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Technical & Best Practice Recommendations

Guidelines for salvage harvest, storage and processing of plantation-grown logs affected by fire


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Foreword

This document has been developed to present a summary of the collective knowledge of many Australian forest industry members with previous experience in the salvage, storage and processing of fire damaged timber. The document fills a gap which was identified during the 2019/2020 fire season where extensive areas of Australian plantation and native forest were burnt. The authors, together with the Technical Expert Working Group, worked to assemble all of the relevant published references and a significant body of grey literature that contains the collective knowledge available for the salvage, storage and processing of fire damaged timber.

The document makes observations, best practice recommendations and identifies knowledge gaps however it is not a definitive document as such, because the variability of the fire events means that there are many possible combinations of inputs and outputs that can be achieved under different circumstances. It is envisaged that the document will be reviewed in advance of the 2021/2022 fire season to capture any additional knowledge arising from the most recent salvage storage and processing of fire damaged timber. As such the knowledge within the document represents the best available at the time of its preparation.

I wish to thank the members of the Technical Expert Working Group and the many other people who have contributed to the information presented in the document. It is hoped that the document will provide a basis for the most effective salvage, storage and processing of fire damaged timber and will provide the basis for an ongoing repository of the knowledge obtained in doing so. The foremost learning from the preparation of this document has been that fire incidents are not unforeseeable occurrences in Australia. Rather fires will continue to occur, maybe even more frequently and intensely, and the impacts need to be planned for strategically at an organisational and collective level to anticipate the likely responses required and minimise the adverse effects. I am confident that this document will contribute greatly to these successful outcomes from future fire events.

Chris Lafferty

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October 2020

Contents

Acronyms

Acronym	In full
AFPA	Australian Forest Products Association
BAU	Business as usual
BCA	Benefit cost assessment
CTL	Cut-to-length
DBHOB	Diameter at breast height over bark
EMC	Equilibrium moisture content
FSP	Fibre saturation point
FWPA	Forest and Wood Products Australia Limited
GIS	Geographic information systems
GRAC	Grower Research Advisory Committee
GSM	Grams per square metre
IFC	In-field chipping
LOS	Light organic solvent
MC	Moisture content
MDF	Medium density fibreboard
MGP	Machine graded pine
MSI	Multi spectral imagery
NBR	Normalised burn ratio
NIR	Near infrared
NIRS	Near infra-red reflectance spectroscopy
NSC	Non-structural carbohydrate
OHS	Occupational health and safety
PPE	Personal protective equipment
RAFIT	Rapid Assessment of Fire Impacts on Timber
ROS	Rate of spread
SED	Small end diameter
SWPTC	Solid Wood Processing Technical Committee
TEWG	Technical Expert Working Group
TIR	Thermal infrared

1 Summary

This document provides a quick reference guide for practitioners and planners as a basis for preparing for each fire season and salvage of forest resources following a fire. It is based on the collective knowledge of fire salvage, informed by industry experience and the literature (published and grey) and distilled into guidelines.

The evidence-based guidelines follow these steps:

- fire type and impacts
- fire impact on trees (moisture content, biological agents and physical agents)
- storage of trees on the stump
- considerations in the log yard (including de-barking)
- storage strategies (logs under sprinklers and immersed in water, and as woodchips).

They also summarise the impact of fire and storage on wood properties.

There is a long history of fires and their impact on plantations in Australia, with individual events documented in a range of publications. In most cases, post-fire salvage of logs has been straightforward, with direct supply into processors and/or alternative markets (e.g. export markets).

There are limited examples of large-scale and longer-term storage of fire salvage logs in Australia. Insights from log storage operations in other countries (e.g. salvage of wind throw and beetle-killed forests) has assisted in developing these guidelines.

Understanding changes in standing trees post-fire underpins development of response options and strategies. Carbon and dust contamination is an obvious and well-understood issue that can be addressed by log specifications, batching and aggressive de-barking. Where there is zero tolerance (e.g. some pulp and paper making), burnt logs need to be prohibited.

The wood properties in fire salvage logs and green harvest logs are different.

1. Dead standing trees dry from the top down, resulting in differential moisture content vertically within a stem and radially across a stem.
2. Insect attack will begin after a fire and stem drying and bluestain will most likely develop.
3. With correct log storage under sprinklers, log condition can be maintained, except for the action of bacteria.

Fire salvage logs are likely to have a lower moisture content and increased porosity and permeability (due to bluestain and bacteria). This creates different behaviours during processing and drying, which can be managed once processors are made aware of these issues.

2 Introduction

2.1 The project

As a consequence of the 2019/20 fires, Forest and Wood Products Australia Limited (FWPA) requested the development of guidelines for fire salvage and burnt log storage and processing for pine and eucalypt plantation-grown fibre in Australia.

Salvage of fire killed plantation timber requires addressing physical issues (e.g. degree of damage to standing trees, ability to harvest, management of burnt logs and processing of burnt logs) and financial issues (e.g. what is the best possible net financial position?). Following a fire, there is a need for rapid adaptation and innovation in response to emerging issues to maximise value recovery and response to unanticipated concerns, particularly relating to capacity to undertake work, and safety and environmental issues (this was a major learning from the salvage of softwood plantations burnt in the 1983 South Australian Ash Wednesday Fires). Decision making is influenced by market requirements, harvesting and processing capacity, fiduciary responsibilities and limitations placed on options by insurance and voluntary third-party certification. Environmental management issues run parallel to production issues (e.g. stabilisation of sites by over-sowing with grass).

2.2 Background

During the 2019/20 fire season, some 140,937 ha of plantations (about 80% *Pinus* species and 20% *Eucalyptus*) across Australia were burnt by bushfires, representing at least 10 million cubic metres of standing trees that have the potential to be harvested and sold either for their intended or an alternative use. Because these trees are now either dead or dying, management must be optimal to maximise their residual value.

Multiple management decisions are required throughout the course of a major savage operation. Vulnerability of fire-impacted trees to degrade and sensitivities of some markets to carbon in their processes are critical to financial outcomes. Management of significant impacts to forests has a long history (Fisher, 1896, p.430), as does considerations of 'fit for purpose' of resulting timbers (Fisher, 1896, p.77):

> *'If it is not possible to submerge the wood, and large quantities of wood must be stored dry for several years (as after insect-attacks, storms, etc), the greatest care must be taken to isolate them from ground moisture. Logs are, therefore, thoroughly barked and rolled into parallel rows one above the other, in shady places which are not exposed to dry winds ; the stacks of logs are also lightly covered with sods, to protect the logs from cracking in dry weather.'*
>
> *'In such cases it is important to decide whether by proper treatment the wood may not still be fit for use as timber. Practical tests for this are found in examination of the ends of the log, of its degree of hardness, dampness, odour, colour and sound given out when struck with the butt-end of an axe. In the case of standing trees, the appearance of the crown, branches and stem may be used to determine their condition'.*

Salvage harvesting is the removal of trees that have been killed or damaged by insects, disease, wind, ice, snow, volcanic activity, or wildfire. The primary purpose is to recover the economic value of trees before they degrade (Fitzgerald et al, 2018, p.1). In response to major wind damage in New Zealand in 1975, it was observed that:

> *'A critical factor in the past has been the lack of experience, the shortage of suitable equipment, and shortage of storage sites. The knowledge accumulated should shorten the lead-time required to establish water spray storage on a large scale. In Germany, wet storage has become part of log merchandising, permitting the central storage of wood for later selection and use without need for insecticides and fungicides with related environmental problems. Several of the storage sites described have been maintained through the years and are filled from time to time with freshly-felled logs to monitor storage experience' (Liese, 1984, p.153).*

A significant body of published information exists and, combined with industry experience, this provides insights and understandings on which to base log salvage systems.

2.3 Objectives and methods

The objective of this research was to identify the key issues arising from fire salvage, storage (as standing trees, under sprinklers, immersed in water and as woodchips) and processing of fire-impacted logs to develop guidelines for addressing them. The project is based on secondary investigations by the project team. Consultation with industry documented experiences, insights and perceptions relating to salvage of fire-impacted trees, storage and processing of salvage logs. Insights were used to focus a review of published information to seek a factual basis and further evidence. While this project focused on fire-impacted stands, broader overseas experience with storage of large volumes of logs has been gained in response to other events (e.g. storm events and beetle-killed forests). The project has been overseen by a Technical Expert Working Group (TEWG).

2.4 Project outputs structure

The project outputs are structured as follows (see Figure 1).

- Part A: A standalone document – Guidelines for salvage harvest, storage and processing of fire impacted plantation grown logs.

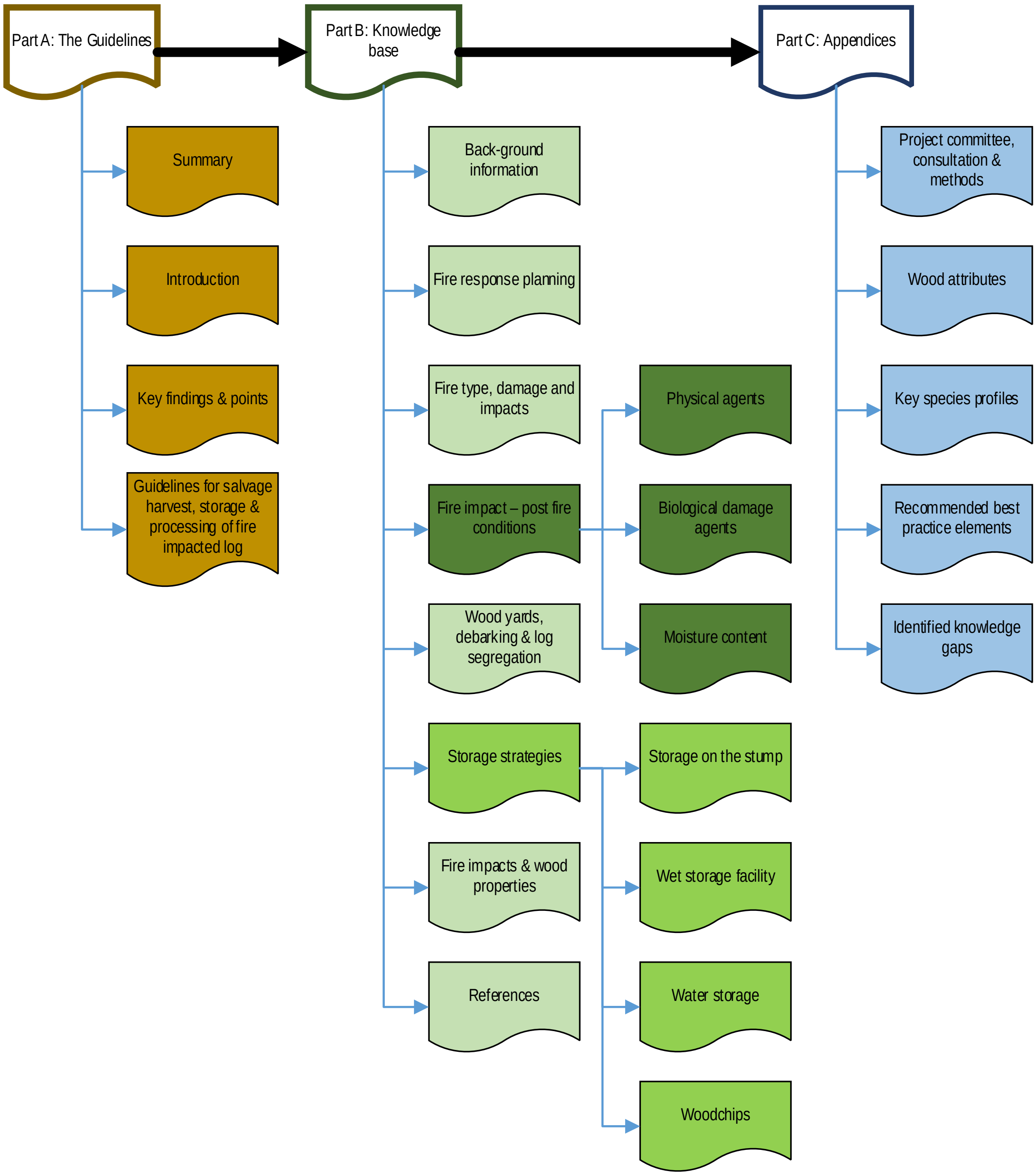
- Part B: The evidence underpinning the Guidelines and the basis of the identified knowledge gaps (this document).

- Part C: Supporting appendices within this document.
    - Appendix 1: Project process and methods
    - Appendix 2: Wood attributes
    - Appendix 3: Key species profiles
    - Appendix 4: Identified best practice elements
    - Appendix 5: Observations

2.5 Observation

Australia has had extensive experience in fire salvage but limited experience in wet storage of logs for any length of time. Globally there is extensive experience in wet storage of log resources salvaged after wind storms. While a range of insights have been collated, the process also identified knowledge gaps (see Appendix 5: Observations).

Figure 1: A roadmap of this document.



3 Key findings

The following are key finding and points relevant to salvage, storage and processing of fire damaged and killed forest resources.

- As the fire impact increases, so too does the departure from ‘business as usual’. Coordination between growers and processors, underpinned by cooperation is needed, with specific, contracted approaches to addressing fire events.
- Planning and implementation of fire salvage is time sensitive with a window of opportunity to effectively triage the task based on fire impact (classification and mapping), pre-fire stand conditions and markets.
- The ability to store fire-affected trees on the stump and match their harvest to processing capacity intake will be limited by the fire’s impacts on the trees (categorised and classified), the rate of tree stems drying out, commencement of insect attack (e.g. Ips) and subsequent development of bluestain. If modelling suggests a mismatch, dedicated storage facilities are needed or a plan to sacrifice upper stem logs (likely to degrade first) after storage on the stump.
- Response strategies should balance increased costs and management of risk of resource degrade.
  - Trees that were un-merchantable pre-fire are likely to be written-off, adding to re-establishment costs.
  - Storage on the stump and a substitution of affected trees for green tree harvesting (to conserve the unaffected resource) is the least disruptive strategy (if permitted by scale).
  - Harvest and stockpiling add costs.
  - Stockpiling can be in wet storage facilities under sprinklers or immersed in a water body (unlikely due to environmental impacts). A range of regulatory issues must be addressed.
- Log segregation and batching is critical to processing fire-impacted logs.
- Moisture content variation due to drying of stems from the top down and radially, affects log processing. Changes in log permeability and porosity (e.g. impacts to vessels and cell pits) due to bluestain in standing trees and logs, and bacteria during wet storage, will affect the drying behaviour of sawn timber. This can be addressed by changes to drying schedules for sawn timber but creates issues for pulp and paper and panel board manufacturing.
- Carbon and other contamination is not tolerated in pulp and paper, and panel board manufacturing. It has limited impact in sawmilling. Carbon can be addressed by quarantine (e.g. non-affected logs taken), aggressive de-barking, changing log specifications (to increase de-barking efficacy and reduce stowaway carbon) and changing markets (a swap to more-tolerant markets particularly for processing residues).
- Bluestain is not tolerated by some pulp and paper markets and panel board manufacturing. Bluestain is cosmetic from a sawn timber strength perspective, but impacts timber treatment due to increased wood permeability, pulping (increasing chemical uptake) and paper brightness (blue-stained fibres are dark in colour). Bluestain can be difficult to identify in trees and logs, with rapid onset possible. Insects attracted to affected trees can inoculate stems with bluestain fungi and can bore into trees potentially affecting export options.

- Sawn softwood timber will most likely be machine graded, with an MGP (machine graded pine) grade or below. Issues with drying fire-affected boards will be identified at this point, except for some internal board fractures. It is possible that systems will require calibration. Pulp and paper is intolerant as carbon and/or bluestain fibres cannot be detected and removed, and can cause whole runs of a paper to be rejected (it is binary – accepted or not rather than a percentage loss).

4 Background information

4.1 Summary

Consideration of fire impacts and salvage must be informed by understanding the interactions between trees and fire. The current plantation estate in Australia covers 1.9 million ha, with 46.1% hardwoods and 53.4% softwoods across a range of species. This section covers fire impacts on bark, phloem, cambium, sapwood and heart tissues and definitions of cellular structures and functions of each tissue type. The role of pits within wood tissue is critical to understanding fire-related impacts on wood. Pits control liquid movements between cells in wood and can aspirate (close), which creates issues with wood drying. Wood attributes of importance to fire impacts are moisture content and, in particular, fibre saturation point (the point at which free water has been removed from wood), after which wood strength increases.

4.2 Introduction

This section presents foundational information on aspects of this analysis: the Australian plantation estate and plantation fires; tree stem anatomy (tissue types) and wood cell types; wood attributes (moisture content, basic density and heat conductivity).

4.3 Australia’s plantations

4.3.1 The plantation estate

This analysis and review focuses on plantation fires in Australia. There are two broad types of trees: angiosperms (flowering plants) and gymnosperms (plants for which seeds are not enclosed in flowers). Hardwood species are angiosperms and softwoods are gymnosperms. Table 1 presents a list of the species noted in this document by broad grouping (softwood or hardwoods), scientific name and common name. Australia’s plantation estate was 1 942 700 ha (2017/18) with 46.1% hardwoods, 53.4% softwoods and 0.5% of ‘unrecorded’ species (Downham & Gavran, 2019, p.1). Figure 2 and Figure 3 present a breakdown of the estate for hardwood and softwood species respectively. Southern pines species is generic name for *Pinus caribaea* and *P. elliottii* and spotted gums include Corymbia species.

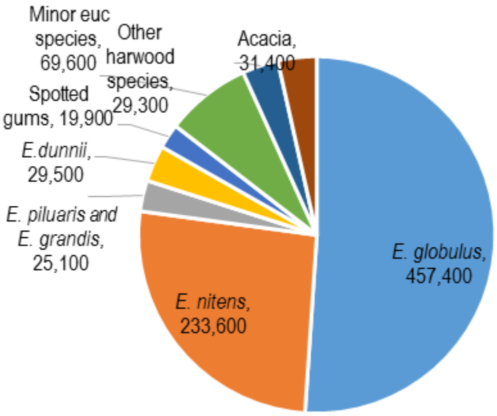


Figure 2: A summary of hardwood plantation species by area for 2017/18 (Downham & Gavran, 2019, p.11, Table 9).

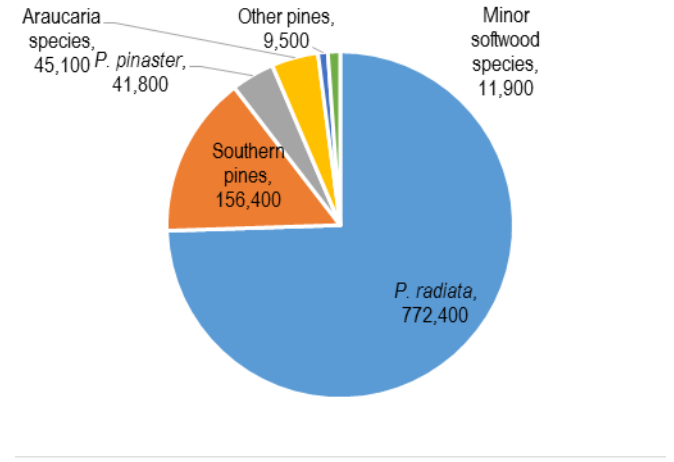


Figure 3: A summary of softwood plantation species by area for 2017/18 (Downham & Gavran, 2019, p.12, Table 10).

Table 1: A list of the species mentioned in this report by scientific and common name.

Broad group	Scientific name	Common name
Softwoods	Araucaria	
	Pinus caribaea	Caribbean pine – one of the Southern pines
	P. elliottii	Slash pine – one of the Southern pines
	P. leiophylla,	Chihuahua pine
	P. patula	Patula pine
	P. pinaster	Maritime pine
	P. pseudostrobus	Smooth-bark Mexican pine
	P. radiata	Radiata pine
	P. taeda	Loblolly pine– one of the Southern pines
Hardwoods	*Acacia*	
	Eucalyptus dunnii	Dunns white gum
	E. globulus	Tasmanian blue gum
	E. grandis	Flooded gum
	E. nitens	Shining gum
	E. pilularis	Blackbutt
	E. regnans	Mountain ash
	E. saligna	Sydney bluegum

4.3.2 Plantation losses to fire

Plantations in Australia are exposed to regular and expected fires (see Figure 4).

4.3.3 Specific fires referenced in this document

Fire and fire impacts have been studied and reported extensively for Australia and internationally (Table 2) and provide a range of insights and lessons. In some cases, studies focused on specific issues; in others, the studies did not take account of the fundamental variation of wood properties. For example, a study considering fire impacts on *P. patula* wood properties following a fire in South Africa in 2007 did not address vertical position within an individual tree or radially across the stem (see Box 1).

