Wilcoxon Signed rank test was used to determine if there was a difference between the ring width on the burnt and unburnt sides for each year. No significant difference was found between the ring widths for any given year (p-values of 0.89, 0.21, 0.72, 0.52 and 0.55 for years 2009 to 2013 respectively).
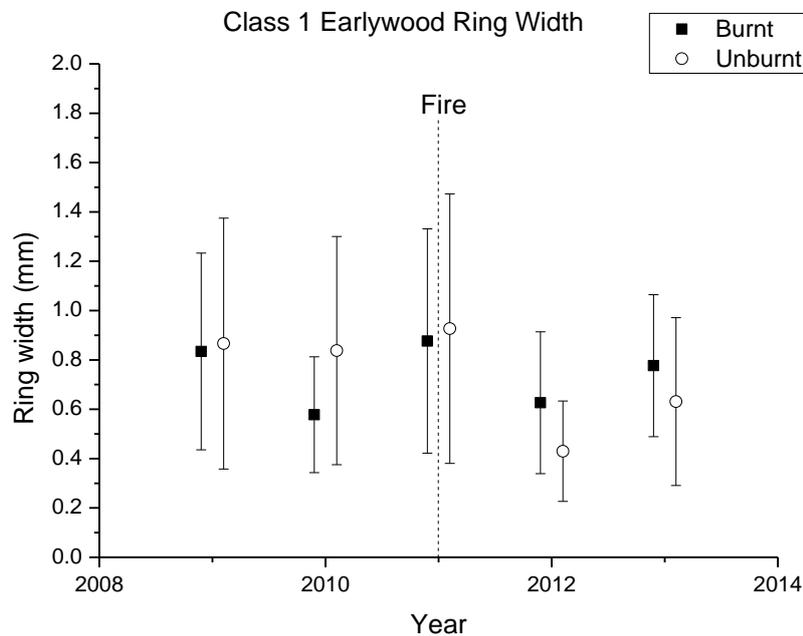


Figure 28: Class 1 Earlywood Ring width with 95% CI values

Although not significant, *Figure 28* shows that the ring width of the years following the fire was slightly smaller. This may indicate a change in growth patterns as a result of the fire. There is a reduction in the variation in ring width in the years after

**Class 1 Latewood**

For the trees from class 1, only one set of ring width values for latewood bands were distributed normally (2010). The Wilcoxon Signed rank test was used to determine if there was a difference between the ring width on the burnt and unburnt sides for each of the years with non-normally distributed values, while the paired T-test was used for the values for 2010. No significant difference was found between the ring widths for any given year (p-values of 0.76, 0.96, 0.88, 0.37and 0.58 for years 2009 to 2013 respectively).
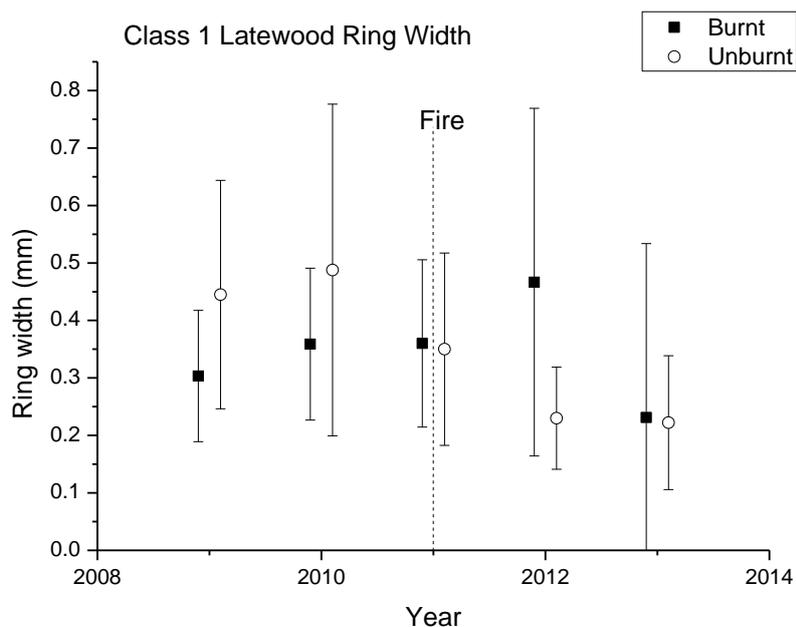
Figure 29: Class 1 Latewood Ring width with 95% CI values.

There is, however, a noticeable difference in the variation of the growth ring width of the latewood bands, as can be seen in *Figure 29*. It seems that the variation in rings on the unburnt sides decreased, while the variation on the burnt side increased after the fire.

As with the earlywood, no significant difference was found between the ring widths for any two different years. There is, however a reduction in the unburnt ring widths for the two years after the fire. Even though this reduction is not significant, it does have an influence in the Lloret indices in *Section 3.6.2.*

**Class 2 Earlywood**
For the trees from class 2, only one set of ring width values for earlywood bands was not normally distributed (2013). The Paired T-test was used to determine if there was a difference between the ring width on the burnt and unburnt sides for each of the years with normally distributed values, while the Wilcoxon Signed rank test was used for the values for 2013.

A significant difference between ring widths of the burnt and unburnt sides of was found for 2009 (p-value = 0.02). All the other years showed no significant difference (p-values of 0.19, 0.86, 0.44 and 0.31 for years 2010 to 2013 respectively). The difference found in 2009 cannot be as a result of the fire. Some other reason may be responsible for this difference.
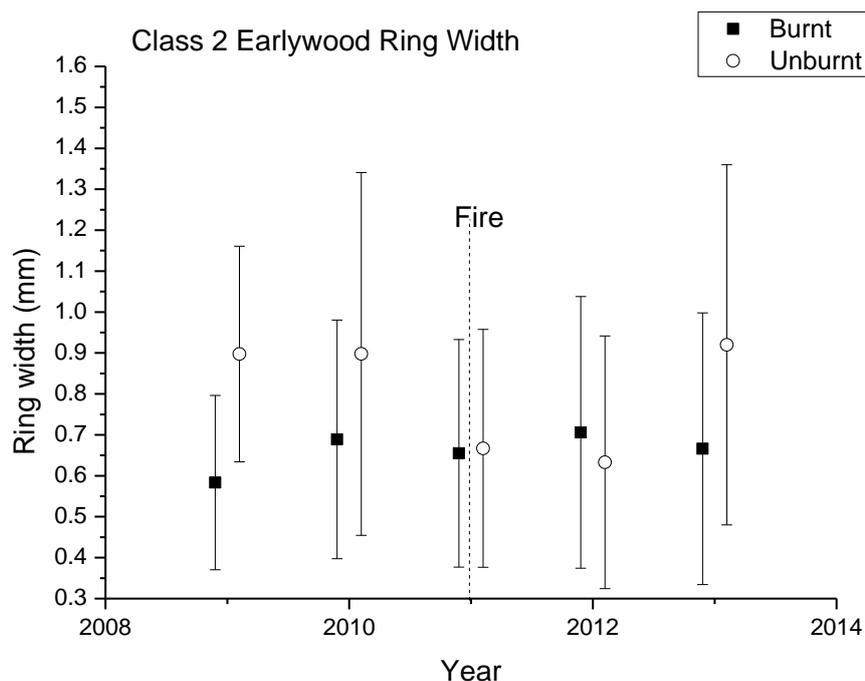
Figure 30: Class 2 Earlywood Ring width with 95% CI values