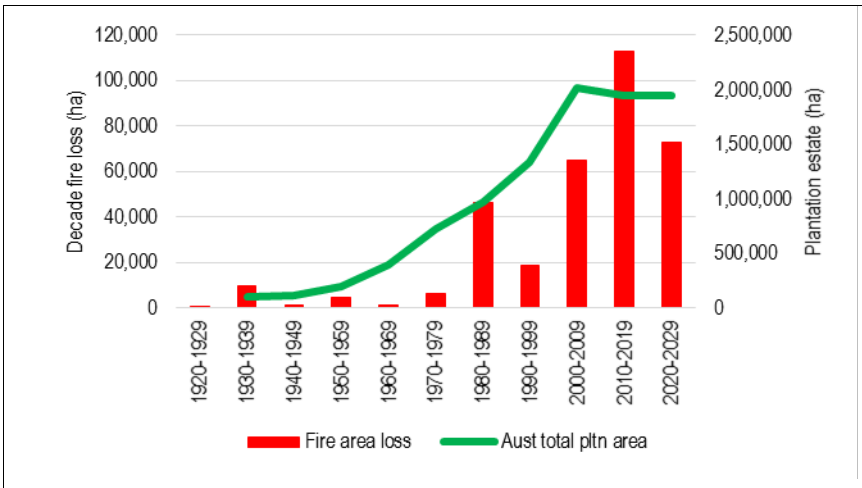


Figure 4: Australia's fire history (Geddes, 2020).

Table 2: A snapshot of studies of fire impacts referred to in this report.

Year	State	Location	Species	Impact	Reference
1939	Victoria	Ash forests	*E. regnans*	Natural forests	Wright & Grose (1970)
1965	NSW	Moss Vale / Penrose / Wingello	*P. radiata*	758 ha/1519 ha; 1552 ha; aged 31 to 38 years	French & Keirle (1969)
1966	Victoria	Creswick	*P. radiata*	28,320 m^3 of logs; aged 35 years	Wright & Grose (1970)
1979	South Australia	South East, Caroline	*P. radiata*	3500 ha burnt; mostly unthinned, with little salvage and no log storage	Geddes (2020)
1983	South Australia	Mount Lofty Ranges, SA		5000 ha burnt, 125,000 t processed by local mills and 45,000 t into two sprinkler storages, using waste water from sewage treatment plants. 210,000 sawlog, 140,000 'pulp', total 350,000 t.	Geddes (2020)
1983	South Australia	South East		16,000 ha burnt, total volume about 5.6 million tonnes – 2.7 mt sawlog (to 25 cm SED) and 2.9 mt pulp and small log.	Thomas (1985)
1994	Queensland	Beerburrum	*P. caribaea / P. elliottii*	4800 ha: about 600,000 m^3 harvested with 400,000 m^3 placed under irrigated storage distribution to sawmills over about four years.	Hunt et al (1995)
1994	WA	Gnangara	*P. pinaster*	850 ha burnt, trees aged 35to 49 years	Burrows et al (2000, pp.251, 252 & 258)
2003	ACT	Canberra	*P. radiata*	10,500 ha burnt.	Geddes (2020)
2006	NSW	Billo Road fire Tumut	*P. radiata*	9526 ha burnt.	Geddes (2020)
2007	South Africa		*P. radiata;* *P. leiophylla,* *P. patula;* *P. pseudostrobus*	17,399 ha burnt.	Malan (2011)
2009	WA		*P. radiata*	2892 ha burnt. Trees aged 9 to 14 years.	Geddes (2020)

Box 1: A South African study of fire impacts on wood quality sampling and assumptions (Meincken et al, 2010, p.456) .

A key assumption:

'It can be assumed that the temperatures in the fierce 2007 fires were high enough to alter several wood properties.'

Sampling protocols:

'For this study various trees from the same growth site were obtained and separated into severely burnt wood, where the entire tree was burnt and dead and slightly burnt wood, where the crown was intact and the tree still alive.

93 Pinus patula logs (provided by Timbadola Sawmill, Komatiland Forests) were cleared of all charcoal (in the case of burnt wood) and cut into boards with a length of 2 m. Of these boards 34 were green wood, 13 were slightly burnt and 46 were severely burnt.'

4.4 Tree stem anatomy

4.4.1 General structure of a tree stem

Figure 5 presents a schematic of a tree stem cross section; and the following describe the function of the components (based on Bootle, 1996, p.3&7; Hood, 2010, p.8, Figure 8):

- Outer bark: Has a protective role that is critical to fire responses.
- Cambium: A thin layer of cells that produces all wood cells and separates bark from wood.
- Phloem: Bark-like tissue that transports food materials downwards to the tree roots from the foliage. It is located on the outer side of the cambium.
- Sapwood: The new cells added on the inner side of the cambium. Sapwood (xylem) is woody tissue that transports mineral nutrients and water upwards in a tree from the root system.
- Heartwood: Heartwood provides structural support to a tree. The cells of heartwood become blocked with deposits on transition from sapwood, which contribute to the strength and durability of wood.

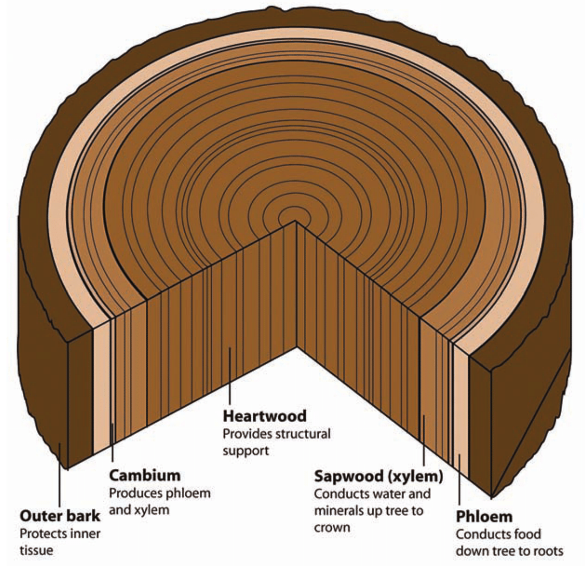


Figure 5: A cross section of a tree (Hood, 2010, p.8, Figure 8).

4.4.2 Tree tissue: wood cell, lignin and vegetative buds

Cells in wood perform at least one of the following functions: conduction, strengthening or storage (Nolan et al, 2003, pp.01-4&5; Conners, 2015, p.1). Most trees have two types of meristems (cells that give rise to various tissues and organs in a plant). Apical meristems are located within vegetative buds and produce branches, buds, foliage, cones and/or flowers. Lateral meristems are located in the vascular cambium (under the bark and phloem) and produce xylem and phloem vascular tissues (Michaletz & Johnson, 2007, p.506).

- Conductive tissue:
    - *Hardwoods*: Conductive cells in hardwoods are longitudinal cells called vessels or pores and are relatively large diameter cells, open at each end, and built on top of one another to make up continuous vertical tubes.
    - *Softwoods*: In softwood tracheids are conductive tissue for sap arranged in rows within the trunk running longitudinally. Resin canals are unique to conifers and are open, tube-like spaces bordered by cells with the ability to secrete resin into the neighbouring opening.
- Strengthening tissue:
    - *Hardwoods:* Longitudinal cells that give mechanical strength are known as fibres. They are elongated, narrow, pointed and closed at the ends.
    - *Softwoods*: Tracheids are the major component of wood in softwoods and are long, thin cells that provide strength.
- Storage tissue: Parenchyma is storage tissue composed of brick-shaped cells with thin walls with numerous pits. Storage tissue remains alive for some years after completion of its development. There are two forms:
    - *Ray-parenchyma*: Known as medullary rays, these are present in horizontal bands that radiate from the pith towards the bark, varying in length, breadth, and depth. Rays are mostly more than one cell wide in hardwoods.
    - *Wood-parenchyma*: This tissue is more abundant and more varied in distribution in hardwoods than in softwoods. In hardwoods, they appear as scattered strands, patches or bands among the pores and fibres, and are normally paler in colour than in softwoods.

In wood, lignin bonds the various types of cells together to produce a degree of rigidity associated with wood and enable woody plants to attain their large size (Bootle, 1996, p.1). Wood can be 22-30% lignin as complex chain polymers of high molecular weight, consisting of about 65% carbon, 6% hydrogen and 29% oxygen (Bootle, 1996, p.4). Lignin is virtually impossible to dissolve without being broken down into simple substances (Bootle, 1996, p.4).

4.4.3 A specific structure: pits

Pit functions and impacts on pits are important considerations in log storage, degrading agents and subsequent wood utility. Pits are regions in cell walls where a secondary wall does not develop (Figure 6). Pits permit liquids to flow from one cell to another (Bootle, 1996, p.3). These are variable in shape and size and may have a flexible membrane that can aspirate (close) when air enters an adjacent cell or when heartwood is formed, reducing liquid movements (Comstock & Cote, 1968, p.280). There are differences between earlywood and latewood pits, with latewood pits not closing (Bootle, 1996, p.2). Bordered pits form the main pathways for flow of fluids from one tracheid to the next in conifer wood (Petty, 1972, p.395). Drying of wood generally causes pit aspiration, which reduces liquid movements (Comstock & Cote, 1968, p.280).

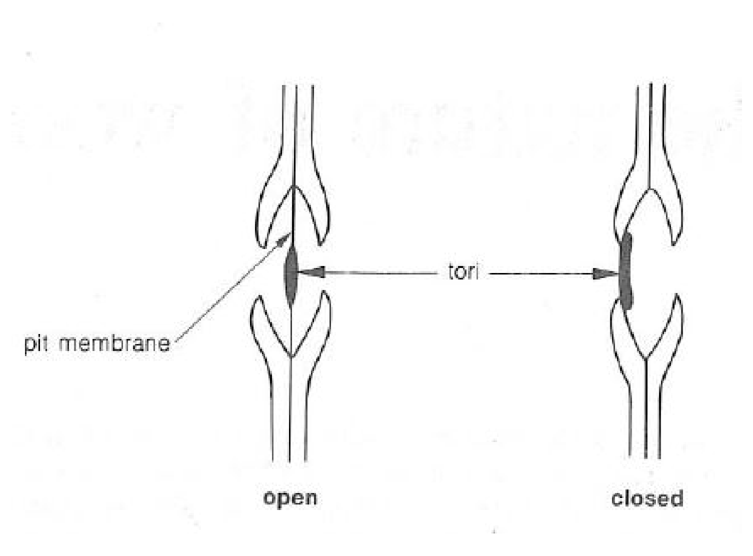


Figure 6: Pits between cells – the pit membrane with a thickened centre (the torus) supported by a flexible cellulose web allowing the torus to move across to close a pit (Bootle, 1996, p.4, Figure 1.1).

4.5 Wood attributes of specific importance to fire impacts

Appendix 2: Wood attributes presents a summary of wood moisture content, basic density and conversion factors.

4.5.1 Moisture content

Moisture content (MC) of wood is a key attribute in utilisation. Bootle (1996, p.3) notes that '*moisture content of wood has a most important effect on its strength and stability*'. Moisture content percentage can be expressed as the weight of water per weight of green or dry wood.While dry wood basis is the usual convention (Bootle, 1996, p.90), published information does not always define which basis is used. This document defines the MC basis quoted as – $\mathrm{MC}_{\mathrm{GREEN\ BASIS}}$ or $\mathrm{MC}_{\mathrm{DRY\ BASIS}}$. There are five key moisture contents:

- Green moisture content: The moisture content of green wood (e.g. freshly felled/sawn timber) varies. It is the moisture of wood that is not bone dry.
- Equilibrium moisture content: Equilibrium moisture content (EMC) is the moisture content of timber synchronised with local environmental conditions driven by relative humidity and temperature of the surrounding air (Nolan et al, 2003, p.017). It can be referred to as air dry moisture content.
- Fibre saturation point: Fibre saturation point (FSP) is the moisture content at which all free water has been removed from wood (Tiemank, 1906, p.82).
- Kiln-dried moisture content: Kiln-dried timber has been dried below FSP to c.10 to 15% $_{\mathrm{DRY\ BASIS}}$.[1]
- Bone dry moisture content: Bone dry moisture content (or oven dried moisture content) is zero as wood has been dried in an over maintained at 103+/-2°C until it is at a constant weight (Bootle, 1996, p.90).

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[1] Information from https://www.woodsolutions.com.au/wood-product-categories/sawn-timber accessed on 16/04/2020.

Fibre saturation point can be segregated by dry-basis moisture content into ‘low’ (≤25%); medium (25% to 35%) or high (≥35%) (Gérard, et al. 2017, p.15) and will vary with species (see Table 3). Seasoned timber has a $MC_{DRY\ BASIS}$ of 9% to 14% (Timber Queensland, 2014).

Table 3: Fibre saturation point for the species listed.

Species	FSP Moisture Content$_{DRY\ BASIS}$	Reference
P. caribaea	28%	Gérard, et al. (2017, p.207)
P. patula	31%	Gérard, et al. (2017, p.756)
P. pinaster	32%	Gérard, et al. (2017, p.567)
P. radiata	29%	Pang & Herritsch (2005, p.654)

4.5.2 Basic density

Basic density is the weight of oven dry wood per green volume of wood. It is a fundamental attribute driving the price paid for wood and many of its uses. Wood basic density is a constant, whereas moisture content will vary.

4.5.3 Thermal conductivity

Thermal conductivity is a measure of the rate of heat flowing through a material when subjected to a temperature gradient (Bootle, 1996, p.57). Thermal diffusivity is a measure of the speed with which a material absorbs heat from the surrounding environment (Bootle, 1996, p.58); it is a temperature change with time on the other side of a material to the side affected by heat or how much a material’s temperature increases (see Figure 7). The thermal conductivity of wood is only a small fraction of that of most materials (Bootle, 1996, p.57) (see Figure 8). Wood’s low thermal conductivity is due to effective resistance to heat flow of air trapped in cell cavities and intercellular spaces (Koch, 1972, p.372). Thermal conductivity of wood is positively correlated with density (stated as specific gravity) and moisture content (Koch, 1972, p.374) but other characteristics have little impact (Koch, 1972, pp.371&374).

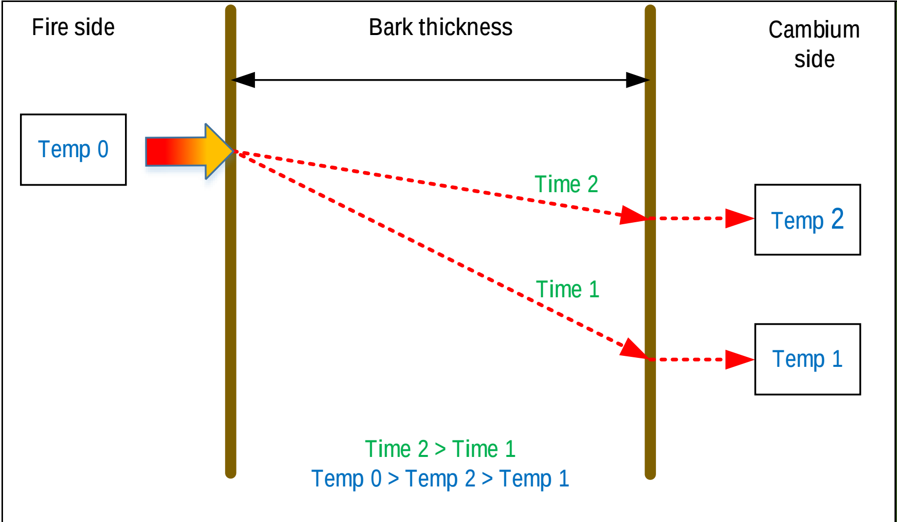

Figure 7: Thermal conductivity through bark resulting in a temperature change in cambial tissue.

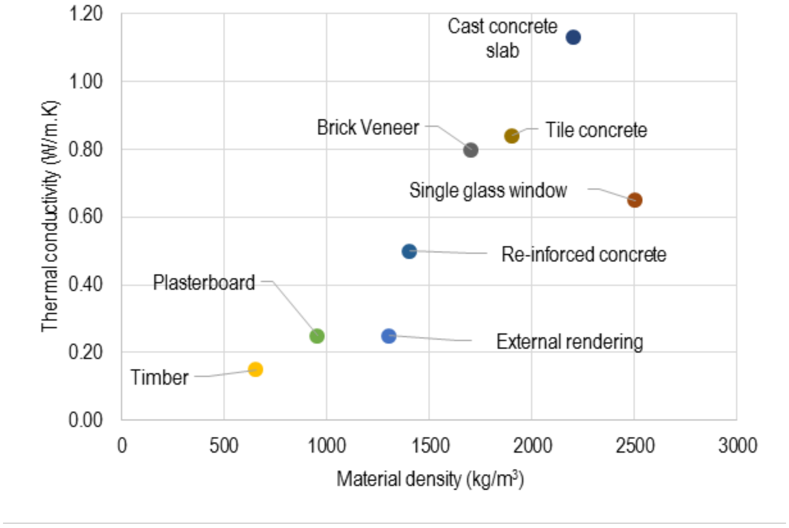

Figure 8: Examples of thermal conductivities for the materials listed (Aldawia et al., 2013, p.665).

4.6 Recommended best practices

Best practice 1: Maintain a fire database to help document fire impacts and history (see https://www.fwpa.com.au/resources/reports/market-access/1966-database-capture-of-individual-significant-scale-australian-forestry-plantation-fire-losses.html).

Best practice 2: Publish details of fire events, preferably in a format that facilitates contribution by operational as well as by research staff.

5 Fire response planning and actions

5.1 Summary

A fire response strategy seeks to balance an ability to supply fire-impacted logs to processors direct, in some cases as a substitute for green unburnt logs (to maximise fire-impacted log consumption and conserve unburnt plantations). The first step is to determine expected volumes of fire-impacted logs. If the expected log volume exceeds local capacity while trees are expected to remain 'fit for purpose' on the stump, a wet storage strategy is required. Wet storage is an extra cost and risk.

A pre-planned approach to triage of fire-damaged stands is required to ensure the best possible outcome (e.g. maximising salvage / recovery / economic return / minimising losses). This should identify which stands to harvest and in which order, and which may be sacrificed. To facilitate such a response cooperation and coordination between all likely parties is needed, and this should be established as part of pre-planning. Cooperation should commence with an understanding of all elements of supply chains, and the needs and limitations of each market (e.g. tolerance to carbon). Mechanisms of cooperation and addressing fire impacts should be formalised in contracts. A range of specific plans should be prepared in advance of and as part of pre-fire season preparations.

5.2 Introduction

Although logs are inputs into industry supply chains, different product-based enterprises are mostly linked with a degree of co-dependence (Ferguson, 1997, p.64). Harvesting may generate logs that do not meet domestic sawlog specifications but can be supplied to a range of alternative markets (e.g. export woodchips, domestic pulping or panel board manufacturing). In other situations, domestic sawlogs may be a by-product of harvesting logs for plywood. Processing of sawlogs generates a range of residues including woodchips and sawdust, and sawmill profitability is enhanced by access to such markets. Industries may develop in clusters to make transport between sites more effective.

A fundamental point of fire salvage is that carbon and other impurities may be a minor concern for sawn timber, it can be critical for acceptance of residue woodchips by a pulpmill. It is not possible to consider processing needs in isolation of other parties in the supply chain. This underpins the requirement to plan for future fire events. This was a recommendation in response to analysis of a fire in 1966 (see Table 4). This chapter addresses planning for future fire events.

5.3 A strategic analysis of a need for log storage and overall strategy development

5.3.1 A 'fit for service' strategy

Experience from a 1965 fire affecting *P. radiata* plantations in NSW suggested two possible courses of action post-fire as: a) clear felling and storage of logs or b) leaving trees standing and cutting selectively (French & Keirle, 1969, p.178). This is a fundamental decision point. A range of issues must be addressed in decision making to create a 'fit for purpose' response.

- How long and under what conditions can fire-impacted trees be stored on the stump?

- At what point does the decision to salvage to log stockpiles need to be made, and when is it too late to do so?
- How will log moisture content variation be assessed?
- What are the potential pest attacks on fire-impacted logs that may affect log quality (e.g. boring insects)
- Will bluestain affect products?
- What are the attributes of a tree suitable for storage in log stockpiles?

Planning is key to the success of a salvage operation, but so too is adaptability. There are four elements to a fire salvage response (see Box 2).

Table 4: Identified priority issues after a 1966 fire salvage (Wright & Grose, 1970, pp.158&159).

Element	Narrative
Planning	Efficient salvage requires careful and thorough planning. Since time is of the essence in salvage operations, as much as possible of this planning should be included in basic management plans. Potential storage sites, with adequate access and water can be selected in planning, and plans can be made to develop and equip such sites immediately after a major fire. However, the reorganisation of utilisation following a fire cannot be planned until the extent of damage and the ability of the wood industries to utilise the fire killed wood under current market conditions are known.
Finance	Additional finance must be provided where large scale log storage is necessary. Government awareness of the need for salvage in 1939 resulted in the relatively rapid provision of adequate finance for log storage. The Act providing loan money was passed six months after the fire. Such assistance may not always be readily available, especially for smaller salvage operations. A permanent fund could perhaps be established to finance the development of log storage sites and the felling and dumping of logs immediately after a major fire. Money for such a fund should be immediately available after a major fire and could be subsequently recouped when stored logs were utilised. Such a fund would allow more positive planning and quicker utilization after a major fire.
Salvage Period	Degrade develops rapidly in standing fire-killed trees as the wood dries. Salvage must commence as soon as possible after the fire to ensure minimum loss of merchantable wood. The period available for salvage of fire killed radiata pine is estimated at about two years.
Storage	Fire-killed trees that cannot be utilised within the estimated salvage period should be felled and stored until they can be utilised. Storage of logs in moist, sheltered locations under water sprays appear to be effective. Radiata pine logs showed no deterioration after one year's storage under water sprays (Finighan & Liversidge, 1968 cited on Wright & Grose, 1970, pp.158&159) and, based on North American experiences, are likely to be still useable after 3 to 5 years of pond storage. Pond storage provides very effective protection, but capital costs may be high. Inclusion of fungicides or insecticides in the spray or pond water is a possible method of delaying wood degrade and improving the efficiency of storage. Use of sections of irrigation reservoirs for log storage merits investigation.

Box 2: The elements to a fire salvage response.

- Expected volumes: The estimated volume of resource by product defines all other decisions. This can include write-off of a stand (no salvage and the cost of removal of trees included as part of site reestablishment).
- Storage on the stump: The expected duration of fire-impacted trees as standing stock in plantations. Harvesting of the expected volume within expected time frames will set the rate of resource flows.
- Current capacity: Whether the expected salvage woodflows can be absorbed by current processors (local or within reasonable haulage distances) will determine if dedicated storage is needed.
- Dedicated storage: Whether there is a need for dedicated medium to long-term storage capacity. This can include stockpiling for storage in stacks under sprinklers or storage in water.

5.3.2 Triage – assigning evidence-based priorities

Triage aims to make the best possible decisions as an immediate response to a fire. Past fire responses have included a focus on capturing value by harvesting higher value trees (based on potential product value) before the onset of bluestain or by harvesting stands expected to degrade soonest and delaying harvesting of stands likely to remain 'fit for purpose' for longer. In both cases, an issue has been predicting change in stem 'quality' while retained as standing trees. Past experiences and outcomes may not always be relevant to current and future potential; there are many variables that combine to create an outcome. For example, following the 1983 Ash Wednesday fires, softwood plantations in South Australia were harvested and successfully stored as logs (under sprinklers and in a lake); insects and bluestain were not an issue (Thomas, 1985, p.11). These fires were followed by a wet, cold period that inhibited insect activity and there was infrequent non-insect transmission of bluestain fungi (Wylie et al, 1999, p.152). However, the 1994 fires in south-east Queensland occurred in September and November, before summer conditions that are favourable for Ips and other damage agents. It was recommended that stands damaged by fires should be salvaged within three months to avoid significant bluestain under Queensland conditions (Hood & Ramsden, 1997, p.7). After a 1965 fire at Creswick (Victoria), it was suggested '*that there will be little loss if fire-killed P. radiata are salvaged within one year of the fire*' and that '*rapid development of wood defect necessitates salvage within about 2 years for mature radiata pine*' (Wright & Grose, 1970, p.149). Based on the same fire event, the acceptable salvage period for younger or smaller trees was shorter than for large trees (Wright & Grose, 1970, p.149).

A key point is that triage processes must be informed by the specific circumstances of a specific event.

5.3.3 Cooperation requirements

The scale of a salvage event will dictate the scope of coordination required between parties – a small event can be business as usual (BAU), whereas a large event requires change to BAU. With increasing scale, increased cooperation between parties is needed to put salvage plans into effect. Broad cooperation between parties for a fire-salvage event is a critical success factor (see Box 3). Pre-fire season planning should identify mechanisms for cooperation.

Box 3: An example of the importance of cooperation in planning a fire salvage (Wright & Grose, 1970, p.158).

'There was excellent co-operation between the Forests Commission and the timber industry in planning the salvage program and putting it into effect. Rapid provision of Government finance for log storage [following the 1939 fire] was also an essential factor in the success of the salvage operation. The extremely buoyant timber market caused by the wartime and post-war timber demand eliminated any marketing problems which may have arisen through greatly increased production of timber'.

Each party needs to consider the needs of all other parties. For example, following a storm at Gundrun in January 2005, the Swedish forest sector (forest companies, government and land and mill owners) immediately cooperated by reducing harvests of unaffected stands, maximising consumption of storm-damaged timber in mills across Sweden, and stockpiling some higher-value sawlogs under sprinklers for future use (Whitehead, et al 2008, p.12). About 90% of affected volumes was salvaged by spring 2006 (Skogsstyrelsen, 2006, cited in Whitehead, et al 2008), with a net loss estimated at €1.7 billion to €3.2 billion (8% to 16% of gross value). Most logs were processed in Sweden and some were exported, but several million cubic metres of the highest quality logs were put into storage for processing over a four-year period. In December of 2006, a further 12 million m^3 of timber was damaged by wind. Most of that volume was placed in storage until earlier stockpiles were processed (Whitehead, et al, 2008, p.12). A similar level of cooperation was noted after the 1994 Beerburrum fire. Consultation with all softwood processors in south-east Queensland, the South East Queensland Electricity Board, Telecom, Caloundra City and Caboolture Shire

Councils, and the Departments of Environment and Heritage, Treasury and Transport, was held within two weeks of the fire to explain the salvage work and to obtain the necessary approvals (DPI, 1995, p.4). Box 4 presents key cooperation issues.

Box 4: Key cooperation issues to be considered by the parties.

Financial impacts: Where contractors or available markets are 'loaned' from an unaffected grower to another party, recognition of financial impacts, particularly loss of cashflow must be addressed by the parties.

Contractor capacity: Contractor crews (equipment and skills) need to be allocated to the most appropriate fire-impacted stands to ensure that felling of fire-impacted trees (with time they become more brittle and lack a foliage sail to reduce the velocity of stems as they hit the ground) results in minimal stem damage.

Log markets: Fire salvage should focus on recovery of highest value log resources as a priority.

Stands harvested: Ceasing clearfelling of green stands until salvage is complete will increase the average age of green resources and increase piece size with time.

Subsequent crop: Salvage operations need to consider site preparation treatments required to establish the next crop and plan accordingly.

5.4 Market dynamics

5.4.1 Markets as a key driver of options

Fire salvage will supply a number of markets, each with different needs and attributes (e.g. log specifications and capacity) and a strategy is required to determine when and how much fibre can be allocated to each. Access to a range of markets that can accommodate increasing fire impacts (e.g. carbon and moisture content) provides the greatest flexibility for salvage. Ideal markets are those with a range of product types.

As part of the 1983 Ash Wednesday salvage in south-east SA, it was determined for smaller salvage operations that particleboard customers could take some burnt sawlog as well as residue woodchips (fall-down roundwood and/or fire impacted woodchips from sawmills).[2]

The nature of a market will determine whether fire-impacted logs are rejected. With a single large-scale site, alternative supply is more difficult, and the site will require strategies to address this. Given the interconnected and highly dependent nature of the industry, an alignment of interests is required to ensure that a major site receives 'it for purpose' inputs (e.g. sawmill residue chips must be carbon and contamination free when providing logs to a pulpmill). Under conditions of maximum market pull for finished goods, a processor may seek to maximise production and take a more flexible view of input feed stocks, pushing the specifications to the lower-end of acceptable limits. Conversely, where a market is depressed, and there is downward pressure on production, log specifications may be at the upper end of acceptable limits. Market education via a communication strategy will be required to ensure acceptance of fire-salvaged material and potential visual defects (e.g. bluestain).

5.4.2 Export markets

Avoidance of log storage is driven by the cost and complexity of such operations. Access to export markets can act as a buffer to a surge in log supply. After the 1983 Ash Wednesday Fires, log export was not an option for

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[2] South Australian industry information.

SA's Woods and Forests Department and storage methods were required.[3] More recent fire salvage events (e.g. the 2002 ACT fires) made strategic use of export markets to take additional logs. The log storage requirement was while assembling log trains to go to Port Kembla.[4] In other cases, log export markets have been used for logs downgraded after storage. While this can succeed during buoyant market conditions, in market downturns such options may not be an option. While log exports are a critical tactic within a salvage strategy, they cannot be relied on given fluctuation in market cycles, especially when combined with other international events such as major salvage operations in North America and/or Europe. Biosecurity issues play a part in exports; de-barked logs commonly undergo methyl bromide fumigation but if logs are infested with ambrosia beetles deep within the log, fumigants may not be able to penetrate (especially if a log has a high moisture content). Recently, China rejected logs from an unspecified state in Australia (Plant Health Australia notification) after finding bark beetles.

5.5 Decision making and development of strategic plans

5.5.1 Direct market supply or log storage?

A direct route from stump to mill gate is the least-cost option and any additional steps in a supply chain add costs and risks. A broad guideline for industry is to avoid log storage unless it is absolutely necessary. After a 2007 fire in South Africa, '*as much timber as possible was sold to available markets for relative quick processing, large volumes had to be stored indefinitely to meet log supply contracts over that period and at the same time prevent deterioration of the logs'* (Malan, 2011, p.21). This complex decision required a detailed analysis of the physical and financial implications in the immediate, medium and longer terms. A fire salvage strategy should seek to reduce costs at an acceptable level of risk. There is a hierarchy of fire salvage log options, each with required actions and inputs, associated cost profile and inherent risks. Overseas experience suggests that '*storing very high volumes of logs for more than a single season is an extraordinary measure, but extraordinary events engender extraordinary responses*' (Whitehead, et al, 2008, p.12). A literature review (Whitehead, et al 2008, p.12) noted examples of significant volumes of fibre stored for up to four years as wet storage after storms in Germany and Denmark in 1967, 1972 and 1990 (Moltesen, 1977; Liese & Peek, 1984; Bues & Läufer, 1993), and in Great Britain in 1987 (Webber & Gibbs, 1996) and of fire-damaged pine sawlogs in South Africa was reported by von dem Bussche (1993).

5.5.2 Fire salvage woodflows

Fire salvage woodflows can overwhelm local capacity. After the 1939 fires in Victoria, the salvage volumes were '*equivalent to about 10 years' supply of logs for all Victorian sawmills at that time. Salvage of this timber involved large scale reorganisation of the sawmilling industry to concentrate utilisation in the fire-killed stands. Roads and tramlines were extended into previously virgin forest, burnt mills were re-established and new mills built'* (Wright & Grose, 1970, p.157). Based on fire impacts, potential woodflows will need to consider the nature and sequence of stands to be harvested. This will inform the decisions required (e.g. process as usual, store wood or find alternative markets) requiring interaction between strategic, tactical and operational

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[3] South Australian industry information.
[4] ACT industry information.

planning. Box 5 presents considerations in regard to expected woodflows. Working back from processor utility, a range of fire impact issues must be addressed (Table 5).

Table 5: Identified priority issues to address in a fire salvage plan.

Issue		Narrative
The fire event	Pre-fire condition	Whether a stand has reached merchantable size is a critical issue. If it has not and continued growth is not expected, a stand is written off. If trees are of a merchantable size, salvage becomes an option.
	Fire impacts	Fire killed and damaged plantations require classification. Impacts to crown, stem and bark are important in determining whether trees are dead or dying and there are significant differences between species.
	Site	The time of year, and therefore likely conditions in the subsequent months, will determine site access and other factors, including stem drying rates and biological damage agents.
	Time	The time since a fire event will determine other impacts. Time in storage also needs to be considered.
Post-fire event	Intended market	Fire impacts must be defined against market requirements: log specifications; tolerance to carbon; log moisture content; tolerance of fungi and insects.
	Storage methods	Whether management of fire-impacted trees is by storage on the stump or in a stockpile (under sprinklers or in a water body).
	Biological agents	Insects, fungi and/or bacteria can result in biological impacts to damaged trees such as pin holes (e.g. boring insects), decay (e.g. due to fungi) and discolouration of wood (e.g. bluestain). Impacts will depend on damage agent and time.
	Log moisture content	Log moisture content is a key attribute affecting log-use and enabling of other damage agents. Tree and log drying rates will be driven fire damage level, weather and storage. There is likely to be variation radially and longitudinally within stems.

Box 5: The required considerations in regard to expected woodflows.

- Supply plans: A detailed, phased supply plan is required to support the strategic decision making process
- Triage: Harvesting priorities need to consider fire severity, value to grower, value to processor, road access, seasonality, availability of suitable road construction and maintenance and harvesting equipment.
- Log mixture: The log mix (e.g. size, age, quality) is likely to vary by season with often older, higher value stands in difficult, dry-weather only harvest areas.
- Capacity matching:
  - Surpluses: Once a schedule is developed, the types of logs surplus to existing markets in a temporal or phased sense becomes apparent.
  - Log grades as a tool: A grower and sawmill may agree to process only high-grade logs (increase standard small end diameter – (SED) – and length parameters) to increase throughput during the salvage phase. This then will release surplus low-grade logs for alternative markets storage.
  - Seasonality: Dry weather only access will affect the quantity and quality of available logs as a season progresses.
- Harvest season: If dry weather logs are not harvested before the onset of the first wet season following a fire event, the risk of logs deteriorating prior to being stored increases and could influence the decision to store.

5.5.3 Processor responses to increased log supply

There are four broad salvage responses and enablers to each response.

1. BAU: A ‘business as usual’ strategy is the usual state of operations in the absence of a fire event.

2. BAU plus:
    - Current levels of processing: At a low level of change to resource flows, fire-impacted logs are blended into current operations with changes to the plantations harvested. The dilution of fire impacted and un-impacted logs does not result in a material change in homogeneity of freed stocks.
    - Increased product storage: Increased primary processing that involves storage of chips or sawn products.

3 Increased capacity: Existing markets / processors adapt and expand where necessary. At a moderate level of change to resource flows, operations of a processing site can to batch impacted logs, add on-site storage capacity or add extra work shifts.

4. Step change:
    - Current markets: At a significant level of impact, major operational changes are required adding to those already undertaken under a current capacity event. Additions can include storage of logs and/or woodchips on a separate site.
    - Alternative markets: Accessing 'non-routine' markets for either logs or products.

Fire impact response strategies will determine required harvesting and haulage contractor capacity with three possible outcomes:

1. Business as usual: With minor changes to cutting plans, fire-impacted trees can be harvested and supplied to existing markets by existing harvest and haulage contractors.
2. Increased workload: The current contractors undertake additional works by increasing hours of operations (e.g. longer shifts and/or extra shifts). This may include increased demand for labour.
3. Increased capacity: Additional contractors are imported to a region to undertake works.

5.6 Pre-fire season planning

5.6.1 Pre-fire season preparations and awareness: a roundtable forum

A pre-fire season roundtable should aim to bring together all parties in a wood supply zone with interests in industry activities, including local community representatives and Local Government / local regulators. This should build on existing community and industry groups. For example, forest managers generally plan harvesting and road construction and maintenance 6 to 12 months in advance of harvest and may include a local briefing process. Before each fire season, the forum should focus on potential fire salvage issues (tactics and strategies). There is a need to ensure that community and firefighting agencies appreciate the value of plantations to inform decision making as to when and where to conduct active back-burning operations. This can be achieved via effective communications and education campaigns facilitated by a roundtable and include such information in basic wildfire firefighting training and standing orders manuals. A key point is to develop protocols and definitions (or make use of existing systems) to define potential salvage requirements following a fire (e.g. a 'small event' salvage can be absorbed into current woodflows, where as a 'large' event will require a change to BAU). Consideration should be given to all regulatory requirements to make use of log dumps for storage and additional road construction and maintenance. Overall outcomes should define protocols for cooperation within and between wood supply zones.

5.6.2 Broader issues and socio-economic considerations and industry multipliers

A local community will be traumatised by a fire event, and an unexpected concentration of harvest and haulage activities adds to such stress and may impede fire salvage. A roundtable forum can create a social licence and provide communities with an understanding of expected industry responses. This can be viewed as an enabler of continuance of local employers' business activities. For example, in North America while unfavourable market conditions required curtailment of production in sawmills processing beetle-killed logs, the social, economic and environmental costs of not harvesting in areas where outbreaks were expanding were significant and sustaining harvests on the periphery of the outbreak were in the public interest (Whitehead, et al, 2008, p.v). Where a local economy is highly reliant on a local wood processing sector, the prospect of exporting logs or woodchips, while a financially viable option, may create angst within the community. This is particularly the case where complexity of supply arrangements may provide no real alternative to exporting and this appears to restrict resource access to local processors.

5.6.3 Contractual arrangements

All arrangements between parties should be articulated via contract details rather than reliance on an understanding between individuals. The following contractual issues should be addressed:

- Growers and processors agreed approach to fire events.
- Growers and harvesting and haulage contractors agreed approach, addressing any premiums due to increased costs.
- Approach of processors and markets to fire events.
- Contractual and fiduciary obligations may exist and there is potential for conflicts in options to address fire salvage. It is prudent to identify and address any such issues.

5.6.4 Yield regulation and planning systems

Once the extent of plantation loss is known, it will be necessary to remove the burnt growing stock from wood flow models to: estimate the impact on future log resource availability; estimate the economic and financial loss; quantify the importance of salvage efforts and set priorities; inform log supply customers of supply implications; and plan the reestablishment of fire areas. Plantation managers should ensure that all elements of their yield regulation and planning systems can incorporate fire impacts to generate:

- Tactical planning: Optimise short-term tactical plans based on fire impacts, markets, harvest and haulage and re-establishment (needs and costs).
- Strategic plans: Plan for strategies to ensure adequate future resources from within an estate where gaps in supply are identified (e.g. thinning and fertiliser strategies to increase future volume).

5.7 Recommended best practices

5.7.1 Pre-event planning

Best practice 3: Address the four underlying considerations in a fire response strategy: expected woodflows; the ability to store on the stump; current processing and market capacity; and whether dedicated storage is required.

Best practice 4: Establish a pre-fire season planning roundtable to pre-plan a range of fire salvage related considerations.

Best practice 5: Define all parties (stakeholders) within a supply area who have an interest and can influence a fire salvage event.

Best practice 6: Develop protocols for cooperation between parties.

Best practice 7: Document potential fire impacts, likely outcomes and options to inform pre-planning.

Best practice 8: Ensure industry yield regulation systems have capacity to take account of expected fire salvage outcomes in the short, medium and longer terms and the management of the non-burnt forest.

Best practice 9: Develop a fire response salvage strategy that includes a range of inter-linked components. A key determinant of a strategy is existing market capacity: can it absorb the expected woodflows or not? Most other aspects are defined by the condition of a stand pre-fire, the fire event and expected woodflows (indicated as the core of a strategy).

5.7.2 Salvage planning – triage, harvesting and logistics

Best practice 10: Determine harvesting sequences and whether any resource is unsuitable for salvage (whole stands) or any sections of individual trees remain un-recovered by a triage system.

Best practice 11: Set harvest priorities as part of the triage.

Best practice 12: Change harvest priorities by a switch of harvest from green plantations to fire-impacted plantation.

Best practice 13: Reduce risks of adverse logs (e.g. limit passenger and carbon within the wood of logs or logs which are brittle) and/or match expected resource flows over a period of storage on the stump to processor capacity by accepting losses of upper stem logs that will dry out first.

Best practice 14: Include in the triage an option to not harvest a stand (e.g. trees are non-merchantable size), change log specifications (changes in stem form, defects and small end diameter) or exclude specific sections of tree stems (e.g. butt log sections by long-butting or upper crown logs which have dried out with time).

Best practice 15: Agree on a definition of acceptable and rejected logs, and log specifications, to increase reduce the risk of log breakage, improve de-barking efficacy and reduce risk of carbon contamination.

Best practice 16: Develop and include fire-impacted log specifications in all log specifications agreed between parties to a wood supply agreement. Industry yield regulation systems should have capacity to take account of expected fire salvage outcomes in the short, medium and longer terms. With time trees will dry-out and this increases the risk of insect attack and bluestain.

5.7.3 Markets

Best practice 17: Store trees on the stump to supply logs direct from plantations to processors, as the cheapest and simplest solution to a fire salvage. Success with this strategy requires the maximum duration of such an approach to be defined by the rate of stem drying combined with insect attack and any resulting fungal infestation (e.g. bluestain). Such changes will be influenced by the nature of fire impacts, fire timing and subsequent weather (e.g. insect impacts may be reduced over cold winters).

Best practice 18: Supply fire-impacted logs to current markets either as supplementary resource or as a replacement of green logs. This will require cooperation and coordination between all parties.

Best practice 19: Access log export markets as a buffer to take a surge in supply. This may take time to develop and requires access to specific infrastructure, or be a relatively simple option.

Best practice 20: Supply fire salvage logs into alternative domestic markets where possible. New markets could be within the same or alternative wood supply zones. The latter requires greater investment in haulage.

Best practice 21: Document the specific needs (log type and specifications) of all processors in a supply area who may be impacted by a fire salvage operation.

Best practice 22: Assess the ability to export logs surplus to local needs and undertake a benefit cost analysis of the impacts of log exports on local industry. This will inform decisions of whether to stockpile logs that are surplus to current processor capacity.