Although there is no significant difference between the growth ring widths, as can be seen in *Figure 30,* it is notable the variation is much higher for the unburnt side for 2013 than for any other year. No significant difference was found between the ring widths for any two different years. It seems that the unburnt side has regained the same ring width in 2013 that it had prior to the fire. For the burnt side, the ring width stayed constant.

**Class 2 Latewood**

For the trees from class 2, only one set of ring width values for latewood bands was not normally distributed (2013). The Paired T-test was used to determine if there was a difference between the ring width on the burnt and unburnt sides for each of the years with normally distributed values, while the Wilcoxon Signed rank test was used for the values for 2013.

No significant difference was found between the ring widths for any given year (p-values of 0.67, 0.52, 0.81, 0.75 and 0.24 for years 2009 to 2013 respectively).
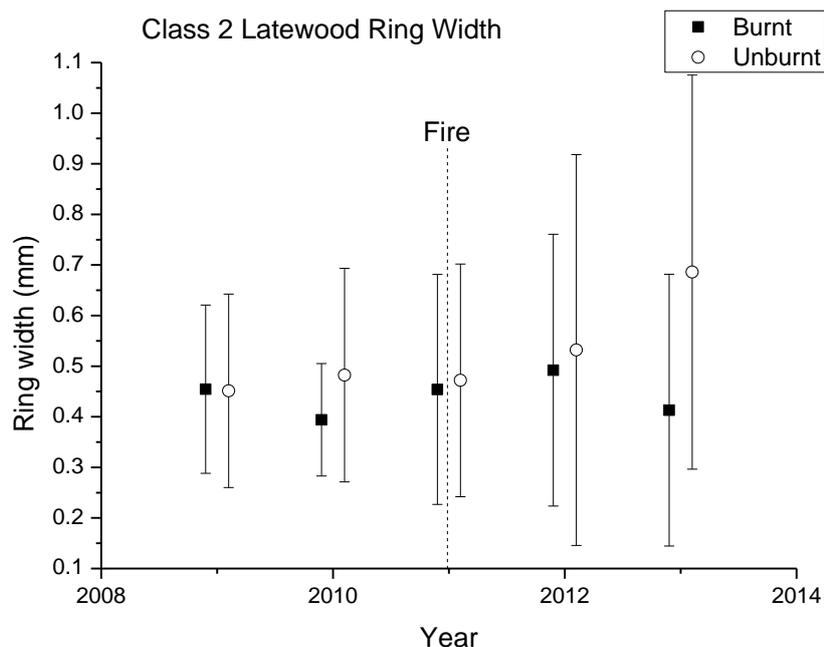
Figure 31: Class 2 Latewood Ring width with 95% CI values

As can be seen from *Figure 31*, there is a notable rise in the variance in the years following the fire. The rise is more pronounced in the unburnt side, which has increased ring widths following the fire. This may be as a result of less competition for resources, as some trees surrounding the class 2 trees died. No significant difference was found between the ring widths for any two different years.

**Class 3 Earlywood**

For the trees from class 3, two sets of ring width values for earlywood bands were normally distributed (2013 & 2015). The Paired T-test was used to determine if there was a difference between the ring width on the burnt and unburnt sides for 2013 and 2015, while the Wilcoxon Signed rank test was used for the values for 2012 and 2014.

The earlywood ring width for all 4 years showed no significant difference between the burnt and unburnt sides (p-values of 1, 0.45, 0.72 and 0.25 for years 2012 to 2015 respectively). This could be expected, as the ring width present before the fire would not be influenced by it.
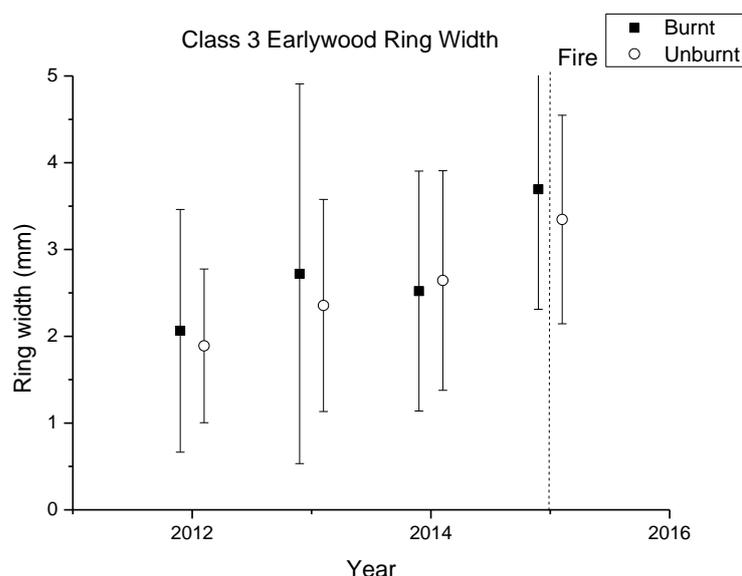
Figure 32: Class 3 Earlywood Ring width with 95% CI values

*Figure 32* shows a steady rise in ring width through the years leading up to the fire. This does however have nothing to do with the fire, as mentioned above.

**Class 3 Latewood**

For the trees from class 3, two sets of ring width values for latewood bands were normally distributed (2014 & 2015). The Paired T-test was used to determine if there was a difference between the ring width on the burnt and unburnt sides for 2014 and 2015, while the Wilcoxon Signed rank test was used for the values for 2012 and 2013.