6 Classification systems: fire type, impact and damage

6.1 Summary

Fires can be segregated into three types: crown (burning tree crowns); surface (burning ground fuels); and ground (burning soil organic layers and duff). There is a limited relationship between fire intensity (the rate of heat transference during a fire) and fire temperature. A tree will be killed when the cambial layer is exposed to 60°C for one second. However, for this to occur, heat must be conducted through the bark to the cambial layer and tree bark is a poor conductor. The degree of protection is determined by thickness of continuous bark sections For example *P. radiata* with bark c.1.1cm thick would require exposure to a fire heat of 500°C for 3.5 minutes to reach a fatal temperature of 60°C. Other anatomical attributes contribute to fire tolerance, and tree mortality models and fire impact classification systems have been developed to reflect this. Such systems are more correctly descriptions of stand condition as they do not relate to expected outcomes. Expected outcomes become more predictive when combined with other stand attributes and changes over time. It is suggested that stand crown condition post fire should be combined with impacts to tree stems as a more robust predictor of outcomes. A suggested predicative model includes fire impacts, stand attributes pre-fire and post-fire degrade.

6.2 Introduction

Fire-caused tree mortality results from events prior to, during and after fire (Hood et al, 2019, p.1). Mechanisms include fundamental biophysical processes linking fire behaviour and tree mortality (Michaletz & Johnson 2007, p.500-501). Tree mortality is a result of multiple stressors, including competition, pest and pathogen activity, and short- and long-term climatic fluctuations (Das et al 2016 cited in Hood et al 2018: p.6). Fire type will define the impact mechanism and resulting damage. For example, tree mortality from ground fires results from '*several complex, coupled processes*' (Ryan & Reinhardt, 1988 cited in Michaletz & Johnson, 2007, p.506; Parker et al., 2006 cited in Michaletz & Johnson, 2007, p.506), which can be direct (e.g. heat transfer and results in tissue necrosis) or indirect (e.g. altered physiology, insect attack and pathogenic infection) (Michaletz & Johnson, 2007, p.506). To assist with response planning and triage, classification systems are required that address fire attributes (e.g. intensity), fire impacts (e.g. which section of a tree is affected) and the resulting damage (e.g. crown scorch). This section address foundation issues of fire type and attributes of fires; mode of impact of fire to trees and the outcomes of trees being burnt; consideration of tree bark as a driver of fire impacts; the effect of pre-fire stand conditions; species difference in regards to fire; the outcomes of fire on trees that have survived; predicting fire impacts; fire damage classification and mapping; and a conceptual combined model to predict fire outcomes.

6.3 Fire type and descriptors

6.3.1 Forest fire types

Three classes of forest fire are recognised: ground fires, surface fires and crown fires (Michaletz & Johnson, 2007, p.506) (see Box 6).

Box 6: A classification of forest fires (Michaletz & Johnson 2007, p.506).

- Ground: Ground fires involve smouldering combustion of duff and litter, which generally occurs after the flaming fire front has passed (Kauffman & Martin, 1989 cited by Michaletz & Johnson 2007, p.506) and can persist for hours or days afterwards.
- Surface: Surface fires involve flaming combustion of fine fuels on the forest floor, including litter, and herbaceous and woody plants.
- Crown: Crown fires involve flaming combustion of fine fuels in tree crowns, such as branches, buds and foliage.

6.3.2 Fire combustion processes

Burning of a standing tree will continue while the wood/bark surface remains at a sufficiently high temperature (Bowyer *et al.*, 2003 cited in Malan, 2011, p.4). The burning process can be divided into three phases (Whelan, 1995 cited by Meincken et al, 2010, p.455; Bowyer *et al.*, 2003 cited in Malan, 2011, p.4):

- Preheating: Fuel just ahead of the fire is heated and partly pyrolysed. From 100 to 200°C, water vapour, carbon dioxide and carbon monoxide is driven off, while chemical decomposition (pyrolysis) commences relatively slowly in the beginning. At greater than 200°C, pyrolysis starts to accelerate.
- Flaming combustion: Between 260 and 350°C, flammable gases start to form which, with oxygen, may self-ignite if the temperature becomes high enough or there is an ignition source.
- Glowing combustion: At greater than 270°C, a fire will support itself as the rate of heat produced is greater than the heat required to generate wood gas.

6.3.3 Fire attributes: fire intensity

Fires are difficult to quantify (Cheney, 1990, p.14). Alexander & Cruz (2019, p.1) define fire line intensity as: *'the rate of energy or heat release per unit time per unit length of fire front (kW/m). Numerically, it is equal to the product of the fuel low heat of combustion (kJ/kg), quantity of fuel consumed in the flaming front (kg/m^2), and the linear rate of fire spread (m/s)'*. One kW/m is equivalent to the energy released by a small bar radiator (DBCA, 2019). Fire intensity depends on how much fuel is burnt and how fast it burns. Severe bushfires (e.g. the Victorian Black Saturday fires) can generate intensities in excess of 100,000 kW/m, whereas prescribed fires are usually less than 500 kW/m (DBCA, 2019). Table 6 describes fire intensity, fire attributes and suppression options. Flame height is related to the rate of heat output or intensity (Byram, 1959, cited by Wotton et al, 2012, p.270) and fire behaviour (e.g. likelihood of scorching, crowning and resistance to control). The quantity of radiant and convective heat from a flame to its surroundings depends on the size, shape and temperature of the flames (Wotton et al, 2012, p.270). Fire temperature and duration *in situ* are important attributes of a fire relating to the impact on trees. The time over which heat is present will determine the impact of a fire. A low intensity fire (flame height <1 m but with a high-residence time) caused fire scars up to a height of 7 m and stem girdling between 22% and 46% of the circumference at stump height (Woodman & Rawson, 1982, p.16). A passing fire front builds up temperature to a maximum for a short duration (the flame residence time / observed flaming) after which temperature drops. Wotton et al (2012) captured data on fire attributes during experimental fires in dry eucalypt natural forests. They observed a maximum temperature of 1100°°C near the flame base and flame temperature exponentially decreased to the visible flame tip where temperatures were 300°C (Wotton et al, 2012, p.270). Data analysis demonstrated that *'maximum flame temperature was significantly correlated with rate of spread, fire intensity, flame height and surface fuel bulk density'* (Wotton et al, 2012, p.270). The highest temperatures will be at the base of an individual tree stem, an important consideration in assessing the impact of a fire. Data for minimum and maximum fire line intensity and maximum flame temperature (Wotton et al, 2012, p.274, Table 1) was plotted to demonstrate temperature outcomes and the results are presented in Figure 9. There is a poor relationship between fire line intensity and maximum flame temperature. While fire events are described using fire intensity, an important point is that there is nil conversion possible from fire intensity to fire temperature. Given specific implications to wood properties, Box 7 presents a description of a fire storm with associated high winds.

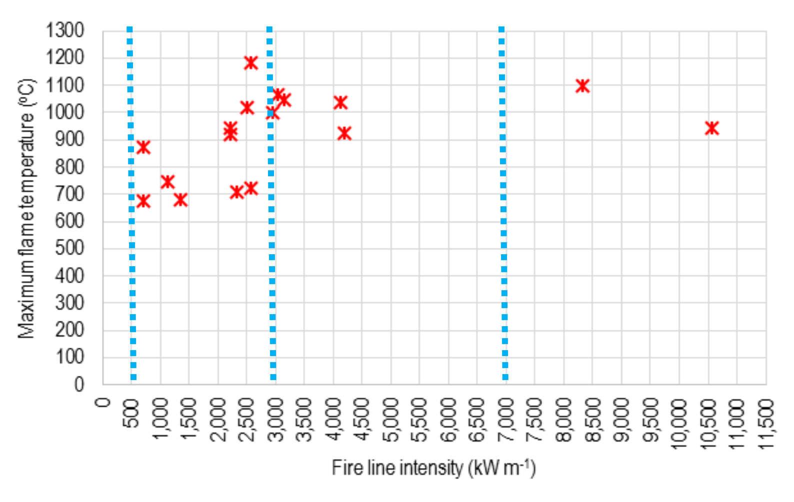

Figure 9: Data from Wotton et al, 2012, p.274, Table 1) for minimum and maximum fire-line intensity and maximum temperature.

Table 6: Fire intensities and average flame heights in open eucalypt forests in Australia (Cheney 1981, p.156, Table 1) combined with fire suppression options (DBCA, 2019) and fire temperature from Figure 9.

Rating	Fire intensity (kW/m)	Maximum flame height (m)	Approximate temperature range (˚C)	Remarks	Suppression
Low	<500	1.5	650	Upper limit recommended for fuel-reduction burning	
	<800				Fire can be suppressed with hand tools with water support as a direct attack.
Moderate	500–3000	6.0	650 to 1200	Scorch of complete crown in most forests	
	800–2000				Fire can be suppressed by machines, tankers and water bombers as a direct attack.
	2000–3000				Fire may be suppressed by machines, tankers and water bombers using an indirect attack.
High	3000–7000	15.0	1000 to 1200	Crown fires in low forest types – Spotting > 2 km	
	>3000				Fire is unlikely to be suppressed.
Very high	7000–70,000	>15.0	900 to 1100	Crown fire in most forest types – Fire storm condition at upper intensities	

Box 7: When a fire becomes a fire storm.[5]

'If a fire gains enough momentum, it generates so much heat that it creates its own wind currents, and becomes a raging inferno sometimes known as a fire storm. The fire's heat creates an extremely strong updraught of air. The air at ground level around the fire is then drawn in strongly towards the fire's centre to replace the rising air. The turbulence this creates can result in fire whirls which spiral and dart around, burning as they go.

The heat of the fire can cause thunderstorms or pyro cumulus clouds. These can produce lightning strikes, which can start new fires. With the right combination of atmospheric conditions, fire tornadoes can be created. These can have wind speeds of greater than 250 km/h and are extremely destructive.'

In a case presented by Wotton et al (2012, p.275, Figure 3), the maximum temperature was c.1100°C built up and peaking over c.30 seconds. An approximate temperature pattern followed: it dropped from 1100 to 800°C over c.15 seconds, from 800 to 500°C over 45 seconds, 500°C to c.200°C over 30 seconds and then remained at c. 100°C for 90 seconds. This is a total of 210 seconds or 3.5 minutes. Overall, it was concluded that '*average flame-front residence time for eucalypt forest fuels was 37 seconds and did not vary significantly with fine fuel moisture, fuel quantity or bulk density*' (Wotton et al, 2012, p.270).

6.3.4 Fire mechanisms

Combustion directly consumes live foliage and buds, small live branches and small trees, and causes tissue death (Hood et al, 2018, p.3). Injuries occur to different parts of trees through heat transfer processes (convection, conduction and radiation), and direct tree death from fire is via heat injuries to crown, bole and root tissues (Michaletz & Johnson 2007, pp.501&502; Hood et al, 2018, p.3) (see Figure 10. Note that the spatial arrangement of plantation trees will be more uniform and continuous).

- Conduction: A collision between molecules transfers energy from the more energetic molecules to less energetic molecules.
- Convection: Convection heat transfer occurs when there is a temperature gradient between a solid body (e.g. a fuel element or tree bole) and a fluid that can undergo bulk flow (e.g. air or water) (Incropera, et al, 2006 cited by Michaletz & Johnson 2007, pp.501&502). Like conduction, convection also transfers energy via diffusion at the molecular level – the movement of hot air. Fire plumes are a free convection process resulting from combustion within a fire front (Michaletz & Johnson, 2007, p.504).
- Radiation: Thermal radiation is the emission of energy in the form of electromagnetic waves or photons (Incropera, et al, 2006 cited by Michaletz & Johnson 2007, pp.501&2). Heat is transferred to living tissues of trees during fire, resulting in injuries (Hood et al, 2018, p.3).

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[5] Downloaded from https://www.science.org.au/curious/bushfires on the 02/05/2020.

Figure 10: A diagram representing the different elements of a fire and the impacts (Hood et al 2018, p.3, Figure 1).

6.3.5 Fire-ground mapping

Increasing risk of wildfire has increased a need for information to support mitigation, response and recovery activities by fire management agencies. Fire extent and impacts are mapped in detail post-fire by using remote sensing and on-ground assessment. This will create a complete statement of the area affected fire. To better understand the likely impact, it is important to understand details of the fire events, such as intensity and movement of the active fire front. This will assist with predicting fire outcomes (e.g. tree mortality). Fire mapping can be supported by ongoing review of current and on-the-horizon information and technology (Jones et al, 2017, p.1). Historically, a range of remote-sensing techniques have been applied to forest fires. Currently, there is a lack of systems capable of precisely and automatically monitoring an active fire. For example, resolution of space-borne sensors is too coarse (both spatially and temporally) and previous studies have extracted fire properties from infrared aerial imagery by manual methods (Valero, et al, 2018, p.241). The ability to detect and monitor active fires at near real-time remains an objective (Lentile et al., 2006; San-Miguel-Ayanz & Ravail, 2005, cited in Jones et al, 2017, p.1). There is variation in thermal energy and speed between a smouldering and actively burning fire front (Dennison, et al, 2006 cited in Jones et al, 2017, pp.2&3), and monitoring of burnt areas to detect traces of latent fire is important (Jones et al, 2017, pp.2&3). A key point is that change from an active fire front to a low-intensity smouldering fire can occur in a short space of time, making the return interval of satellites (sensors) an important part of detection (Jones et al, 2017, pp.2&3). An algorithm to automatically locate a fuel burning interface of an active wildfire in georeferenced aerial thermal infrared (TIR) imagery has been developed (Valero, et al, 2018, p.241). In this case a 'fuel burning interface' is the part of the fire perimeter that shows active combustion at a given moment

(Valero, et al, 2018, p.243). The information generated was used to measure temporal evolution of a fire perimeter and automatically generate rate of spread (ROS) fields. The information was exported to standard geographic information systems (GIS) (Valero, et al, 2018, p.241). Mapping of the burnt area is based on changes in spectral responses after fire impacts on vegetation. The soil type, prior vegetation and seasonality can all impact on the sensor response for active and post fire assessments (Randriambelo, et al, 1998; Stolle, et al, 2004; White, et al 1996: cited in Jones et al, 2017, p.3).

6.4 Modes and impacts of fire on trees

6.4.1 General tree fire tolerance and survival strategies

Softwoods are indigenous to many regions where periodic fires are common. Fire impact and plant response outcomes combine fire severity (Agee 1998 cited Fernandes et al, 2008, pp.246 & 247) with stand-history characteristics (Rowe, 1983) in fire-prone environments. Fire-tolerant softwood species cope with fire by either species persistence (e.g. sexual reproduction) or individual survival (Keeley & Zedler, 1998 cited in Fernandes et al, 2008, pp.246 & 247). High-severity fire regimes are stand-replacement events, and the associated species are either ‘fire evaders’ storing a canopy seed bank in serotinous cones or ‘fire endurers’ that recover after fire by sprouting (Fernandes et al, 2008, pp.246 & 247). Softwoods under low-severity fire regimes are typically fire resisters, possessing traits enabling survival of low to moderate intensity fire: tissue insulation from lethal temperature provided by thick bark, large and protected buds, relatively thick needles, deep rooting habit, and a crown structure favourable to heat dissipation, hence less crown scorch (Fernandes et al, 2008, p.246 & 247). Self-pruning and lower branch shedding due to competition or fire, can contribute to crown fire avoidance (Fernandes et al, 2008, p.247).

6.4.2 Actual mechanism of tree death or impact

Elevated temperatures in trees induce a variety of biophysical repercussions, but work to date has focused primarily on meristem necrosis (localised cell death) in the stem and crown, as meristems can regenerate tissues and organs that may be injured during the fire (Michaletz & Johnson, 2007, p.506). Vascular cambium necrosis results from conduction of heat through bark (e.g. a ground fire), and root apical meristem necrosis by heat conduction into the root tip (e.g. a surface fire) (Michaletz & Johnson, 2007, p.511). Heat-induced necrosis is thought to result from protein denaturation (Rosenberg et al., 1971 cited in Michaletz & Johnson 2007, p.511). In fire mortality studies, necrosis is usually assumed to occur above a threshold temperature of 60°C (e.g. Van Wagner, 1973; Gutsell & Johnson, 1996; Michaletz & Johnson, 2006a all cited in Michaletz & Johnson 2007, p.511). More precisely, heat causes tissue death at a temperature of 60°C for 1 second (Hood et al, 2018, p.3). While cell mortality is essentially complete at temperatures above 60°C, necrosis can occur at lower temperatures given sufficient exposure time (Dickinson & Johnson, 2004; Dickinson et al., 2004 all cited in Michaletz & Johnson, 2007, p.511). Although bark is a good insulator, trees damage by direct heat at a temperature of 200°C for more than half a minute resulted in cambium death (de Ronde, C. 1982; Vogl, et al., 1977: cited in Cope, 1993, p.6).

The probability of tree deaths is related to species, severity of the fire, and age and size of the trees (Wright & Grose, 1970, p.151). Cambium necrosis around the entire stem circumference (e.g. girdling) will result in the stem being unable to regenerate phloem and xylem. Cambium necrosis is always accompanied by phloem necrosis because phloem is external to the cambium. The crown of a girdled tree will continue to fix carbon and grow, but with a phloem girdle, photosynthates will not be transported to roots. The root system then relies on carbohydrate reserves; eventually, these reserves will be depleted, fine-root production will cease, and the tree will die from water stress (Michaletz & Johnson, 2007, p.508). When cambium necrosis does not occur around the entire stem circumference, partial stem girdling may occur and produce a fire scar. Fire scars generally occur during windy conditions and have been observed to form on the downwind (leeward) side of stems. Higher surface temperatures have been measured on the leeward side of stems and cylinders in fires (Fahnestock & Hare, 1964; Tunstall et al, 1976 cited in Michaletz & Johnson, 2007, p.508). Even if a small portion of circumference of cambium remains alive (as little as 10%), a tree will likely survive, though the overall vigour could be reduced considerably (McCreary & Nader, 2011, p.1).

6.4.3 Soil impacts and roots

Heat transfer in soil is important. Soil is a porous, composite material composed of organic matter, mineral matter, gas and/or water (Hillel, 1998 cited by Michaletz & Johnson 2007, p.504). Hence, heat transfer through soil is a complex phenomenon involving conduction, convection and radiation (Michaletz & Johnson, 2007, p.504). Forest soils typically have a distinct layer of duff – the decomposing organic matter below the undecomposed litter but above mineral soil (Miyanishi, 2001; Miyanishi & Johnson, 2002 all cited by Michaletz & Johnson, 2007, p.504). In forest fires, a duff layer can either reduce or increase heat transfer through the soil (Michaletz & Johnson, 2007, p.504). Flaming combustion heats the surface by convection and radiation, while smouldering combustion heats the surface by conduction, convection and radiation (Michaletz & Johnson, 2007, p.504).

Soil and root heating primarily occur through conduction during smouldering combustion of duff and large logs (Hood et al, 2018, p.3). Michaletz & Johnson (2007, p.510) noted that there '*has been very little work addressing fire effects on roots, so our understanding of this area is limited*'. The fundamental processes that govern the effect of fire on roots relate to heat transfer from a forest fire to roots via three processes: 1) heat transfer from the fire to the soil surface; 2) heat transfer through the soil; 3) heat transfer from the soil and into the root. Heat transfer from the fire and through the soil will heat the surface of roots, and the temperature gradient from the root surface to the root interior will drive conduction into the root (Michaletz & Johnson 2007, p.510). Species such as *P. pinaster* are deep rooted and use this as a fire tolerance mechanism (Ryan *et al.* 1994, cited in Botelho et al, 1998a, p.235).

While bark is a good insulator, cambial damage can occur from extended smouldering of duff around the root collar. Such damage is likely in previously unburnt stands of mature trees where a deep organic layer has accumulated. Whenever heat penetrates the soil, feeder roots and beneficial soil organisms are likely to be killed (Malan, 2011, p.5)

6.4.4 Crown damage

Tree crowns have three components: branches, buds and foliage. Heat transfer from a fire and plume to crown components occurs by radiation and convection processes, although convection is the dominant process (Packham, 1970; Van Wagner, 1977; Cruz et al., 2006 all cited by Michaletz & Johnson, 2007, p.511). Crown damage reduces capacity for photosynthesis and requires stored carbon reserves to rebuild leaves (Hood et al, 2018, p.3). During a forest fire, the vast majority of trees that are killed die because of damage to the crowns, either from radiation and heat flux from the burning undergrowth and plantation debris, or as a result of the burning of crowns themselves causing all the major life-supporting physiological processes to stop (Malan, 2011, p.2). For example, *P. radiata* crowns are susceptible to crown scorch due to fine needles (de Ronde et al. 2004 cited in Seifert et al, 2017, p.4) and it has been demonstrated in South Africa that survival of a surface wildfire only occurred where crown scorch was less than 90% (de Ronde, C. 1982; de Ronde, 1990: cited in Cope, 1993).