Latewood ring width for all 4 years showed no significant difference between the burnt and unburnt sides (p-values of 0.14, 0.67, 0.12 and 0.49 for years 2012 to 2015 respectively).
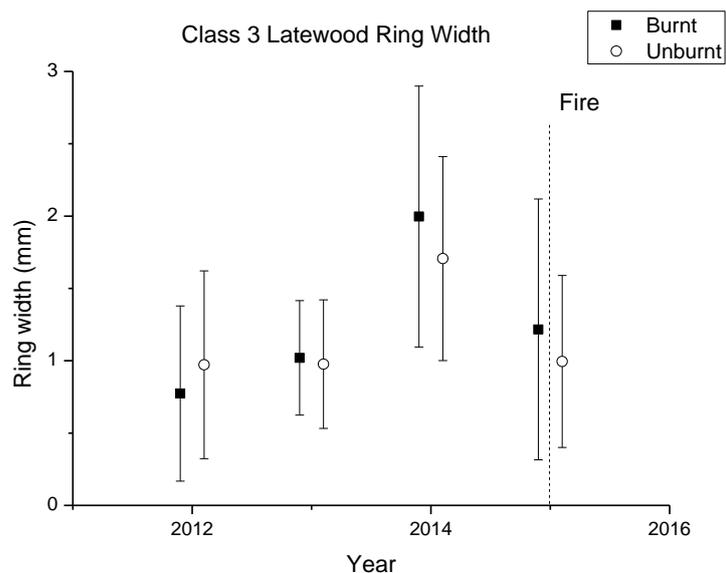


Figure 33: Class 3 Latewood Ring width with 95% CI values

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No significant difference was found between values for a given year and the year prior to or thereafter. Because of wide rings, some samples did not fit into the scanning area and thus the earlier years could not be included in the scans.

### 3.6.2 Lloret Indices

Lloret *et al.* (2011) identified several indices that were used to investigate the effects of a drought period on trees. The same indices were used to investigate the effects of the fire in this study. Trees from class 3 were not used for these indices, as there was no growth after the fire occurred.

Resistance is explained as the reversal of the reduction in performance during a stressful event. It is measured as the ratio between the performance before and during a stressful event (Lloret, et al. 2011). In this case it would be the ratio between the growth ring width before the fire and the width of the growth ring in the year of the fire.

$$Resistance = \frac{Fire}{PreFire}$$

A resistance ratio smaller than 1 shows that the tree could not resist the effects of the fire and that growth ring width was negatively influenced. A ratio of 1 and higher shows that the tree resisted the effect of the fire.

Recovery is explained as the ability to recover from a stressful event. It is measured by the ratio between the performance during and after the stressful event (Lloret, et al. 2011). In this case the growth ring widths during and after the year of the fire.

$$Recovery = \frac{PostFire}{Fire}$$

A recovery ratio smaller than 1 shows that the tree was unable to produce a growth ring that was the same width or wider than the ring produced in the year of the fire. A ratio larger than 1 shows that growth has increased from the year of the fire.

Resilience is the ability to reach the same performance levels as before the stressful event. It is measured by the ratio between the performance before and after the stressful event (Lloret, et al. 2011). In this case it would be the ratio between the growth ring width of years before and years after the fire.

$$Resilience = \frac{PostFire}{PreFire}$$

A resilience ratio smaller than 1 shows that the tree was unable to produce growth rings of the same width after the fire as before.

Relative resilience is the resilience weighted by the damage caused by the stressful event. It is estimated by the following equation:

$$Relative\ resilience = \left( \frac{(PostFire - Fire)}{(PreFire - Fire)} \right)\left( 1 - \left( \frac{Fire}{PreFire} \right) \right)$$

*Table 3* shows the values for different measurements described above. The years prior to the fire and after the fire were averaged to give *PreFire* and *PostFire* values respectively.

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Table 3: Lloret Indices

| Class | Side | Band | Resistance | Recovery | Resilience | Relative Resilience |
|---|---|---|---|---|---|---|
| Class1 | Burnt | Earlywood | 1.2 | 0.7 | 0.8 | -0.3 |
| Class1 | Burnt | Latewood | 0.9 | 0.9 | 0.8 | -0.1 |
| Class1 | Unburnt | Earlywood | 1.1 | 0.6 | 0.6 | -0.5 |
| Class1 | Unburnt | Latewood | 0.7 | 0.6 | 0.4 | -0.2 |
| Class2 | Burnt | Earlywood | 1 | 1 | 1.1 | 0 |
| Class2 | Burnt | Latewood | 1.1 | 1 | 1.1 | 0 |
| Class2 | Unburnt | Earlywood | 0.7 | 1.2 | 0.9 | 0.2 |
| Class2 | Unburnt | Latewood | 1 | 1.3 | 1.3 | 0.3 |

**Class 1 Resistance**
From *Table 3* it can be seen that, with the exception of two cases, the trees resisted the fire well. As no samples were taken from trees that had any visible scarring on the wood, it is highly unlikely that the width of growth rings formed before the fire was influenced thereby.

**Class 2 Resistance**
Trees from Class 2 seemed to have recovered better than the trees from class 1. The unburnt sides of the class 2 trees performed better than the burnt side, which may be because the burnt side suffered some damage that has influenced the growth. One possible explanation for the recovery being better for trees from class 2 than for class 1 could be that areas where class 2 trees were found had higher rates of tree mortality, leaving less competition and a chance for higher growth rates.

**Class 1 Resilience**
The resilience measured for trees from class 1 shows that growth ring width was lower after the fire than before. This indicates that the fire did influence the growth ring width even for class 1 trees.

**Class 2 Resilience**
Trees from class 2 seem to have been more resilient, as *Table 3* shows that there was an increase in the growth ring width. This may also be explained by the higher mortality rate around class 2 trees, resulting in less competition for resources, as mentioned earlier.

### 3.6.3 Early to latewood ratios

 shows the early- to latewood growth ring ratios for trees from class 1. No significant difference was found between the burnt and unburnt sides for any given year. No significant difference was found between any two years either. There was however a higher EW/LW ratio, as well as an increase in variance, for 2013 than for 2012.

Table 4: Early- to latewood ratios and 95%CI for classes 1 and 2

| | | Pre fire | | | | Fire | | Post Fire | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **EW/LW** | | **2009** | | **2010** | | **2011** | | **2012** | | **2013** | |
| | | **Burnt** | **Unburnt** | **Burnt** | **Unburnt** | **Burnt** | **Unburnt** | **Burnt** | **Unburnt** | **Burnt** | **Unburnt** |
| **Class 1** | **Mean** | 3.14 | 2.06 | 1.74 | 2.01 | 2.86 | 2.64 | 1.71 | 2.12 | 2.91 | 2.86 |
| | **95CI** | 1.75 | 0.74 | 0.56 | 0.61 | 1.71 | 0.9 | 0.63 | 0.86 | 1.18 | 1.27 |
| **Class 2** | **Mean** | 1.57 | 2.3 | 1.84 | 1.99 | 1.86 | 1.72 | 1.88 | 1.55 | 1.99 | 1.57 |
| | **95CI** | 0.44 | 0.45 | 0.62 | 0.69 | 0.85 | 0.55 | 0.83 | 0.37 | 0.5 | 0.28 |

For class 2, no significant difference was found between the burnt and unburnt sides for any given year. No significant difference was found between any two years either. The variance in EW/LW ratio was smaller for unburnt side in the two years following the fire. The EW/LW ratios and variances for 2012 and 2013 remained very similar for the burnt and unburnt sides respectively.
Class 3 trees were not included, as there was no growth after the fire occurred and the trees came from a different location.
In the years following the fire, trees from class 1 had higher, but more erratic and varied EW/LW ratios than the trees from class 2. The variance may be because trees from class 1 were subjected to fires of a wider variety, but lower intensity. This could have led to the growth patterns in class 1 trees being altered more erratically.

## 3.7 Cell wall thickness
## Class 1 Earlywood

Values for 2010 and 2013 were normally distributed, while the values for 2009, 2011 and 2012 were not normally distributed.

A significant difference was found between the burnt and unburnt sides for 2012, while no significant difference was found for any of the other years tested (p-values of 0.33, 0.32, 0.14, 0.01 and 0.57 for years 2009 to 2013 respectively). The difference in 2012 may be as a result of changed growth patterns after the fire.
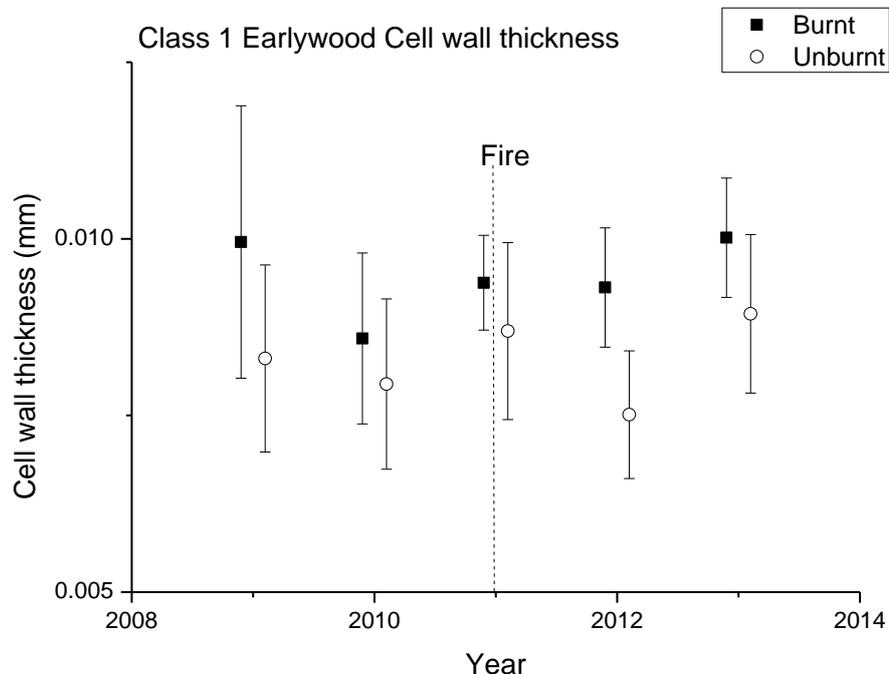


Figure 34: Class 1 Earlywood cell wall thickness and 95% CI

It can be seen from *Figure 34* that cell wall thickness on both the burnt and unburnt sides between individual years are comparable within the 95% CI.

This shows that the fire did not affect the already existing wood, but it did affect the wood growing in the subsequent year on the side that was more exposed to high temperatures.

## Class 1 Latewood

Values for 2010, 2011 and 2012 were normally distributed, while the values for 2009, and 2013 were not normally distributed.

A significant difference was found between the burnt and unburnt sides for 2009 and 2010, while no significant difference was found for 2011 to 2013 (p-values of 0.03, 0.04, 0.43, 0.31 and 0.38 for years 2009 to 2013 respectively).

In the latewood a clear difference in the already existing wood is noticeable. The larger cell wall thickness (see *Figure 35*) for 2009 and 2010 may be explained by the swelling of the cell walls, as explained in *Section 1.7.1*. The latewood growth after the fire event seems unaffected and no differences between the sides can be observed.
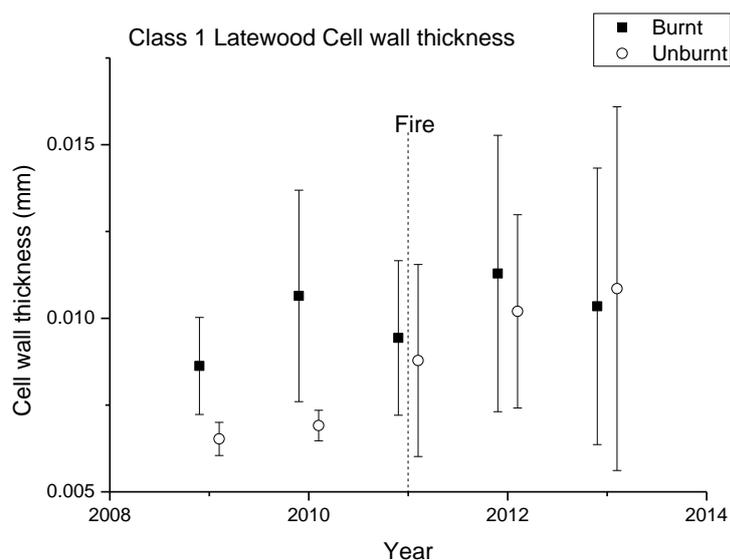
Figure 35: Class 1 Latewood cell wall thickness and 95% CI

**Class 2 Earlywood**

Only values for 2012 were not normally distributed, while the rest were distributed normally. No significant difference was found between the burnt and unburnt sides for any given year (p-values of 0.83, 0.12, 0.66, 0.22 and 0.51 for years 2009 to 2013 respectively).
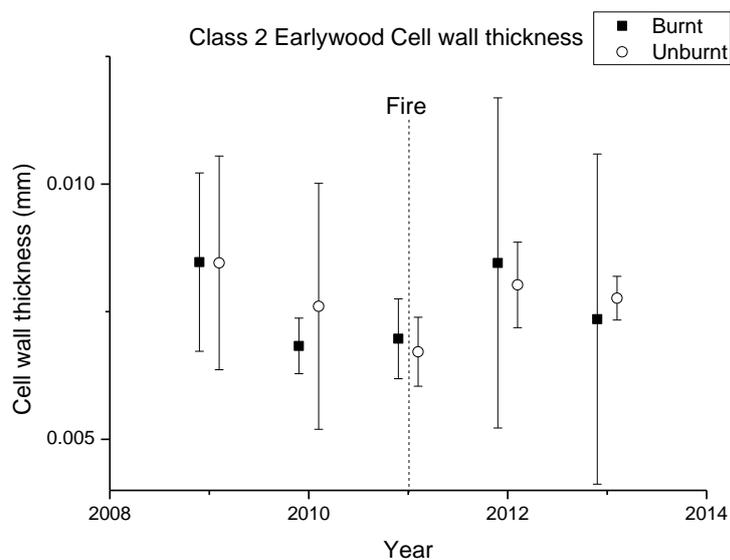


Figure 36: Class 2 Earlywood cell wall thickness and 95% CI

In *Figure 36* it can be seen that there is a big difference between the 95% CI for the burnt and unburnt sides in the years following the fire. The cell wall thickness on the burnt side of the trees shows a much larger variation. This could be due to the fire influencing growth patterns. The slightly lower cell wall thickness in 2010 on the burnt side may be the result of mass loss due to the exposure to high temperatures. The lower cell wall thickness on both sides in 2011 is probably due to slowed growth in the fire year.