6.5 Bark as a fundamental driver of tree survival

6.5.1 Bark insulation properties

Bark thickness is a key determinant of tree survival after fire. The non-conducting outer bark thickness explains much of the variation in overall bark thickness and has been shown to be a defensive mechanism (Paine, et al, 2010, p.1202). Thicker bark helps to protect cambial tissue from injury by fire generated heat (McCreary & Nader, 2011, p.2). While heat is conducted through the bark of trees, as bark is a poor conductor, it protects the live cambium underneath from heat (Hood et al, 2018, p.3). Variation in thermal conductivity has minor effect on conduction through tree bark, so bark thickness is the primary variable controlling cambium necrosis in fires (Peterson & Ryan, 1996, p.800). Peterson and Ryan (1996, p.800, Equation 10) developed a simple model to determine the time taken to cause cambium death and a scenario is presented in Figure 11. This scenario assumed a fire flame heat of 500°C with an ambient air temperature of 20°C; the impact of bark thickness is apparent. With 1.0 cm thick bark, a fire would require 2.9 minutes *in situ* to kill cambial tissue. Experiments demonstrating the low thermal conductivity of bark have shown that a tree with 25 mm thick bark would require 15 minutes exposure for cambium mortality (Malan, 2011, p.4). Applying an example of the Peterson and Ryan (1996) function (Figure 11) to 25 mm bark, it would have taken 19.6 minutes to reach cambial tissue lethal temperature. A Portuguese study (Fernandes at al 2008 p.252 Table 4) applied the Peterson and Ryan (1996 p.800, Equation 10) bark thickness mortality model to European pine species. Data on bark-thickness (from Fernandes at al 2008, p.252, Table 4) was combined with data from Appendix 3: Key species profiles and the results are presented in Figure 11. Variation between species is evident.

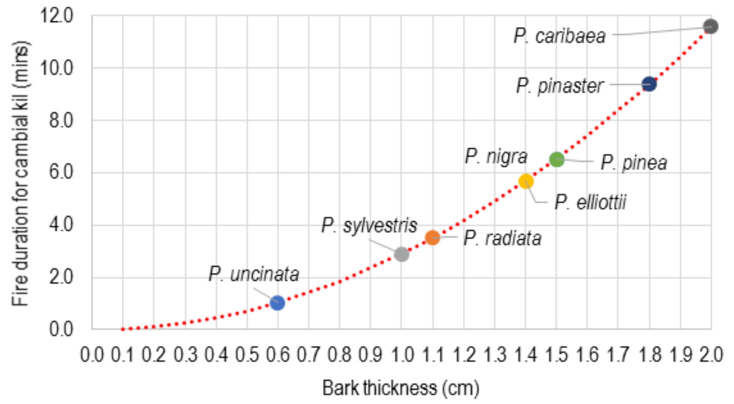


Figure 11: Modelled fire duration (minutes) at 500°C to heat bark tissue and transfer adequate heat to kill cambial tissue for bark thicknesses of the species indicated.

6.5.2 Fire damage to the bark of a standing tree

Fire impacts result from combined elements of fire. Most charring of bark results from burning of biomaterials in the immediate vicinity of the stem (and not the stem), and fire intensity is largely determined by the amount, type and nature, and prevailing weather factors (e.g. wind, moisture levels and temperature) (Malan, 2011, p.2). For example, in *P. pinaster*, a low intensity back-burning (c.350 kW/m) in deep/heavy needle bed fuels killed c.50% of large trees (age 43 years): scorch and stem char heights were relatively low. The stands had not been burnt prior to the wildfire, hence the needle bed fuel burnt completely under the very dry conditions. Inspection of trees noted that crowns were mostly undamaged or slightly damaged, indicating that trees had been killed by stem girdling. The bark was burned down to the cambium, from ground level to 40-80 mm, which was the height of the needle beds (Burrows et al 2000, pp.257&258).

Damage to tree stems during a forest fire is predominantly confined to the outer layer of the bark (Malan, 2011, p.2). For example, in *P. radiata*, a low-intensity fire (flame height <1 m but with a high-residence time) caused fire scars up to a height of 7 m and stem girdling between 22% and 46% of the circumference at stump height (Woodman & Rawson, 1982: p.16). Bark thickness decreases with stem height and more so in young individuals (de Ronde, 1982 cited in Fernandes & Rigolot, 2007, p.2): for example, basal bark thickness in *P. pinaster* at the age of 10 years is almost double the thickness at 1.3 m. A bark thickness of greater than 10 mm reduces injury to the stem to an irrelevant contributor to *P. pinaster* mortality under prescribed burning conditions, provided that smouldering combustion is avoided or minimized (Ryan et al, 1994 cited in Fernandes & Rigolot 2007, p.3).

Bark charring considerations include height of char on the stem of a tree and the quantity of bark consumed (McCreary & Nader, 2011, p.2). Fire will affect tree bark by combustion, drying and in an extreme event by bark stripping (Bootle, 1996: p.22). Damage can result where resin on the outer bark of *P. pinaster* trees ignites and causes some stem damage (Burrows et al, 1988, p.3). A reduction in bark thickness will affect protective properties. The bark of *P. pinaster* and *P. elliottii* is laminated and outer layers are exfoliated during combustion, which is thought to contribute to expelling heat from tree stems (Fernandes & Rigolot, 2007, p.3; Landers, 1991, cited in Carey, 1992, p.5). Outer bark layers of *P. elliottii* overlap and protect grooves where the bark is thinner (de Rhonde, 1982, cited in Carey, 1992, p.5). South African studies of trees killed by forest fire indicated that in the vast majority of cases, fire damage to the tree stems was confined to the outer 2–3 mm of the bark layer. The deeper layers of the bark showed no or very few indications of heat damage (Malan, 1999; Malan, 2000 cited in Malan, 2011, p.7).

There is a greater chance of lethal cambium damage if the bark has been severely blackened, and charring has reduced bark thickness. Ruptured bark (e.g. long vertical cracks up stem bark or separated from the wood) would indicate that the cambium is almost certainly dead, and survival is unlikely as the cambium is exposed (McCreary & Nader, 2011, p.2). Rupturing of bark (breaking the protective layer) permits entry of oxygen and a wide variety of organisms (bacteria, decay fungi and other fungi) into living wood. Production of phenolic compounds by hardwoods and terpenes by softwoods forms part of a tree's response (Bootle, 1996, p.22). The extent of bark damage and the season of the damage event will determine the biological agents entering a tree and the rate of any discolouration (Bootle, 1996, p.23).

6.5.3 Variation in bark thickness

Tree bark thickness varies:

- Bark structure: Bark's insulating properties are determined by the thinnest section of bark. Hence, a deeply fissured bark would be measured from the base of fissures rather than the outer layer.
- Within a tree: Most softwoods have thicker basal bark is the more exposed and more valuable part of the stem (Malan, 2011, p.4)
- With tree age: Bark thickness varies linearly with bole diameter (Spalt & Reifsnyder, 1962, p.4; Ryan & Reinhardt, 1988), hence cambium necrosis in small individuals with thin bark occurs before large individuals with thick bark.

- With tree growth: Bark thickness is strongly correlated to tree diameter at breast height (Ryan and Reinhardt 1988, Hood et al 2008, Kelley et al 2014 all cited in Hood et al, 2018, p.8). Larger trees have thicker bark and are resistant to fire damage (McCreary & Nader, 2011, p.2).
- Between species: Bark thickness varies between species (Spalt & Reifsnyder, 1962, p.5), and cambium necrosis will occur in larger trees for species with relatively thin bark (e.g. *P. sylvestris*) compared to species with thick bark (e.g. *P. caribaea*) (see Figure 11).
- Within species: Variation in bark thickness within species and between provenances has been noted for:
  - *P. caribaea:* (Birks & Barnes, 1990, p.32).
  - *P. pinaster:* (Tapias et al. 2004: based on p.58; Table 2 & p.62, Table 6).
  - *P. radiata:* (Stephens & Libby, 2006, pp.648&650 Table 1). Natural population variation in basal bark thickness has been linked to anthropogenic fires with differences in bark thickness for mainland populations (0.7- 6.6 cm) with anthropogenic fires compared to island provenances (0.3–4.0 cm) with limited anthropogenic fires (Stephens & Libby, 2006, p.648&650 Table 1).
  - *P. patula*: *P. patula* is a thin barked tree with bark accounting for up to 12% of the volume of a mature tree (Wormald, 1975, p.108). Mature bark is grey brown and vertically ridged (Wormald 1975, p.5). A rough-barked variety in South Africa is considered to be more vigorous and to give higher yields than the typical variety.

6.6 Pre-fire condition influencing tree survival

6.6.1 Pre-existing stress

Drought and competition can increase vulnerability to fire through increased plant stress and by influencing the physical fire environment to increase fire intensity (Hood et al, 2018, p.5). Drought is a common stressor for conifers, and pre-fire drought has been shown to increase the likelihood of tree death following fire (van Mantgem et al, 2013; van Mantgem et al, 2018 all cited in Hood et al, 2018, p.6). Stress before fire events can be increased by insects and pathogens affecting tree growth and non-structural carbohydrate (NSC) reserves, and impairing hydraulic conductivity. This can result in delayed mortality in trees that otherwise would have survived fire injuries (Parker et al, 2006; Kane et al, 2017 all cited in Hood et al, 2018, p.6). Trees rely on NSC reserves for resumption of spring growth which requires an accumulation of NSC prior to dormancy (Tixier et al, 2019, p.1).

6.6.2 Tree size and impact on fire behaviour

Fire damage outcomes (survival or mortality) have been linked to tree size, in particular stem diameter at breast height over bark (DBHOB) (McCreary & Nader, 2011: pp.3&4). While physical assessment can determine the state of cambium tissue at a specific point, it is the percentage of a tree's circumference that is damaged that will determine the outcome. If cambial tissue has been killed all the way around the stem, the top of a tree will eventually die, though this may take several years (McCreary & Nader, 2011: p.1). This can be predicted based on the circumference of a stem or trunk that is charred (McCreary & Nader, 2011: p.2). Specific analysis of fire behaviour indicates that development of leeward vortices vary with horizontal wind velocity and stem diameter, and fire scar formation is more likely in high-velocity winds or with large-diameter trees (Michaletz & Johnson, 2007, p.506). Small trees rarely have fire scars because they do not alter air flow and cause vortices, and because they are often killed by complete stem girdling or crown necrosis (Michaletz & Johnson, 2007, p.506). Bark thickness varies linearly with stem diameter (Spalt & Reifsnyder, 1962, p.4; Ryan & Reinhardt, 1988). It is reasonable to expect cambium necrosis (and death) will occur in small individuals with thin bark before large individuals with thick bark. North American experience provides the following guide to which trees are likely to die from fire damage (McCreary & Nader, 2011, pp.3&4):

- Trees less than 15 cm DBHOB: Scorched all the way around the base.
- Trees 15–30 cm DBHOB: Continuous charring around the base, with reductions in bark thickness.
- Trees are greater than 30cm DBHOB: Continuous charring, pronounced reductions in bark thickness, and occasional exposure of underlying wood.

6.7 General species information

6.7.1 Softwood plantations

Fire tolerance is a function of species attributes and fire intensity. There are significant differences between species in needle size and arrangement; branch habit; rate of disintegration and ‘packing down’ of the litter; 'flakiness’ of bark; combustibility of green foliage (Douglas, 1964, p.120). Softwood species generally do not coppice (Spinelli et al. 2017, p.219) with some exceptions (e.g. *P. canariensis* – Arévalo & Fernández-Palacios, 2008, p.64). Softwoods general produce few epicormic shoots on their stems (Büsgen & Münch, 1929; Bond & Midgley, 2001; Del Tredici, 2001 cited in Meier et al, 2012, p.575) with most persistent epicormics either buried in the bark and containing only rudimentary bud scales or with detached meristems. Internal development of both these meristem types is low and a significant stressor is needed to initiate sprouting (Meier et al, 2012, p.575). Under some conditions, such as following the removal of a high proportion of the green crown by pruning, short shoots may develop, giving rise to adventitious (epicormic) branches, particularly on the sunny side of a tree (Mead, 2013, p.68).

A detailed profile of *P. caribaea*, *P. elliottii*, *P. pinaster* and *P. radiata* is presented in Appendix 3: Key species profiles. A summary is presented in Table 7. Overall, *P. radiata* is more vulnerable to fire than *P. elliottii*, *P. caribaea* and *P. pinaster* (Luke & McArthur, 1978, p.146; Forest Fire Management Group, 2007; cited in Mead, 2013, p.22). *P. radiata* is regarded as very fire sensitive (Dawson, 1982, p.1) but will tolerate low-intensity fires (Fernandes et al, 2008, p.246). In Fiji, *P. caribaea* was found to be more fire tolerant than *P. elliottii* during a fire event in the 1950s and this has been supported by evidence from Queensland coastal plain plantations of the two species (Lamb, 1973, p.141). Fire damage to stems of *P. radiata*, is more likely than in *P. pinaster* (de Ronde, 1982: cited in Fernandes et al, 2008, p.248). A caveat of fire tolerance is it will depend on tree age and condition. For example, fire rarely kills mature *P. caribaea*, but seedlings and pole-stage pines can suffer high fire mortality (Munro 1966 cited in Paysen et al, 2006, p.423, Figure 4). In summary:

- *P. radiata* is less tolerant than *P. pinaster*, *P. caribaea* and *P. elliottii*.
- *P. elliottii* is less tolerant than *P. caribaea*.

Table 7: A summary of fire tolerance and mechanisms for the species indicated based on Appendix 3: Key species profiles.

	P. pinaster	***P. radiata***	***P. caribaea***	***P. elliottii***
Fire tolerance	Highly resistant to fire.	Described as 'very fire sensitive'.	Fire rarely kills mature *P. caribaea*, but seedlings and pole-stage pines can suffer high fire mortality. From 5 years of age the species are rarely killed by fire.	Young *P. elliottii* are susceptible to fire, but mature trees are fire resistant.
Bark	Thick and laminated allowing exfoliation during fire.		Thick bark on mature trees.	The outer bark layers overlap and protect grooves where the bark is thinner. During fire, the platy bark flakes-off to dissipate heat.
Crown	*P. pinaster* has resistance to crown kill due to bud tolerance to heating, bud shielding from heat provided by needles, and time-temperature thresholds for needle and bud necrosis. Needle kill is not always synonymous with crown kill, allowing tree survival after total defoliation	Survival possible with less than 90% crown scorch. Trees scorched for more than half of their crown length reduced DBHOB increment by 59% (dominant trees) and 38% (co-dominant trees).	Needles are dropped after scorch and green regrowth is typically seen within three weeks of drop.	High, open crowns allow individual *P. elliottii* to survive fire. Once natural stands of *P. elliottii* are 10 to 12 years old, it will survive a fire that does not crown. *P. elliottii* is tolerant of crown scorch as scorched foliage is replaced by new shoots.
Self-pruning	*P. pinaster* is poor at self-pruning.	*P. radiata* does not readily self-prune within normal rotation lengths.	Self-pruning limbs reduces fire reach into the crown.	Self-pruning limbs reduces fire reach into the crown.
Relative tolerance	Based on bark, *P. pinaster* is more fire tolerant than the other three species.	It is more vulnerable to fire than *P. elliotti*, *P. caribaea* and *P. pinaster.*	*P. caribaea* is more tolerant than the other three species.	*P. elliottii* is less tolerant than *P. caribaea.*

6.7.2 Eucalypt plantations

In eucalypt plantations, trees can recover and be harvested for a number of years after low-intensity fires. The shoot branching process involves the formation of axillary meristems in leaf axils and growth of axillary buds (Shimizu-Sato & Mori 2001, p.1405). Under pre-fire conditions, suppressive auxins will inhibit axillary bud development in eucalypts (Jacobs, 1955, pp.42&43). Where eucalypts have been burnt and the crown removed, but cambial tissue protected, auxins are not produced, and axillary buds will develop a flush of foliage. This response allows a plantation manager to determine which trees have been killed by fire and, where trees have survived, whether rain and natural processes will remove surface carbon and other impurities from the stem of a tree. This approach has been applied in Australia. If lower branches have been burnt off, trees may continue to grow, occluding over the branch stub. In such instances, there is a risk of retained carbon in the stem, which cannot be removed in mechanical debarking and delimbing. The ability to consider salvage will vary with the stage of tree development:

- Where branches are not burnt the risk of carbon is reduced.
- Trees that have self-pruned are at the least risk.
- Branches close to the ground have the highest risk of carbon contamination as fire may run up such trees (candle).
- The degree of branch occlusion and the risk of fire burning back into the stem.
- Where dead retained branches are burnt, this can result in carbon nodules under the bark.

6.8 Fire-impacted but not killed trees: surviving tree growth

Trees can survive a fire and grow. For softwoods, there are impacts on growth rates, wood properties and resin content. For example, it is reported that larger trees can survive more intense fires (Ryan & Reinhardt, 1988; Beverly & Martell, 2003; Kobziar et al., 2006 cited in Fernandes et al, 2008, p.247) mainly because of thicker bark and greater above-ground height of foliage. In an example (from the United States), trees unlikely to die after a fire include trees that: lost all of their foliage but sustained only minor stem damage; have spotty scorching around their base, with at least 10% of cambium alive; are more than 30 cm DBHOB and are scorched all the way around their base with nil reduction in bark thickness (McCreary & Nader, 2011, pp.3&4). Research has shown that while trees may survive, productivity can be affected. A South African study demonstrated that fires without crown damage affected growth and tree ring structure of *P. radiata* and indicated that stem char could be associated with a significant decrease in ring width and latewood/ earlywood ratio (Seifert et al, 2017, p.1).

Trees can survive fire (e.g. experimental, fuel reduction burning or wild) and grow on. For example:

- *P. radiata*: Wright and Grose (1970, p.151) noted that mature *P. radiata* with 75% crown damage from fire reduced DBHOB increment to 80% of pre-fire levels with impacts maintained for two years after the fire.
- *P. pinaster*: Nicholls and Cheney (1972, pp.165&177) considered stands subjected to experimental burning and a wide range of fire intensities did not affect growth-ring width. Fire caused a small reduction in maximum wood density in the first year after the fire in young trees subjected to the most intense of fire. No change in late wood ratio could be attributed to fire treatment in any group. In another case, green-crown height reduction by fire was followed by several years reduction in

DBHOB increment, but where branch kill is limited to the lower crown, the impact appeared to be negligible (McCormick, 1976, p.3).

- *P. elliottii:* Van Loon (1967, pp.6&16) described the effect of wildfire on a 6-year-old plantation of *P. elliottii* and *P. taeda.* After 10 years, *P. elliottii* trees that had few or no green needles remaining after the fire, produced greater mean DBHOB increment than more-affected trees, but a decrease in growth of the two worst damaged classes remained for three years after the fire. For ages 9 to 13, periodic increment for all classes of fire-damaged stems was comparable with unburnt thinning plots.
- *Pinus species*: After a wildfire in South Africa, Malan (2011, pp.6&7) noted that growth rates of trees partially damaged during a fire, was reduced but eventually recovered.

6.9 Predicting fire impacts by combining fire impact mechanisms in a tree mortality model

6.9.1 Damage, impacts and time

It is difficult to predict the degree of damage accurately from the outward appearance of trees (McCreary & Nader, 2011, p.1). Even when predicting fire effects on individual tree components (roots, stems or crown), the challenge remains of linking these to predict tree mortality (Michaletz & Johnson 2007, p.511). This issue is compounded as damage may take time to manifest (McCreary & Nader, 2011: p.2). For example, a stand of *P. radiata* (aged c.35 years) was killed by a January 1966 fire. The pattern of drying varied, depending on how soon trees died after the fire (Wright & Grose, 1970, p.154).

- Killed outright: Killed outright by crown fire and the cambium and wood of the upper boles commenced to dry within a few weeks after the fire. The drying was rapid in the upper bole, but slower and less extensive in the lower bole.
- Complete crown scorch: Trees subjected to very severe ground fires with complete crown scorch retained a few green needles at the tip. The wood did not start to dry until the onset of the following summer, when the needles died and drying of the cambium and bole wood extended rapidly.

Some trees are killed immediately by fire; others die up to several years later (Hood et al, 2018, Figure, 5, p.10). Delayed death may result as fire injured trees are more susceptible to other stressors (e.g. insect attack and drought) (Hood et al, 2018, Figure, 5, p.10). In relation to North American bark beetles, host suitability and attraction after fire varies by tree and bark beetle species, but in general, bark beetles attack and kill trees with intermediate levels of both crown scorch and cambium injury, or higher levels of either crown scorch or cambium kill (Jenkins et al 2014 cited in Hood et al 2018, pp.6&7). As fire damage can change both tree resistance to beetles after low-severity fire (Lombardero & Ayres, 2011; Hood et al, 2015; Kane et al, 2017 all cited in cited in Hood et al, 2018, p.7) and local bark beetle population pressure (Jenkins et al, 2014 cited in Hood et al, 2018, p.7), post-fire mortality needs time to become evident.

6.9.2 Combining fire impact mechanisms in a tree mortality model

Damage to a tree stem is primarily determined by the duration and intensity of the heat a tree was exposed to; the average tree size; characteristics of the bark (thickness and amount of resin and other flammable material on the surface); the volume, nature and type of undergrowth and plantation debris that surround the tree at the time of a fire; and the prevailing weather (Malan, 2011, p.4). One way to accurately determine the degree of fire damage is to cut away a portion of the bark to observe the cambium beneath (McCreary & Nader, 2011, p.2). Assessment should be made several weeks after a fire (McCreary & Nader, 2011, p.2).

- If the cambium is dark or yellowish, a tree is probably dead.
- If it is white or pink, a tree is most likely alive.

Predicting tree mortality after fire is fundamental to effective fire response planning, triage and salvage. A range of models has been developed to predict fire induced mortality of trees (see Table 8). Bark thickness or tree DBHOB (strongly correlated to bark thickness) is used as a surrogate for resistance to basal heating (Ryan & Reinhardt, 1988; Hood et al, 2008; Kelley et al, 2014; all cited in Hood et al, 2018, p.8) because bark thickness has the largest influence on heat transfer to the underlying cambium (Bova & Dickinson, 2005 cited in Hood et al, 2018, p.8). Researchers considering prediction of natural forest softwood mortality in California found that crown length and crown volume injury variables predicted tree mortality equally well, and that cambium kill rating was significant in predicting mortality in all models. The researchers noted that '*the models confirm the overall importance of crown injury in predicting post-fire mortality compared to other injury variables for all species. Additional variables such as cambium kill, bark beetles, and tree size improved model accuracies, but likely not enough to justify the added expense of data collection*' (Hood, et. al, 2010, p.750).

Table 8: Examples of models developed to predict fire induced mortality of trees.

Species	**Descriptor**	**Reference**
P. pinaster	Non-linear, logistic and exponential regression models were developed to predict post-fire tree mortality as a function of the following fire injury and heat resistance variables: ratio of crown length scorched to pre-fire crown length, proportion of pre-fire crown volume scorched, and diameter at breast height.	Botelho et al (1998a, p.235).
Softwoods	Time for cambium death based lethal temperature to cambium, fire increase in temperature, bark thickness, bark thermal diffusivity and time.	Peterson & Ryan (1986, p. 800).
Eucalypt forests	Prediction of threshold DBHOB for survival of fire based on heat output (MJ/m^2), fuel moisture (% oven dry basis), scorch height (m) and Keetch Byram Drought index (mm equivalent).	Tolhurst (1995, p.50)

Figure 12 shows the complexity of tree mortality due to fire. It shows a tree mortality model for natural forest softwoods in the United States (Peterson & Ryan, 1986, p.797). A run of this model requires stand data inputs to calculate fire intensity via a fire behaviour model. The fraction of crown volume killed is calculated for each species in a stand based on mensuration data. Duration of basal lethal heat is calculated from fuel consumption and burning times. The fraction of crown volume killed and the ratio of critical time for cambial kill to duration of lethal heat are independent variables in a function that calculates the probability of mortality.

6.10 Documenting fire impact damage and mapping

6.10.1 Fire impact damage classification

Table 6 presents a classification system applied to a fire event. Fire intensity is a specific attribute of a fire at the time of the fire. Fire impact is the outcome defined by damage to standing trees. Where a classification system relates observed and documented impact (damage) to expected outcomes (e.g. tree death or change in wood properties), classification of an area of burnt plantations allows prioritisation for salvage operations.

To expedite assessment of fire impacts, a range of fire impact classification systems have been used to define damage to trees and forests. A five-point system of fire damage was applied to a *P. elliottii* plantation in 1956 in NSW (Table 9). This system was used to relate tree damage to impacts on tree growth after 10 years (van Loon, 1967). A system of classifying southern pine plantation fire damage was developed within two weeks of a 1994 fire in Queensland (DPI, 1995, p.4) as the basis of stand classification (Wylie et al, 1999, p.149; Hood &

Ramsden, 1997, p.7). Trees were assigned one of three classes according to the degree of crown scorch present immediately after the fire (Table 10). A four-point damage scale was used in NSW to classify fire damage to *P. radiata* in 2006 (Table 11). An assessment of 8‑13-year-old *P. radiata* used a three-point scale in south-west Western Australia in 2009 to classify stand damage 12 months after the fire event (Table 12). All systems include crown damage, and Table 11 and Table 12 include stem damage. Stem damage due to ground fire and resulting cambial death needs to be addressed. An initial damage classification may not relate to the ultimate outcome and affected stands that are allowed to grow on rather than salvaged may not survive.

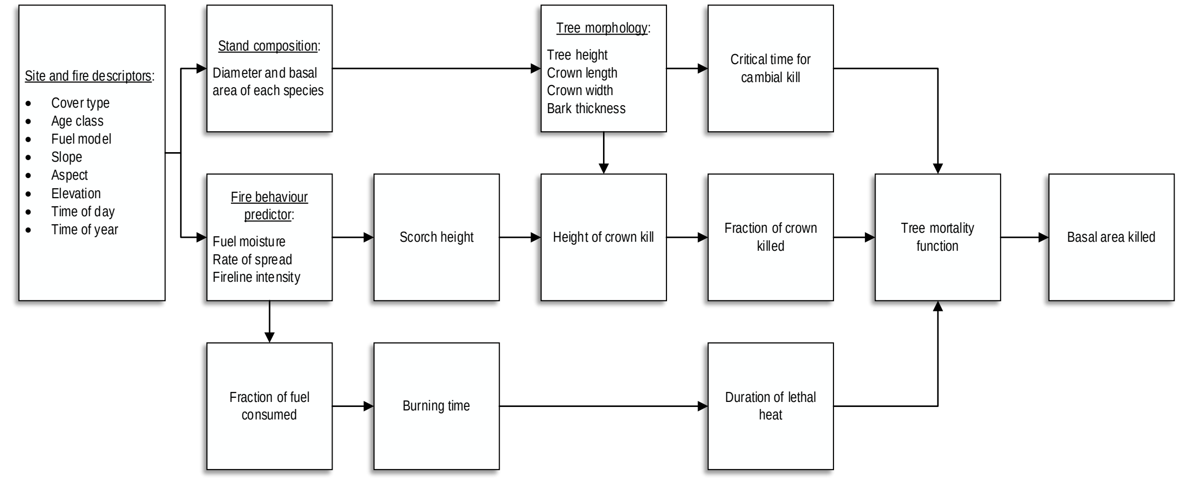


Figure 12: A schematic of fire processes resulting in tree mortality (Peterson & Ryan, 1986, p.798).

Table 9: A 1956 fire impact classification system applied to *P. elliottii* in north coast NSW (van Loon, 1967, p.13).

Code	Narrative
1	No green needles, few or no brown needles remaining; leader drooping.
	Intermediate between 1 and 2.
2	Few or no green needles, brown needles mostly present on tree; leader erect or drooping.
	Intermediate between 2 and 3.
3	Green needles at top clearly visible; leader erect.

Table 10: A 1994 fire impact classification system applied to southern pines in Queensland (Wylie et al, 1999, p.149; Hood & Ramsden, 1997, p.7).

Code		Descriptor
0	Burnt	No green foliage, no living foliage present.
1	Moderate to severe	1-2 whorls of green foliage present, tufts of green foliage at shoot apices only.
2	Light to moderate	More than 2 whorls of green foliage present, low to moderate green foliage present through the upper crown.

Such systems rely on ground-based assessment. Remote-sensing methods can be effectively used to categorise fire-damaged plantations to prioritise salvage. Forestry Corporation NSW has developed the Rapid Assessment of Fire Impacts on Timber (RAFIT) analysis to assist with operational planning for fire salvage and recovery (Sutton, 2020) (see Table 13).

Table 11: A 2006 fire impact classification system applied to P. radiata by fire in NSW (Joe, 2007).

Descriptor		Narrative
Black trees	Crown fires	Trees that are fully burnt. Trees are charred to the top of each tree.
Brown trees	Areas impacted by ground fires	Trees that have dead needles and are fire impacted in the lower trunk.
Green – light trees	Areas with minimal impact as fire passes through a stand	Trees that have had a very light fire under the stand with minimal damage. Some moderate crown scorch.
Green – dark trees	Nil fire impact	Unaffected by fire but can be drought stressed.

Table 12: A 2009 fire impact classification system applied to *P. radiata* in WA applied 12 months after a fire (Dumbrell, 2010).

Descriptor	Narrative
High fire intensity	Trees totally defoliated.
Moderate fire intensity	Trees killed at the time of the fire but needles still intact.
Low fire intensity	Trees have only recently died (red tops).
Very low fire intensity	Charred bark but trees still alive.

Table 13: A classification of fire damage in NSW (Sutton, 2020) (NBR = normalised burn ratio).

Class	Description	NBR range
1	No indication of vegetation loss.	NBR < 200
2	Burn, drought or other plant health impacts. Understory present. Crown mostly green with some browning.	200 < NBR < 350
3	Crown mostly intact, with green and brown leaves, understorey burnt.	350 < NBR < 500
4	Leaves browned but mostly not crowned, understorey complete burn.	500 < NBR < 680
5	Crowned/mostly crowned and complete burn.	680 < NBR < 1000
6	Active fire.	NBR > 1000

A key point is that a fire impact classification system is based on tree attributes assessed *after* a fire event and it should not be confused with fire intensity (e.g. the system in Table 12. A fire impact classification system should include crown and stem impacts.

6.10.2 *Fire impact mapping*

The RAFIT system evolved from past experience where remote-sensing data was used to classify stands Table 13). It was reported by industry that fire impact will be evident within 24 hours of a fire as the foliage changes colour rapidly. While this system provides increased speed of assessment, issues remain:

- Pre-existing issues: It is difficult for routine imagery to identify issues linked to drought impacts.
- Cloud: Imagery is via satellite, needing several passes to get cloud-free images.
- Smoke: During active and large-scale fires, smoke obscures visibility and therefore the ability to undertake mapping. Smoke has not been a problem with past smaller fires but the 2020 fires generated widespread smoke affecting access to imagery.
- Stand conditions: In recently thinned compartments, ground reflectance overwhelms crown reflectance and distorts impact allocation.

Previously, mapping of fire impact was by manual interpretation of remote-sensing data. The current approach automates data and mapping based on defined spectral rules (see Table 13). The system uses Sentinel 2 imagery to calculate normalised burn ratios (NBR). Normalised burn ratio is defined as multi spectral imagery (MSI) bands (8-12)/ (8+12), where near infrared (NIR) =8 and THERMAL=12. This index relates to vegetation vitality, and water content of vegetation and soil (Veraverbeke et al, 2010 cited in Häusler et al, 2018, p.6057). Near infra-red and short wave infra-red (SWIR/THERMAL) are sensitive to vegetation and albedo (light that hits a surface and reflected without being absorbed). Fire intensity is determined by calculating the difference between pre-burn and post-fire images of an area. Automated interpretation of remote sensing of wind-storm damage has been compared with manual interpretation and found to be an appropriate method for wind-damage assessment using commercial remote-sensing systems (Donoghue et al., 2006a). Automation of fire damage classification of stands attempts to apply mean values across plantations. Depending on the fire, it is likely that a stand will have multiple classes of impacted trees. Where a fire impact is more variable (patchy), a higher resolution would assist mapping and planning to determine which area warrant retention of standing trees for later harvest. Rather than harvesting on a mosaic of differently burnt trees, harvest planning will stratify stands into logical management units considering ongoing management (e.g. subsequent re-establishment) of sites.

6.10.3 A need for temporal data

The impact of a fire may change with time, driven by a range of damage agents that may or may not develop, which creates uncertainty. For example, following the 1983 Ash Wednesday fires in South Australia, insects and bluestain were not a problem (Wylie et al, 1999, p.152). The fires were followed by a wet, cold period that inhibited insect activity and there was little non-insect transmission of bluestain fungi (Wylie et al, 1999, p.152). The 1994 fires in south-east Queensland were in September and November, ahead of summer. In this case, it was recommended that stands damaged by fires be salvaged within three months to avoid significant bluestain (Hood & Ramsden, 1997, p.7). Experience in Queensland with Southern Pines (Table 10) suggests that:

- Class 1: Moderate to severe: Trees with severe crown scorch dried more rapidly and developed substantial bluestain more quickly, except towards the base of the stem (Hood & Ramsden, 1997, p.7). The sapwood of green-crowned trees dried gradually and developed bluestain more slowly but even green-crowned trees attacked by Ips eventually became substantially affected by bluestain. In a supplementary study, bluestain was found only in association with Ips attack, which was a reliable indicator of the presence of bluestain in fire-damaged stands (Hood & Ramsden, 1997, p.7).
- Class 2: Light to moderate damage: It was expected that compartments with trees with more than four green whorls remaining after fire would survive and such stands would be not be harvested. Trees that are successfully attacked by Ips will eventually succumb, and several such affected stands with full green crowns left unharvested died in the spring and summer following the fire (Wylie et al., 1999, p.149). If there is a link between previous logging of a plantation and timing of attack by Ips following fire, then compartments in areas that had been thinned or clear-felled within eight months before the fire could be prioritised for early salvage (Wylie et al., 1999, p.152).

As part of the fire response in south-east Queensland, a system of forest health surveillance was established to monitor the onset of attack by insects and fungi and subsequent negative impacts on wood quality. Experience of subsequent spread of bark beetles, other insects, bluestain fungi and decay fungi fluctuated widely with location and weather conditions, resulting in constant reassessment of harvesting priorities and log product specifications (DPI, 1995, p.4). This highlights a need for temporal data and monitoring as initial fire intensity scores may not always relate to the ultimate fire impact.

Normalised burn ratio is useful to classify outcomes of a specific fire event at that point in time. As well as changes in evapotranspiration, temporal changes identified by remote sensing can detect change in burn impacts; further degradation or recovery (in the case of Southern Pine and eucalypts). For example, monitoring of evapotranspiration over 1–3 years after the 2009 Black Saturday wildfires found that evapotranspiration was on average 41% lower in 'high severity' burnt forests compared with unburnt forest, whereas evapotranspiration from forest burnt at 'moderate severity' was only 3% lower than unburnt forest over 1–2 years post-fire, but on average 9% higher over 2–3 years post-fire (Nolan et al, 2014, p.1363). A study in Portugal made use of evapotranspiration data derived from remote sensing to determine changes post-fire (Häusler et al., 2018, p.6499 – Abstract). Comparing damaged and undamaged sites 23 years after the fire events, differences in evapotranspiration became non-significant for all NBR classes.

6.10.4 Developing a fire impact map to support a salvage plan

An understanding of fire impacts and damages can be used to expand the utility of fire mapping (see Table 13) to predict actual impacts over time. An improved method would incorporate factors such as fuel loads prior to a fire and speed of a burn (Wylie et al., 1999, p.152). This would take into account minimal damage to tree crowns given that '*localised occurrences of a slower but more intense burn, such as may occur at night, in areas with considerable fuel load on the ground resulting in severe stem burn but no crown damage*' (Wylie et al., 1999, p.149). Such information is generated based on fire and stand histories. A category of less than 1m stem scorch is needed, where trees generally survive and grow but it is likely that butt logs will be affected (category '1.5' in Table 13). Reservoirs for Ips attack could remain in unburnt harvest residues. One trend that emerged from post-fire surveys in Queensland was a possible link between timing of attack by Ips in a fire-damaged compartment and logging history of the area. Compartments where thinning or other harvesting operations had taken place within several months prior to the fires appeared to have a higher incidence of infestation than comparable compartments that were unthinned or where harvesting operations had taken place prior to 1994 (Wylie et al, 1999, p.152). The insights of the model in Figure 12 could be added to primary data from remote sensing and combined with stand data to better predict the outcomes of a fire. Table 14 presents a summary of elements of a fire event and Figure 13 presents a schematic of the combined elements to predict fire outcomes.

Table 14: A summary of component of a fire impact, damage and outcomes.

Aspect		Narrative	Impact
Fire attributes	Fire type	A fire can be surface, ground and/or crown based.	Whether the fire damaged the crown and/or lower stem.
	Intensity	Fire intensity from 'low' (<150 kW/m) to 'very high' (7,000–70,000 kW/m)	Defines the height of fire impacts and the fire type.
	Duration	The time of fire residence in an area and time at different intensities.	Defines foliage and stem cambial damage.
	Fire mapping	The extent of a fire and potentially impacts.	Defines the gross area within which salvage must be undertaken.
Ground conditions		In most cases a fire will have removed all organic matter to expose bare soil across a site and any rocks or other non-biological elements.	Changes machine traction and traffic conditions (exacerbated by rainfall events).
Pre-fire stand attributes	Compartment history	Tree age class, management and any inventory data	Allows allocation of stand priority based on products.
	Underlying conditions	Whether a stand is under external pressures (e.g. drought or infestations) prior to fire.	Affects a tree's resilience determined by reserves of NSC.
	Species	The species of tree planted.	Dictates bark attributes with age and fire resilience.
	Age	Tree age will define potential products and tolerance to fire.	Dictates merchantability. Older trees will generally have thicker bark.
	Stocking	The stocking of a stand of trees will result from management interventions. Thinning is the most critical issue.	Fire salvage will most likely be a clear-felling operation. If a stand is not at usual final stockings, there will be more trees to handle per hectare, potentially creating congestion issues.
	Harvesting	Previous harvesting will define current tree attributes and fuel levels due to harvest residues.	Fire intensity, temperature and duration on-site contributing to tree mortality. Level of post-harvest residues can act as a potential source of infestations.
Post-fire mapping	Fire impact classification	Development and application of an impact classification system, ideally informed by known causal outcomes (e.g. species X by impact Y is likely to result in Z).	Classifies stands likely to be dead now, die slowly or survive.
	Initial impact mapping	Application of remote sensing systems to map fire impacts.	Identifies stands likely to be dead now, die slowly or survive. This is a fundamental step
	On-ground monitoring	Verification of remote sensing and identification of areas subject to low intensity but long duration surface and ground fires. To monitor insect pest populations.	Determines areas of trees likely to die due to cambial tissue damage. Determines timing of insect attack.
	Ongoing mapping	Ongoing remote sensing monitoring to detect change in stand status over time.	Determines changes in areas of trees likely to die due to cambial tissue damage.
	Harvesting	Burnt trees may lack the sail area created by a green tree's foliage, creating different behaviours during felling (e.g. much faster with increased impact force).	Helps with planning of salvage by equipment and contractor matching to compartments.
Post-fire monitoring data	Tree moisture content	Monitoring tree stem drying.	Affects product options and stratification of logs.

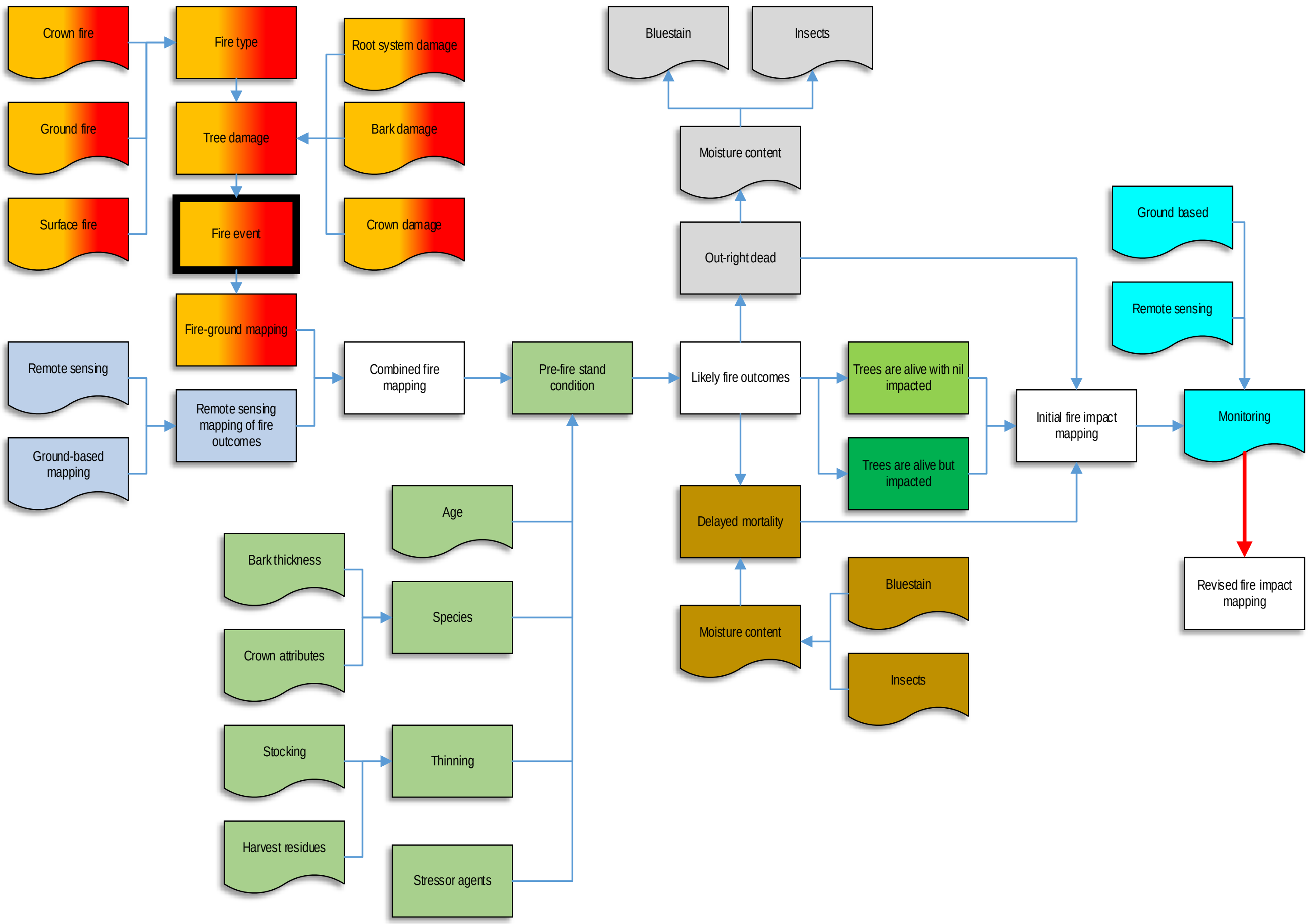


Figure 13: A schematic of combining current remote sensing with other elements driving fire impacts and outcomes towards predicting tree mortality.