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**Class 2 Latewood**

Values for 2009 and 2011 were normally distributed, while the values for 2010, 2012 and 2013 were not normally distributed. No significant difference was found between the burnt and unburnt sides for any given year (p-values of 0.67, 0.12, 0.73, 0.88 and 0.39 for years 2009 to 2013 respectively).
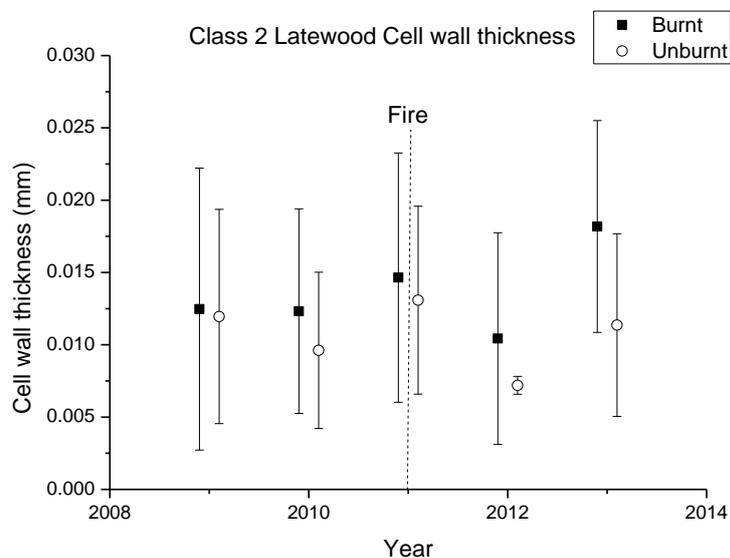


Figure 37: Class 2 Latewood cell wall thickness and 95% CI

It seems that the cell wall thickness for latewood was affected less than that of earlywood. The variation on the burnt side is, however, much larger than on the unburnt side. The variation to larger values may be the result of a thickening of cell walls due to plastification caused by high temperatures, while the variation to lower values may be caused by material loss due to degradation.

**Class 3 Earlywood**

None of the values were distributed normally. No significant difference was found between the burnt and unburnt sides for any given year (p-values of 0.29, 0.46, 0.95 and 0.96 for years 2012 to 2015 respectively).
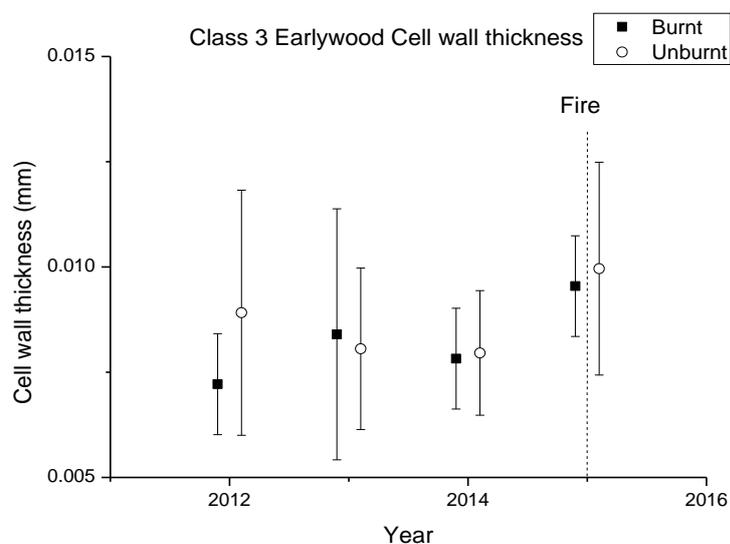


Figure 38: Class 3 Earlywood cell wall thickness and 95% CI

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The earlywood cell wall thickness for trees from class 3 was lower in the years leading up to the fire, as is shown in *Figure 38*, but in no year a significant difference between the burnt and unburnt side can be observed. This may have been caused by material loss due to the heat. It is unlikely however, that the rings from several years before the fire would lose material faster than the rings produced last. The similar means for the last 3 years suggests that the effect on the burnt side due to thermal degradation was negligible.

### Class 3 Latewood

None of the values were distributed normally. A significant difference was found between the burnt and unburnt sides for 2014, while no significant difference was found for any of the other years tested (p-values of 0.29, 0.83, 0.04 and 0.25 for years 2012 to 2015 respectively).
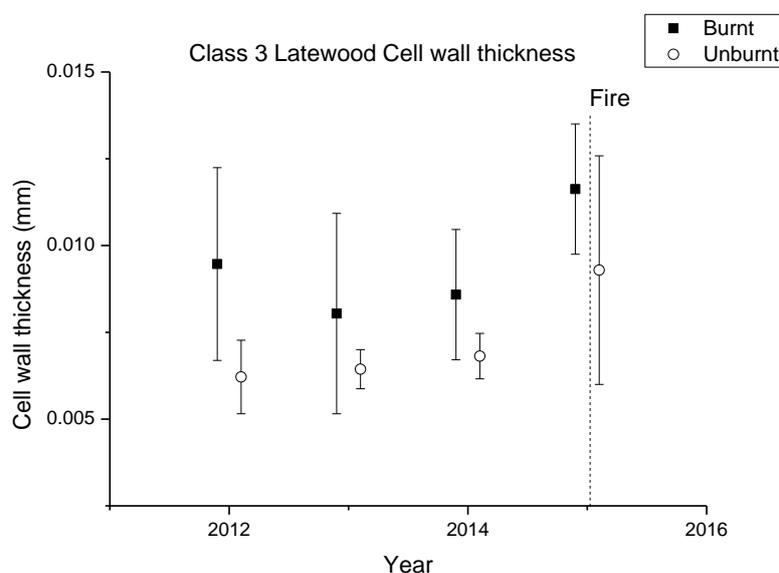


Figure 39: Class 3 Latewood cell wall thickness and 95% CI

*Figure 39* shows that the burnt side had a higher cell wall thickness in the years preceding the fire. This may be attributed to the swelling of the cell walls as explained in *Section 1.7.1*. In contrast with the latewood cell wall thickness of trees from class 2, it seems that the latewood cell wall thickness was affected more than the earlywood for trees from class 3. The variance on the burnt side is also notably larger than on the unburnt side, adding to the conclusion that the fire had a larger effect on the latewood bands of the class 3 trees.