Table 15: A proposed two-way matrix classification of fire damage as it can relate to impacts and outcomes.

	Crown impact		Stem impact					
Class	**Description**	**NBR range**	**Nil damage**	**Nil stem damage**	**<1 m height**	**Bottom third**	**Up to middle third**	**Whole stem**
			S1	S2	S3	S4	S5	S6
			A green tree with nil fire impacts	A surface and/or ground fire damage to tree base. Bark is not charred but root system may be impacted	A surface and/or ground fire damage to tree base. Bark is charred to this height.	Surface and/or ground fire damage extends into the bottom 1/3 of tree stems. Bark is charred to this height.	Surface and/or ground fire damage extends into up to the bottom 2/3 of tree stems. Bark is charred to this height.	Surface, ground and crown fire damage to the whole of tree stems. Bark is charred to this height.
R1	No indication of vegetation loss.	NBR < 200						
R2	Burn, drought or other plant health impacts. Understory present. Crown mostly green with some browning.	200 < NBR < 350	Unlikely combination.	A slow moving fire (e.g. at night) with minimal radiant heat damage, but potential tree root impacts.	A slow-moving fire (e.g. at night) with minimal radiant heat damage, but potential tree root impacts.	Unlikely combination.	Unlikely combination	Unlikely combination
R3	Crown mostly intact, with green and brown leaves, understorey burnt.	350 < NBR < 500	Unlikely combination.	Possible combination.	A slow-moving fire (e.g. at night) with minimal radiant heat damage, but potential tree root impacts.	Unlikely combination.	Unlikely combination	Unlikely combination
R4	Leaves browned but mostly not crowned, understorey complete burn.	500 < NBR < 680	Unlikely combination.	Unlikely combination.	A slow-moving fire (e.g. at night) with minimal radiant heat damage, but potential tree root and lower stem impacts.	A moderately moving fire with minimal radiant heat damage, but potential tree root and lower stem impacts.	A moderately moving fire with minimal radiant heat damage, but potential tree root and lower stem impacts.	Unlikely combination
R5a	Crowned / mostly crowned and complete burn.	680 < NBR < 1000	Unlikely combination.	Unlikely combination.	Unlikely combination.	Unlikely combination.	Unlikely combination.	A crown fire in the absence of a fire storm.
R5b	Crowned / mostly crowned and complete burn.	680 < NBR < 1000	Unlikely combination.	Unlikely combination.	Unlikely combination.	Unlikely combination.	Unlikely combination.	A crown fire with high winds from a fire storm.

6.11 Recommended best practices

6.11.1 Fire impacts (classification, physical, biological)

Best practice 23: Combine remote sensing and on-ground information in a fire classification system as a basis of mapping fire impacts. This should include crown damage, stem damage and fire intensity.

Best practice 24: Develop a two-way matrix fire damage classification system matrix with crown damage based on remote sensing data and stem damage initially based on ground based assessment. The aim is of this system is to define tree damage that can be related to subsequent impacts (e.g. tree mortality, lost volume and changes in tree moisture content).

6.11.2 Post salvage management

Best practice 25: Ensure resource modelling systems incorporate a modified fire impact classification system.

6.12 Observations

Observation 1: Predicting tree mortality following a fire as a critical step to planning and effective and efficient fire salvage operation. There is a need to develop a predictive tool that combines remote sensing data (e.g. NBRs), pre-fire conditions (e.g. stand conditions and fuel loads) and fire intensity. This should be species specific. This can result in enhanced mapping of stands and will allow linkages between fire outcomes (e.g. mortality, damage and resource properties) and post-fire stand classifications.

Observation 2: Calibrate fire intensity classification to impacts on plantation species; current bark mortality models are based on temperature by time and not fire intensity.

Observation 3: Develop and implement mechanisms to gather / collate / capture Australian data on fire outcomes (i.e. burnt crown, scorched crown, char score/severity, etc) and consequent impact for the main hardwood and softwood species.

Observation 4: Map areas of plantations burnt by a fire storm with associated high winds as opposed to a lesser crown fire.

Observation 5: Review current tree improvement programs to consider potential for improving fire tolerance by enhancing bark thickness.

Observation 6: Understand the attributes of fire in plantation forests, the impact of fuel levels and the ability to change management practices (e.g. harvesting residues) to mitigate potential fire temperatures. A key issue with a fire is the heat generated and duration of that heat. Maximum temperature is at the flame base and this will impact the lower stem of trees.

Observation 7: Review and understand trade-offs between harvesting methods, plantation fuel loads and nutrient removals. Consider strategies for *in situ* fuel modification to maintain site nutrient levels.

Observation 8: Understand immediate and later impacts of fire as they relate to a damage class assessment protocol to assist in stand impact mapping and triage.

Observation 9: Capture and collate data on insect attack and linkages to season, weather and stand condition. Include consideration of spatial arrangement of harvest residues and other potential sources of infestation.

Observation 10: There is a need to develop an agreed and standard protocol to establish and monitor plots within and around fire impacted stands for stand condition changes linked to fire impact classifications.

Observation 11: Address anomalies in remote sensing assessment of fire intensity such as RAFIT (e.g. recently thinned stands where ground reflectance overwhelms crown reflectance), and quantify the accuracy in terms of fire intensity/damage severity. Determine the relationship between fire intensity mapping and survival and salvage across different age-classes and thinning regimes. Test approaches over a range of plantation types (e.g. climate, species and management).

7 Fire impacts – post-fire conditions – physical impact agents

7.1 Summary

Fire impact and damage can result in unwanted physical items attached to a log, including carbon and grit. Carbon (charcoal) can be classified as inherent (resulting from combustion of tree structures, e.g. bark, wood and branches), or acquired post-fire as a passenger carbon (e.g. soot, flecks or nodules). In a similar manner, grit (e.g. sand particles) can become embedded in the surface of a tree during a fire or be acquired during harvest and haulage of logs. Both carbon and grit can increase repairs and maintenance requirements during processing, breakdowns and associated lost production. Carbon has an added impact by increasing health hazards to staff where particulates become airborne. Carbon and grit can be addressed by de-barking. Sawn timber products are only affected if a board has a section of wood that has been burnt. Plywood manufacturing will peel a log to beyond any burnt wood and therefore all carbon and grit is removed, with a reduction in recovery rates. Pulp and paper, export woodchips, medium density fibreboard (MDF) and particleboard are all highly sensitive to carbon, which creates cosmetic but unacceptable imperfections in products. Care is needed to eliminate carbon and grit (e.g. carbon prohibition, changes to log specifications) where one processing system generates residues as feedstock into another process.

7.2 Introduction

A first step towards supply of logs to a processor is to understand whether the logs are ‘fit for service’. This includes consideration of wood properties and products, as well as markets for processing residues as inputs to other manufacturing processes. Another key consideration is any impact on cost of production (e.g. due to change in labour inputs, repairs and maintenance). Fire damage to a tree can be obvious (e.g. charred bark) or more obscure and affect the ‘fit for purpose’ status of logs. This section considers carbon and grit impacts on processing and production.

7.3 Carbon

7.3.1 A classification of carbon

Carbon can originate from combustion of a tree (e.g. bark or branches) or become attached to a log after contact with the forest floor. Time and rain since a fire event assist in removal of carbon from a site. There are six types of carbon associated with a log:

1. Inherent carbon: Carbon from combustion of a tree.
    a. Bark: Charcoal embedded in bark resulting from bark combustion.
    b. Burnt wood: Wood is burnt and remains as charcoal.
    c. Branch stubs: A dead branch is burnt back into a stem and remains as a carbon nodule.
2. Passenger carbon: Carbon attached to the outside of logs.
    a. Soot: Fine carbon loosely attached to logs and/or bark, including attached to resin or sap.
    b. Flecks: Small units of carbon attacked to a log surface or outer bark.

c. Charcoal: A nodule of carbon embedded in a log surface or attached to a log end, but not as a result of combustion of that log at that point (it is picked up during harvest and haulage).

Inherent carbon can be within trees that have survived a fire event and grow on, and a carbon nodule becomes occluded under stem bark.

7.3.2 Impact on sawn timbers

With the exception of burnt sections of boards and cosmetic issues with surface appearances, carbon is not an issue with sawn timber. Industry experience suggests that carbon on logs can increase maintenance during processing and manufacturing due to mechanical abrasion on cutting edges and in equipment bearings. For example, chipper knives and saw wear almost doubled due to carbon. A study at Mississippi State University showed that dulling due to a char layer is a chemical reaction of carbon with iron or cobalt materials to form compounds that could be abrasive or could be eroded away by friction (Malan, 2011, p.17). There is a reduction in revenue from 'burnt' bark. Overall, industry reports increased costs associated with handling salvage logs, including additional wages, an increase in personal protective equipment (e.g. PPE – masks, coveralls, etc) and repairs and maintenance.

Based on past events, the sawn timber sector is aware of the issue of carbon and the ability to supply processing residues to a range of markets. An ideal solution would be finding an alternative market for chips affected by carbon.

7.3.3 Pulp and paper impacts

Fire salvage experience in South Africa noted that *'removal of all carbon residues from the logs prior to chipping is of crucial importance as pulp mills have a zero tolerance for charcoal'* (Malan 2011, p.19). Carbon impurities introduced into woodchip in-feeds for pulp and paper manufacturing flow through into finished goods and will result in rejection of a whole batch of production (e.g. a full reel of paper). Industry noted that one burnt branch stub the size of a thumb can spread through a 40 tonne reel of paper, which will be rejected by customers seeking 'perfect paper'. Carbon in paper creates specks in the appearance (optical properties) of a sheet of paper. Canadian experience noted that charcoal stands out as dots or potential pin holes in paper (Watson & Potter, 2004, p.476). Carbon cannot be 'screened' for and excluded from pulp and paper making. Burnt woodchips are difficult to track as there is no established method to determine the amount of carbon on chips. Careful metering is essential to keep burnt woodchip input to a process at uniform levels (Watson & Potter, 2004, p.476). Woodchips from burnt trees generally have the same density (kg/m^3) so burnt fibres cannot be separated by pulp cleaners, unlike bark or other contaminants. When burnt materials enter the pulping process, weight differences are not adequate for separation based on density, which is the approach take to clean pulped fibres. Carbon cannot be chemically stripped from pulp either.

Woodchip export markets have different tolerances to carbon; for example, in Western Australia, a hierarchy of carbon tolerance (least to most tolerant) is:

1. Plantation eucalypt woodchips: Zero tolerance.
2. Softwood plantation woodchips from thinnings and sawmill residues: Zero tolerance.
3. Natural forest export woodchips: Some tolerances.
4. Biomass for energy: Any product not accepted by the woodchip market is acceptable.

As an example, Midway Limited specifies that woodchips supplied (plantation *E. globulus*, *E. nitens*, *E. grandis*, *E. dunnii* and natural forest hardwoods, and plantation softwoods) '*shall be substantially free from char, metal, bitumen, polypropylene, plastics, vinyl and coal….*' While it may be possible to attempt to address fire-impacted logs, some sites exclude carbon-impacted logs with a preference for zero carbon on logs entering log de-barkers. Where alternative markets are available, sawmills can divert residue woodchips to more tolerant markets. The following is an example of a sawmill strategy to address carbon on fire-impacted logs:

- A site processing green sawlogs supplies processing residues to an export woodchip market.
- Where scale crosses a trigger level, fire-impacted logs are batch processed.
- Residue chips from processing burnt logs are sent to alternative manufacturing sites rather than to export.
- At the end of batches of impacted logs, un-burnt green logs are processed.
- Woodchips continue to be supplied to alternative markets for 1.0 to 1.5 hours to ensure a 'flush out of carbon'.
- There is nil extra maintenance undertaken to clean systems between log types.
- Subsequent production is resumed as supply into export markets.

There is a need to understand the level of tolerance to carbon in woodchips and the best price for impacted chips. With an increase in the supply of burnt logs into processing sites, an increased focus on monitoring will become more of an imperative. This is a complex matter as carbon cannot be readily detected in woodchips. Current protocols include spot sampling of woodchip outfeeds and a key objective would be the ability to measure carbon in green woodchips on a conveyor.

7.3.1 Panel boards

Medium density fibreboard (MDF) can be utilised in appearance and non-appearance applications. With appearance grade products, surface uniformity is critical. MDF can have an exterior layer of melamine. It is a commodity product available in a small range of basic colours and is commonly used for structural elements of cabinets or furniture where the material is not seen (Bord Products: https://www.bord.com.au/product-category/laminate-and-melamine/). The surface melamine layer is thin and carbon contamination can create shadows in the product. Considering the integrated nature of a wood supply hub, MDF manufacturing can receive sawmill residues and carbon remains an issue in such materials. A key point is an ability to identify any resource potentially containing carbon to allow allocation to non-appearance grade products.

Particleboard is made from flaked fibre material and resins: the aim is to use flakes that are as uniform as possible to maintain product appearance. This is achieved by careful blending of input resources. Particleboard has three layers: a core and two outer faces. The outer faces must be as smooth as possible and of uniform colour. This is achieved by including finer particles, which results in increased surface smoothness. In some cases, a resinated paper layer is applied as a coating: the paper can be 65 grams per square metre (GSM) in Australia and as low as 35 GSM in Japan. For reference, standard A4 photocopy paper is 80 GSM. If a surface is not uniform in colour or flake size, this will show through the paper coating layers. Carbon discolouration can be an issue with decorative products where carbon impurities are visible through surface laminated 1 mm thick papers, which are resonated to give the final finish. A key approach to utilising fire-impacted logs and sawmill residues is to maintain provenance and apply a blending strategy to maintain the risk of carbon to an 'acceptable' level by dilution. Industry information suggests that carbon is a minor contributor to increased wear and tear on plant and equipment. Passenger carbon can be removed during chip washing prior to presentation into manufacturing.

Logs are processed without segregating fire impacted and green logs. It is reported by industry that carbon is addressed by routinely peeling logs until they are round and all bark and carbon are removed. Peeling residues are used as boiler fuels. Under this regime 'light' to 'medium' burnt logs have been processed and found to be acceptable. There is a need to address processing of severe burnt logs.

7.4 Grit

It is reported by industry that fire-impacted salvage logs have a higher level of grit (embedded soil particles) and that there is little understanding of the mechanism for this extra grit. Grit can be embedded in a tree stem due to fire winds or become attached during harvest and haulage (passenger grit). Increased dulling of saw blades during processing of logs with charred bark was caused by sand and dirt particles embedded in bark's carbon layer during handling. Such embedded materials are not removed in washer systems, emphasising the importance of mechanical de-barking of burnt sawlogs (Malan, 2011, p.17). Saw blades fitted with tungsten carbide tips are particularly sensitive to impacts by hard objects such as grit. Such tips are hard and highly resistant to blunting but don't withstand shocks due to brittleness (Malan, 2011, p.17). Chip washing attempts to remove grit (Smook, 2002, p.57) prior to pulp refining. Where increased grit passes through the pulping process, it impacts screening equipment where pulped fibres are screened. This extra wear is blamed for a need to replace pulp screening components between scheduled mill maintenance. Screens are 3 m in diameter and cost c.$55,000 each. A pulpmill needs to cease production for a day, which can cost c.$350,000 in lost production. Embedded grit or stones in bark can also damage peeler knives during plywood manufacture, resulting in additional maintenance.

7.5 Abiotic discolouration

Discolouration of wood can result from flavotannins, which diffuse into sapwood from the bark (Liese, 1984, p.128).

7.6 Recommended best practices

7.6.1 Salvage harvesting and logistics, environmental and safety management

Best practice 26: Establish a strategy to address carbon risk by either prohibiting fire-impacted logs from a site or applying management strategies to address carbon. Management strategies need to address passenger and inherent carbon on logs.

Best practice 27: Use site management strategies, including segregation and batching of fire impacted and green logs.

Best practice 28: Have an overall strategy to address logs with carbon impacts with a range of possible alternatives.

7.7 Observations

Observation 12: Establish acceptable limits of carbon and impurities in products and processing systems.

Observation 13: Explore options to detect carbon and impurities in primary products and processing residues prior to entering a manufacturing system.

Observation 14: The option to combine scanning technology systems within supply chains needs to be considered along with the various options in a supply chain where it is possible or best advantage to detect carbon and impurities. The option to combine this with log identification and tracking should be addressed.

Observation 15: Investigateall options and strategies to address carbon and impurities in the supply chain this could include in situ de-barking for reduction/removal.

Observation 16: Investigate in situ de-barking in the forests to reduce risk of carbon and impurities embedded in bark which impact processing operations and costs.

Observation 17: Explore options for reduction/removal of carbon and impurities from the supply chain.

8 Fire impacts – post-fire conditions – moisture content

8.1 Summary

After the impact of embedded or passenger carbon, variation in log moisture content is the main underlying causal agent for all other issues in processing fire-impacted logs. Past studies have found stem moisture content varies with fire damage, position within a stem and time since a fire event. The rate of drying of tree stems is greatest in upper sections with the lower section (butt logs) maintaining higher moisture levels. Within the stem, moisture content will vary radially and between inner and outer sapwood. Such variation in moisture content reduces log homogeneity, which creates issues with processing.

In sawmills, drier logs affect processing by heating saw blades, requiring a reduction in feed rates, and can damage saw blades by diversions into drying-related cracks. Drier than expected logs will produce boards with less moisture per unit weight, adversely impacting batching for kiln drying based on green density with subsequent over-drying and associated defects in some boards. Less-aggressive kiln drying combined with an equalisation process can reduce these impacts. Pulping dry woodchips can have issues with under-cooking (when woodchips float) or over-pulping (when woodchips take up excess pulping liquors). Dry logs also create issues for particleboard and MDP manufacturing, affecting flake uniformity (dry wood breaks rather than flakes). Batch-processing of fire-impacted logs is the simplest way to address adverse moisture content variation.

8.2 Introduction

Any element of supply and processing chains that relies on homogeneity is affected by processing fire salvage logs. Industry recognises and can define when logs are no longer ‘fit for purpose’ (e.g. log breakage during de-barking or wood discolouration evident when sawing) and a challenge is to determine when this point is about to be reached. An assessment of wood quality by site and time since death due to beetles in the United States (Trent et al, 2006, p.iii) found that moisture content reduced. Other wood and fibre properties fundamental to sawn timber and pulp and paper production (e.g. fibre length, coarseness, wood density, microfibril angle, wood stiffness and decay) did not appear to be affected up to five years after mortality. Other studies indicated that bluestain has no impact on the mechanical properties of sawn timber, but reduced moisture content of beetle-killed logs reduces volume and value recovery in sawmills, affects log transportation (Jokai, 2006, p.2) and increases processing and conversion costs (Whitehead, et al, 2008: p.4). This section considers tree and log moisture content issues following a fire.

8.3 Standing tree moisture content

8.3.1 Variation in tree moisture content

Tree moisture content changes over time after a fire will depend on local weather and site differences. Drivers of commencement and rate of deterioration of wood in dead standing trees include moisture content changing with time since death, tree age, season, prevailing weather conditions, height above ground and the thickness and soundness of the bark layer. In general, softwood bark is an excellent water barrier, even when heavily charred, and can protect the wood underneath from moisture loss and deterioration for many months, provided it remains undamaged (Malan, 2011, p.2). While stem bark remains intact, moisture loss is slow but as the inner bark layer loses moisture and deteriorates bark starts to separate from the wood surface, accelerating the change (Malan, 2011, p.9). The first signs of deterioration occur in the upper stem where bark is thinner and tree diameter is smaller. Upper stem wood reduces to critical moisture levels first, allowing deterioration, which then extends to the lower stem and deeper into the stem as more moisture escapes (Malan, 2000). If fire-killed trees cannot be harvested and processed within a reasonable period, surface checking will start to occur once wood reaches FSP, especially where the protecting bark layer has been damaged or started to peel off (Malan, 2011, p.15).