### 3.8 Lumen diameter
### Class 1 Earlywood

Values for 2009, 2010, and 2013 were normally distributed, while the values for 2011 and 2012 were not normally distributed. No significant difference was found between the burnt and unburnt sides for any given year (p-values of 0.27, 0.77, 0.06, 0.31 and 0.35 for years 2009 to 2013 respectively).
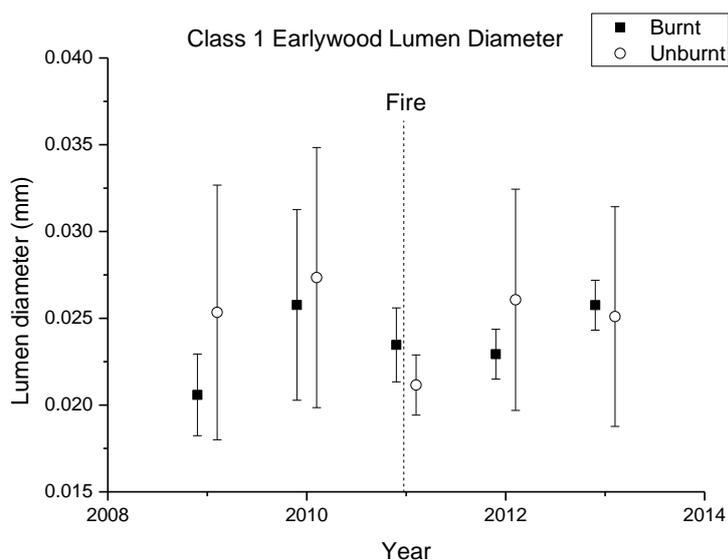
Figure 40: Class 1 Earlywood lumen diameter and 95% CI

In *Figure 40*, it can be seen that the variation on both sides was much smaller for 2011 than for any other year. The variation on the burnt side was largest in 2010 (the year before the fire) possibly as an effect of the fire. In the years after the fire the variation became smaller again.

**Class 1 Latewood**
Values for 2009 and 2012 were normally distributed, while the values for 2010, 2011 and 2013 were not normally distributed. No significant difference was found between the burnt and unburnt sides for any given year (p-values of 0.94, 0.37, 0.44, 0.89 and 0.07 for years 2009 to 2013 respectively).
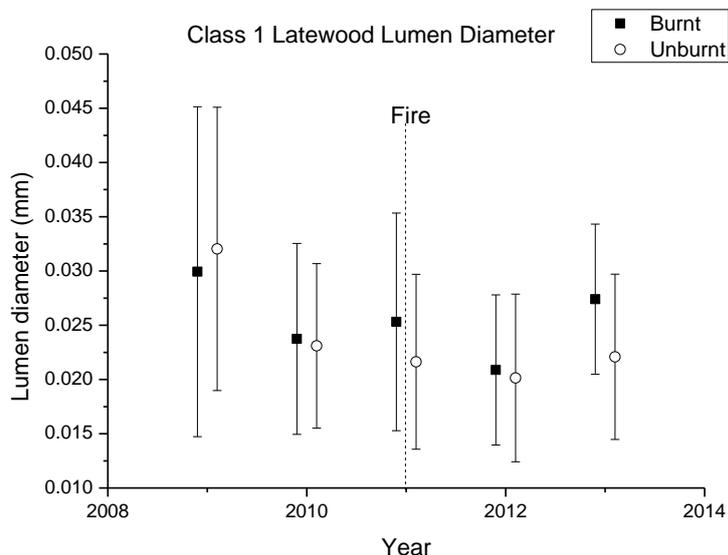


Figure 41: Class 1 Latewood lumen diameter and 95% CI

*Figure 41* shows that the lumen diameter was somewhat lower for the year following the fire. No differences between the sides were notable.

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## Class 2 Earlywood

All the values were distributed normally. A significant difference was found between the burnt and unburnt sides for 2009 and 2013, while no significant difference was found for the years in between (p-values of 0.04, 0.14, 0.53, 0.19 and 0.01 for years 2009 to 2013 respectively).
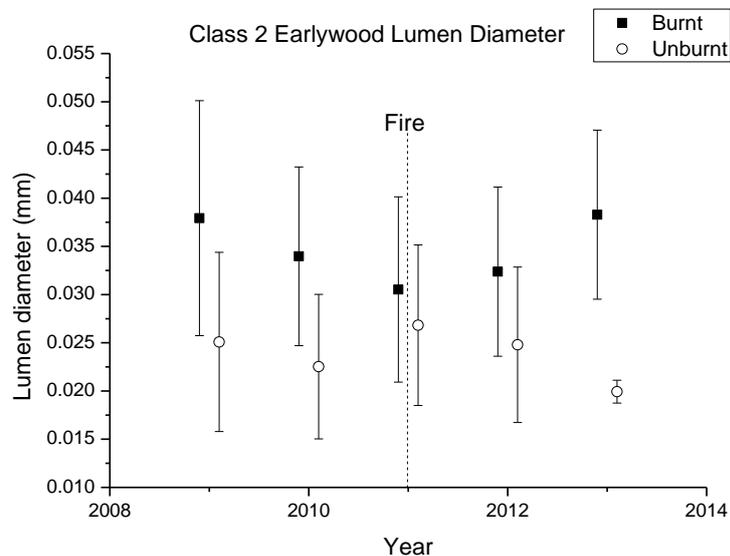


Figure 42: Class 2 Earlywood lumen diameter and 95% CI

While the lumen diameter for the unburnt side seemed to remain fairly similar for all years, *Figure 42* shows that there is a notable, but not significant drop in diameter in the years leading up to the fire and a rise in the years following it on the burnt side. The reduction in lumen diameter before the fire may be explained by the swelling of the cell walls into the lumen. Because the temperature experienced by the wood material would be lower as the penetration into the wood increases, earlier rings would be affected less.

## Class 2 Latewood

Values for 2009, 2010 and 2012 were normally distributed, while the values for 2011 and 2013 were not normally distributed. No significant difference was found between the burnt and unburnt sides for any given year (p-values of 0.61, 0.57, 0.58, 0.21 and 0.51 for years 2009 to 2013 respectively).
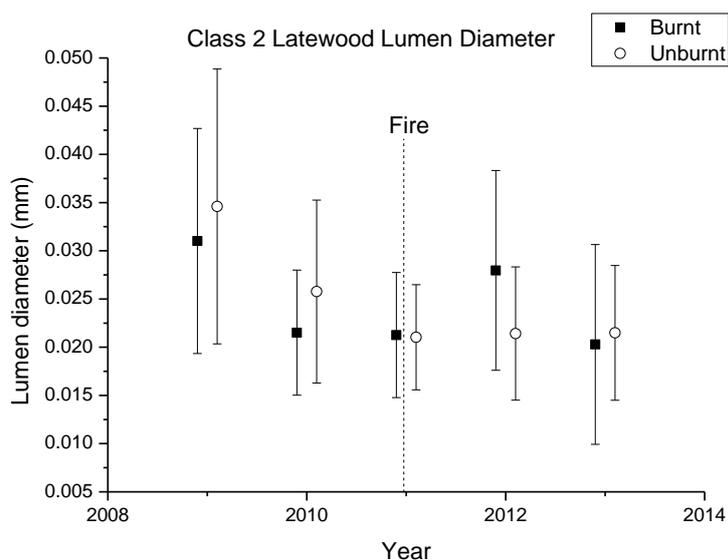
Figure 43: Class 2 Latewood lumen diameter and 95% CI

In *Figure 43* it can be seen that there is a notable drop in the lumen diameter for the years leading up to the fire, on both the burnt and unburnt sides, but as it is the same on both sides it is probably not an effect caused by the fire. In the years following the fire, the variation on the burnt side is larger.

**Class 3 Earlywood**
Values for 2012 were not normally distributed, while the values for 2013, 2014 and 2015 were normally distributed. No significant difference was found between the burnt and unburnt sides for any given year (p-values of 0.12, 0.89, 0.43 and 0.34 for years 2012 to 2015 respectively).
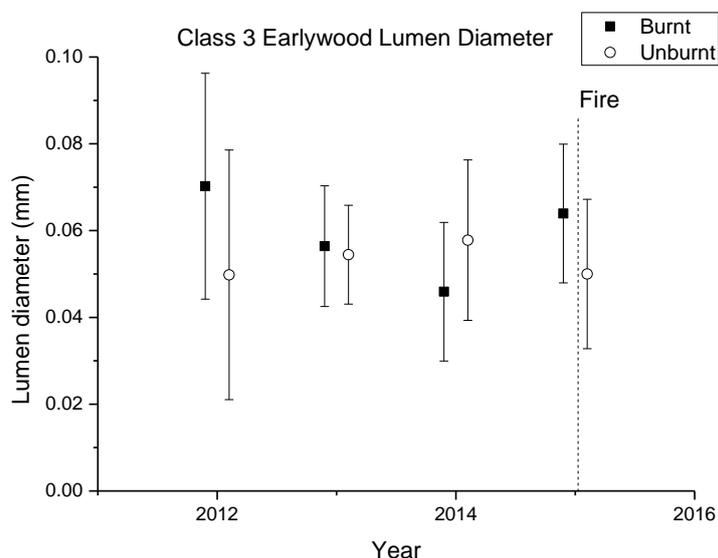


Figure 44: Class 3 Earlywood lumen diameter and 95% CI

A notable decline in lumen diameter can be observed on the burnt side in the years before the fire, as shown in *Figure 44*. The unburnt side's lumen diameter remains fairly constant. The wide 95% CI for 2012 is probably as a result of the number of samples being lower than for the other years.

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**Class 3 Latewood**

None of the values were distributed normally. No significant difference was found between the burnt and unburnt sides for any given year (p-values of 0.12, 0.6, 0.51 and 0.17 for years 2012 to 2015 respectively).
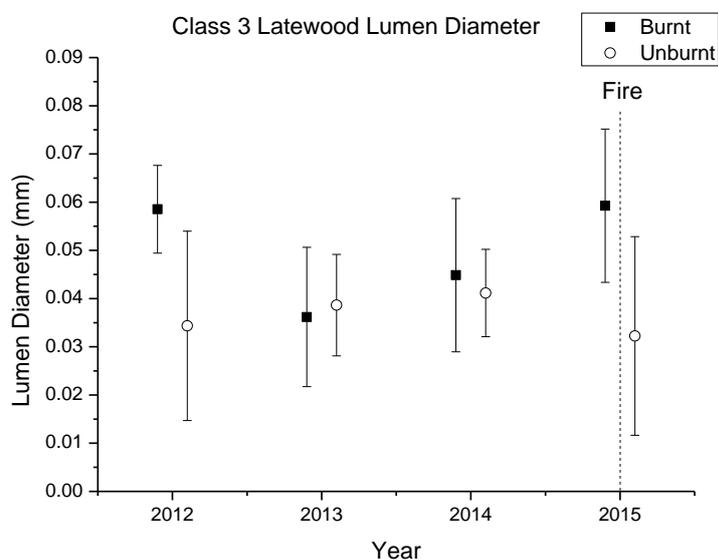


Figure 45: Class 3 Latewood lumen diameter and 95% CI

As can be seen in *Figure 45*, the variation on the burnt side is larger than on the unburnt side and the lumen diameter is notably larger on the burnt side in the year of the fire. This can potentially be caused by material removal due to thermal degradation. *Figure 39* in the previous section showed that the cell wall thickness was higher for the burnt side in the year of the fire. It would be expected that the lumen diameter would be inversely related to the cell wall thickness, but it is seemingly not the case here.

# 4. Conclusions

Significant differences between the MC could be determined on the burnt and unburnt sides of the standing trees for all three classes. The difference became larger with the severity of the damage to the trees. Class 1 trees were only slightly affected, while trees from classes 2 and 3 showed an increasing difference in MC between the burnt and unburnt sides The MC values on the burnt side were found to be increasingly lower on the burnt side. This variance in MC may cause difficulties in the drying process and could result in boards with a large drying gradient, which can lead to later deformation, such as warping (Meincken, Smit and Steinmann 2010).

Table 5: Summary of MC, Wood density and lightness measurements

| Class | Side | Standing MC | | Density | | Lightness | |
|---|---|---|---|---|---|---|---|
| | | Mean | 95% CI | Mean | 95% CI | Mean | 95% CI |
| Class 1 | Burnt | 89.0 | 7.7 | 614.5 | 63.0 | NA | NA |
| | Unburnt | 90.2 | 7.7 | 545.0 | 39.0 | NA | NA |
| Class 2 | Burnt | 83.3 | 5.9 | 571.8 | 13.4 | 73.8 | 1.4 |
| | Unburnt | 95.8 | 4.5 | 550.2 | 30.6 | 74.6 | 1.9 |
| Class 3 | Burnt | 33.8 | 3.2 | 488.3 | 17.5 | 71.7 | 1.4 |
| | Unburnt | 99.6 | 4.1 | 488.1 | 12.5 | 72.4 | 1.8 |

No significant differences were found between the lightness values on the burnt and unburnt sides for either class 2 or class 3, however, wood that was more thermally degraded (class 3) tended to be darker, which is probably caused by degraded extractives that migrated to the surface.

The macroscopic density showed a clear correlation to the fire exposure and lower density values were measured the more thermally degraded the wood was.

The mean and 95% CI values are given in *Table 5*. With the density requirement for S5 structural lumber of 360 $^{kg}/_{m^3}$ it can be seen that the mean values for all three classes met the required density. Although density is an indicator of other mechanical properties, each property should be evaluated to ensure that it meets requirements set out by SANS.

The cell wall density in earlywood of class 1 and 2 trees behaved similarly. In both classes the cell wall density in the years before the fire was lowered and increased again in subsequent years. This effect was more noticeable on the burnt side, where the density was notably lower than on the unburnt side. The differences between the sides in the latewood bands for classes 1 and 2 were much less pronounced than in the earlywood.

Both the early and latewood samples showed a lower cell wall density in the years before the fire for both sides in class 3 trees. The effect was more pronounced on the burnt side. This reduction in density is most likely due to mass loss as a result of fire exposure.

For trees from class 1, the earlywood ring width became narrower in the years following the fire. The latewood rings followed this trend, with the exception of a spike in the year following the fire. The latewood bands showed considerable more

variation in the years following the fire. It can be concluded that the ring width for trees from class 1 were slightly affected by the fire.

The earlywood ring widths for trees from class 2 remained constant on the burnt side, while there was a drop in width for the year of the fire and the following year. The latewood band also showed a constant width for the burnt side, while the unburnt side's ring width remained constant until two years after the fire.

Growth rings from class 3 trees could not be affected by the fire, as no new growth took place after the fire.

The Lloret indices show that trees from both classes 1 and 2 resisted the effects of the fire fairly well, with the exception of class 1 unburnt latewood and class 2 unburnt earlywood.

Trees from class 2 showed a better recovery than trees form class 1. This may be due to the fact that more trees around the surviving class 2 trees died as a result of the fire and therefore lowered the competition for resources.

Trees from class 2 also proved to be more resilient than trees from class 1. This may, however, also be attributed to the availability of resources.

The relative resilience of class 1 shows that growth ring widths decreased in the years following the fire. The relative resilience of class 2 trees on the burnt side indicates that the growth ring width remained constant. The unburnt side's ring width increased after the fire.

There was a significant difference in the cell wall thickness between the burnt and unburnt sides for earlywood in class 1 in the year following the fire. This is most likely due to the growth patterns being affected by the fire.

The latewood bands of trees from class 1 showed large variation in ring width. There was a notable drop in the width of the unburnt side's rings. The rings on the burnt side became wider for the year directly after the fire and narrowed down to the same width of the unburnt side in the following year. Although no clear trend is present, the fire definitely had an effect.

For both early and latewood from class 1 the cell wall thickness was higher on the burnt side in all years. A significant difference was found between the burnt and unburnt sides for the earlywood rings in class 1. This difference is most likely due to a change in growth patterns. The difference did not persist.

For class 2, a rise in the cell wall thickness, in the years following the fire, of the earlywood bands of both the burnt and unburnt sides was noted. The cell wall thickness was lower in the years preceding the fire and this was somewhat more pronounced on the burnt side.

In the latewood bands a slight increase in cell wall thickness following the fire could be observed on the unburnt side and most notably the burnt side shows a much larger variation than the unburnt side.

A slight increase in cell wall thickness was observed for both the early and latewood bands and the burnt and unburnt sides, for trees from class 3. In the latewood bands, the cell walls were notably thicker and had larger variation on the burnt side than on the unburnt side for all years. The thickening of the cell walls can be explained by the

plastification and subsequent swelling of the cell walls as a result of the exposure to heat. The effect is possibly more pronounced in the earlywood bands because the latewood bands are denser and thus less likely to swell into the lumen.

Lumen diameter for the burnt side of the earlywood bands in class 1 showed less variation in the years following the fire. The diameters increased in size in the years after the fire. This may be due to the growth patterns returning to normal. The lumen diameters showed a decrease in size for class 2 earlywood burnt side samples in the years leading up to the fire. In the years after the fire there was a rise again. Latewood samples from class 3 showed an increase in lumen diameter variation in the year of the fire, showing that the fire may have had an influence on the lumen diameter.

The lumen diameter should be inversely related to cell wall thickness. In this study the trends in cell wall thickness and lumen diameter did not correlate very well. This may be due to inaccuracy in measurements, which may be addressed in future studies by scanning at a higher resolution.

*Pinus radiata* is known to resist fire fairly well. It was shown by previous studies that physical and chemical changes start taking place from around 150°C. The loss in density confirms that temperatures of this magnitude and possibly higher were reached.

## 5. Recommendations

The biggest challenge of this project was the sample acquisition, which resulted in 3 different sample batches harvested at different times over a timespan of two years. Harvesting operations at the plantation in Somerset West were very erratic; making it difficult to get access to the plantation. The operations were shut down over the wet winter months, adding to the difficulty in collecting samples. By the time sample collection started, most trees from class 3 were already removed. The MC measurements were done before the trees were removed, making the MC results comparable. In order to obtain sufficient samples from class 3, trees from another plantation after another fire were used. These trees were younger and smaller, which explains the wider growth rings and adds to the lower density.

It is impossible to determine the exposure temperature and time of the trees without having measuring equipment present during the time of the fire. While other studies mentioned earlier in this study clearly show changes related to temperature and exposure time, the results are difficult to compare to the ones presented in this study, as they were obtained under controlled laboratory conditions. The varied fire exposure that the trees in this study experienced may add to the weak correlation of the results presented here compared to those other studies. The difference in fire exposure on individual trees can also be seen in the large variances measured determined in this project.

It is clear from the standing MC and wood density results that fire severity has a large effect on the trees. As the mechanical properties like MOE and MOR are related to density, it can be assumed that these properties will decrease with a decrease in density. Even though the sampled wood in this study fulfilled the density requirements for structural timber, the MOE values would have to be evaluated before it is used. If the MOE requirements are not met, the timber would still be ideally suited for industrial timber. Burnt trees can be used for pulping, as long as they are properly stripped of all char and treated with an adjusted pulping recipe.

This study did not show meaningful trends in the cell wall thickness and lumen diameter measurements. There were however visible increases in the variance of these properties that supports the findings of previous studies. Clearer results may have been obtained if the sample number had been larger. It would also be recommended that samples for future studies be taken over a shorter timeframe and only from one source. If possible, the inclusion of more growth rings before the fire is also recommended. These older rings can be used as a benchmark, unaffected by the fire, to relate affected rings to.

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