8.3.2 Sampling tree moisture content

Three standing tree moisture content sampling regimes conducted post-fire follow:

1. In Queensland, after the 1994 Beerburrum fire, sample softwood trees were fallen to determine tree moisture content and bluestain (Hood & Ramsden, 1997, pp. 7&8). Sample trees were taken from five 60-tree-plots Trees were assessed for fire impact and allocated to a class based on a three-point scale (see Table 10) and one tree of each class per plot was harvested; 15 sample trees in total. From each tree, eight discs were cut at equal distances from within each stem up to merchantable limits defined by an over-bark small end diameter (SED) of 13 cm (Figure 14). Measurements were made on each disc of the quantity of bluestain (as a percentage of disc surface area) and for discs 3 and 7 sapwood moisture content (dry weight basis) was determined. Mean sapwood moisture content was calculated as an average of the sampled discs in each stem.
2. In NSW after the 2006 fires near Tumut, a series of plots were established to monitor tree impacts. Fire impacts were classified as per Table 11. Tree moisture content assessment was based on wedge samples (Figure 15) taken from discs recovered from set heights: initially at 3 m and then at 6 m intervals to defined SED limits (Joe, 2007, p.2). Stem moisture content (dry basis) was based on a stem section volume, on a weighted average by wedge moisture content basis.
3. In Western Australia, after a fire in February 2009 in a *P. radiata* plantation, an assessment of the standing resource was conducted in February 2010 to determine average moisture contents of the trees (Dumbrell, 2010, p.1). Samples were collected from 19 trees, covering the range of fire impacts (see Table 12) and position in the landscape. Each tree was felled and three discs were recovered: L (= lower stem near ground level); m (= mid stem near mid-point of the tree); U (=upper stem from the upper crown). Moisture content was estimated for each stem section based on ‘fresh weight’ and oven-dried weight of each disc (% DRY BASIS).

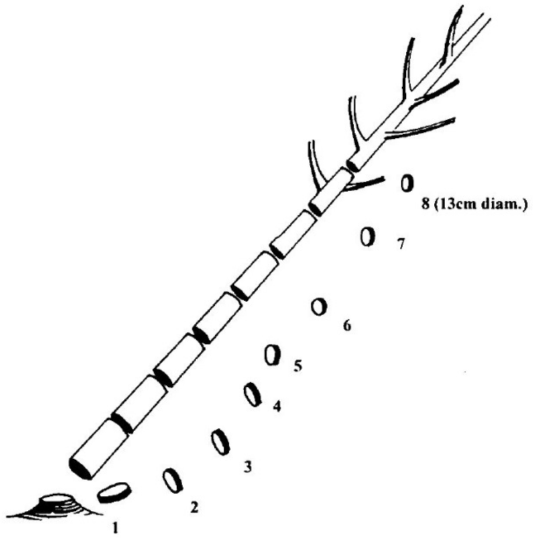


Figure 14: Sample points within a tree stem (Hood & Ramsden, 1997, p. 8: Figure 1).

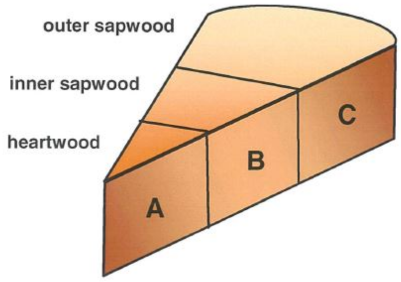


Figure 15: A wedge sample (Joe, 2007, p. 7: Figure 8).

8.3.3 Variation in stem moisture content with vertical position in a tree stem

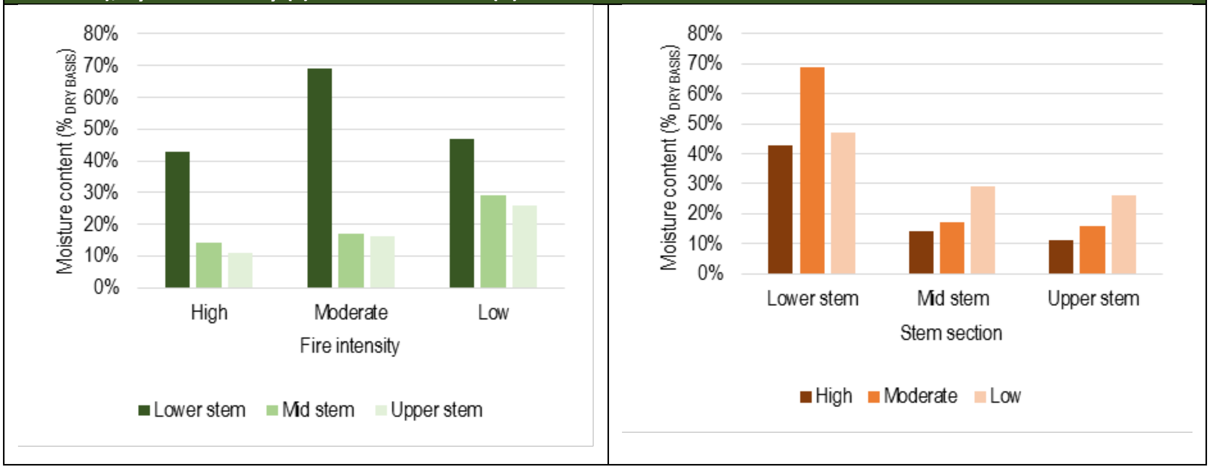
Variation in moisture content with height will define the utility of stemwood and susceptibility to insects and pathogens. Assessment in Canada noted that fire killed trees take approximately one year to dry out to FSP (Neilson, 1998 cited by Watson & Potter, 2004, p.474). Moisture content variation in logs prepared from fire-damaged trees stored on the stump may have lower and more variable green moisture contents dictated by tree size, duration, height in the tree and the extent that bark remained intact (Malan, 2011, p.18). A stand of *P. radiata* (aged c.35 years) was killed by a January 1966 fire. The pattern of drying varied according to how quickly trees died after the fire (Wright & Grose, 1970, p.154).

- Killed outright: Where killed outright by crown fire, the cambium and wood of upper stems commenced to dry within a few weeks of the fire. Drying was rapid in the upper bole, but slower and less extensive in the lower bole.
- Complete crown scorch: Trees subjected to very severe ground fire with complete crown scorch, retained a few green needles at the tip. The wood did not start to dry until the onset of the following summer, when the needles died and after which drying of cambium and stem wood increased rapidly.

A Western Australian assessment (Dumbrell, 2010, p.1) indicated within-tree variation in moisture content. Figure 16 (left) presents variation in young *P. radiata* stem moisture content. Under all fire intensities, upper sections were drier than mid and lower sections. This suggests drying of stems occurs from the top down and that the bottom section had not dried at the same rate as the sections above. Figure 16 (right) presents the same data by stem section. This indicates lower moisture contents with high fire intensity: more fire-impacted trees dried faster. The averaging approach to stem moisture content applied in Queensland (Hood & Ramsden,

1997) and NSW (Joe, 2007) masks fire, drying impact and options, and risks post fire. Whole-stem weighted average moisture content would include some sections with higher or lower actual moisture content. While not possible from the data presented, it would be useful to understand how within tree moisture content varied with height and the associated level of bluestain.

Figure 16: Stem moisture content for 8 to 13 year of P. radiata trees 12 months after a fire event (based on Dumbrell, 2010), by fire intensity (L) and stem section (R).



8.3.4 Variation in tree moisture content over time

The data in Figure 16 was collected 12 months post-fire and provides a relative comparison between fire impact classes at that time rather than change since the fire or compared to unburnt trees. To plan management responses to fire, change in moisture content after a fire event will dictate opportunities and risks (e.g. processing and pathogens). Figure 17 presents change in estimated whole-stem moisture content over time since a NSW fire by fire impact classification (brown = less impact or black = higher impact) and by site (1 or 2). In general, tree moisture content reduced, with differences between sites (more than between fire intensity). Within sites, trees classed as 'black' dried faster than trees classed as 'brown'. Increases in recorded tree moisture content are noted but unexplained. Decline in tree moisture content was most noticeable for Site 1, from 128% DRY BASIS (week 8) to 86% DRY BASIS (week 23) for 'black' trees, and from 152% DRY BASIS (week 8) to 101% DRY BASIS (week 23) for brown trees (Joe, 2007, p.11).

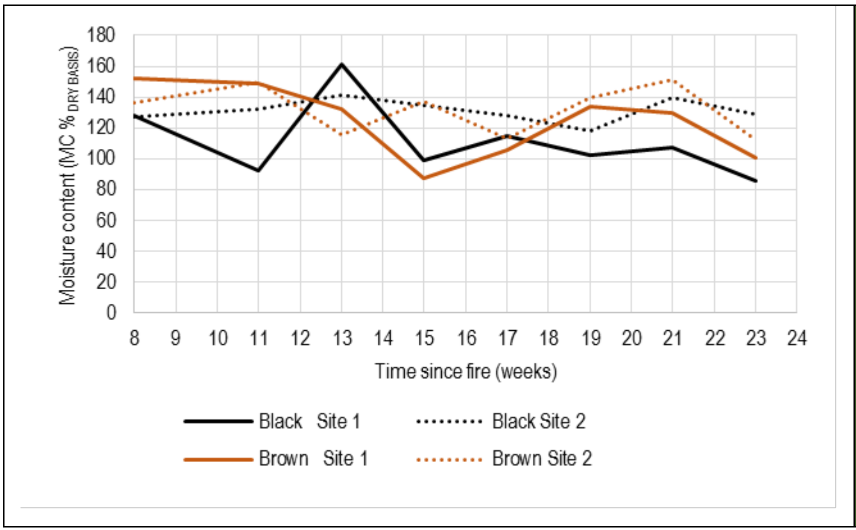


Figure 17: Variation in mean stem moisture content with time for two fire impact classes (based on Joe, 2007, pp.10&11).

Figure 18 presents whole tree average moisture content variation with time following the 1994 Queensland fire for inner sapwood (left) and outer sapwood (right) by fire impact classification (based on Hood &

Ramsden, 1997). Both inner and outer sapwood lost moisture post-fire with moderate to severe (1) impacted trees losing moisture at the fastest rate. The pattern of moisture loss shows a degree of lag effect, more so for outer sapwood. Outer sapwood of moderate to severely impacted trees mirror nil foliage black trees (0). Variation in stem inner and outer sapwood moisture content with time by site was recorded (Figure 19 and Figure 20). Variation between sites is indicated and it is unclear whether the outcomes were uniform within sites by damage class.

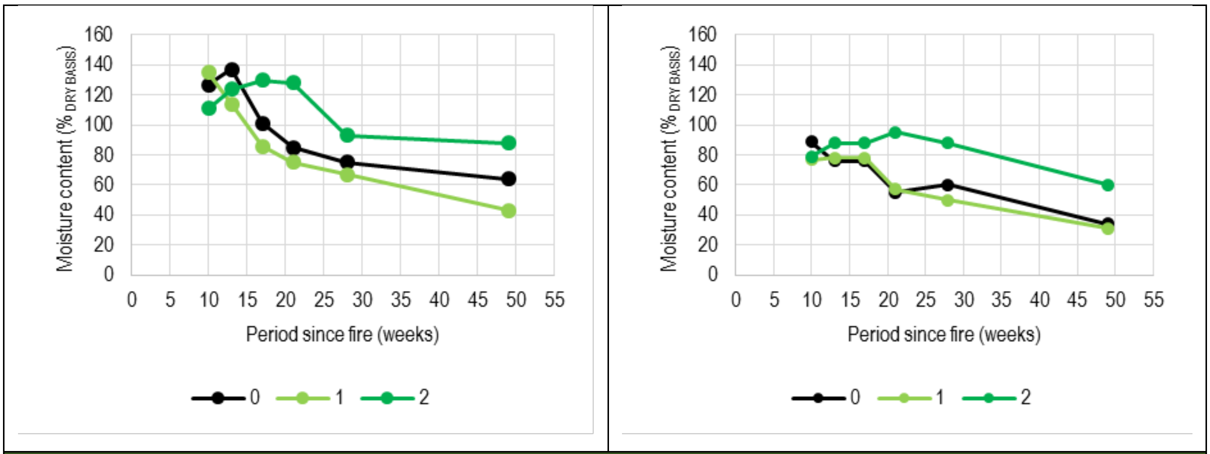


Figure 18: Variation in stem moisture content over time by fire impact class (based on Hood & Ramsden, 1997): inner sapwood (L) and outer sapwood (R).

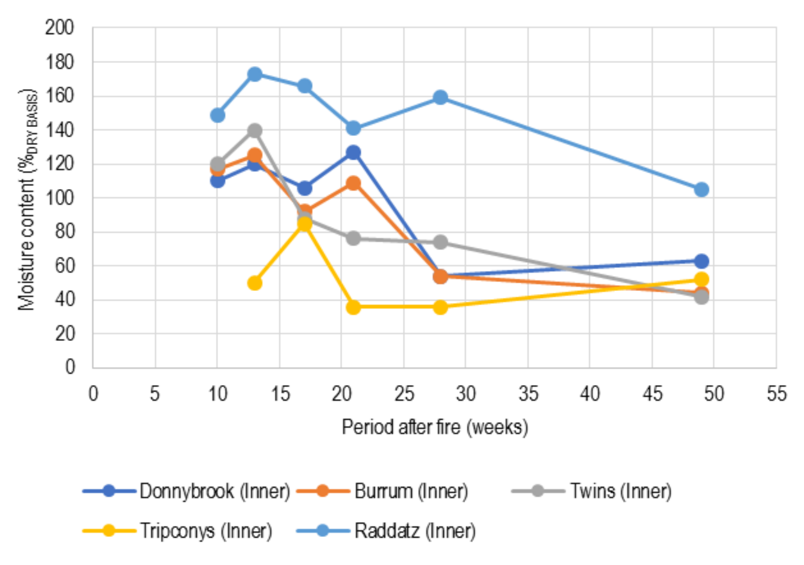


Figure 19: Variation in inner sapwood moisture content over time for five sites (based on Hood & Ramsden, 1997).

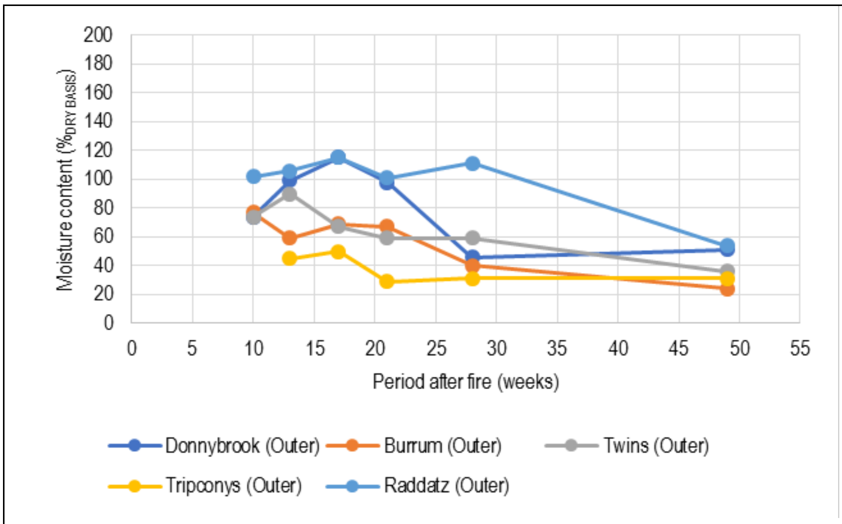


Figure 20: Variation in outer sapwood moisture content over time for five sites (based on Hood & Ramsden, 1997).

8.4 Sawlog moisture content and log processing

8.4.1 Significance of change in log moisture content

Variation in log moisture content is the root cause of all processing issues once carbon (and grit) has been addressed. Differences in drying rates between sapwood, heartwood and corewood radially across logs create differences for core to outer wood moisture content; corewood usually holds less moisture and may dry out further. Variation in log moisture content will change log population attributes (green moisture content) and all subsequent steps in processing. Routine plantation harvest delivers green logs after a short period of storage on landings and logs are generally homogeneous in moisture content. In contrast, moisture content varies between fire-killed and damaged trees and logs, and within trees and logs.

Processing beetle-killed logs in North America was problematic in sawmills finely tuned to homogeneous log inputs to maximise production due to frequent switching between live (green) and beetle-killed (dry) logs (Whitehead, et al, 2008, p. iv).

Figure 21 presents delivered softwood sawlog moisture content over time since a fire; with time, log moisture content steady decreased. The sudden drop in average log moisture content between weeks 17 to 20 was thought to be associated with reduced moisture content of upper stem logs (recall differences in stem drying presented in Figure 16). Importantly, moisture content (dry basis) whole-log averages varied from 85% to 25% (heartwood moisture content below FSP).

8.4.2 Issues with sawing variable moisture content logs

Provided logs are ‘green’ (e.g. well above FSP) sawmills experience few problems with processing fire-impacted logs (once cleared from carbon by de-barking) (Malan, 2011, p.2). As wood dries below FSP, strength and elastic properties increase exponentially, logs become more difficult to process necessitating slower feed speeds, increased cutting tool maintenance (Malan, 2011, p.15) and increasing energy consumption (Whitehead, et al, 2008, p. iv). In North American mills seasoning checks (cracks) develop, split log ends and delamination of corewood layers occurs when sapwood moisture content falls below FSP. On sawing, band saws can follow cracks causing in damage by deformation and/or twisting. Lower log moisture content can also result in saw blades over-heating (Whitehead, et al 2008: p.iv). Reduced log moisture content results in increased log breakage during handling and processing (reducing volume recovery) with an increase in the proportion of small-dimension products (reducing value recovery) (Whitehead, et al, 2008, p.iv). A Western Australian processor sawing logs at below FSP found the logs insides were bright orange and these logs overheated saws. A solution was to slow mill feed-rates when processing fire-impacted logs (Barr, pers. comm). Overall, green mill processing of drier (fire-impacted) logs increases the frequency of band saw and chipper knives changes while increasing the risk of band saw failures.

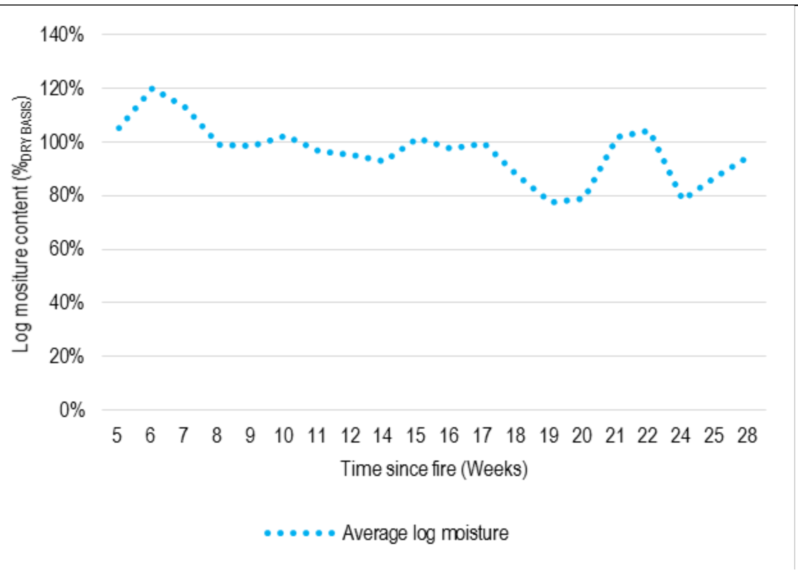


Figure 21: Variation in delivered softwood sawlog moisture content with time since a fire (based on WESPINE, Barr, pers. comm).

8.4.3 Kiln drying by green density classes

Adverse impacts and outcomes of drying wood with variable moisture content is well documented. In 1933, it was noted that: *'If the moisture is quite non-uniformly distributed in a piece of wood, the outer shell may be well below the FSP while the inner part still contains free water. The moisture-strength curve for specimens with moisture non-uniformly distributed may consequently be higher than the correct curve and may be so rounded off from the driest toward the wettest condition as entirely to obscure FSP'* (Wilson, 1933, p.8). The degree of variability entering kiln drying will influence variability post kiln drying. Over-drying of a larger-than-usual proportion of total production can result in deterioration of grade yields and financial impacts. Boards with moisture contents lower than the racked board population averages (defined by green density classes that assume a fixed moisture content range) can be over-dried in kilns and result in degrade (e.g. twist, mechanical damage and creation of brittle wood as permanent damage). Increased board distortion necessitates increased culling prior to planing in the dry mill. Therefore, management of drying aims to minimise variability of a population of boards introduced into a kiln by segregation during racking in the green mill. Boards are batched in green mills by green density using gamma radiation detectors, but as moisture content decreases, homogeneity of rack of boards is compromised. For example, green boards are aggregated in racks as follows:

- Small: <500 kg/m^3
- Medium: 500 to 650 kg/m^3
- High: >650 kg/m^3.

Consider boards with a green density of 500 kg/m^3. At a moisture content of 80%$_{\text{DRY BASIS}}$, this equates to 222 kg/m^3 of water to address, whereas at 50%$_{\text{DRY BASIS}}$, it equates to 167 kg/m^3 of water, reducing homogeneity of inputs.

Experience with processing fire-impacted logs suggests differences between batch and continuous kilns. Batch kiln drying has more control over the drying process (testing moisture content entering kilns and through the drying process) whereas with a continuous kiln there is less measurement of wood moisture content (a ‘set and forget system’). Other issues identified by industry when kiln drying fire impacted resources included:

- Reduced moisture available during initial conditioning in the kiln (with vents closed) to provide plasticisation and prevent distortion of finished product.
- Potential increased risk of kiln fires due to drier boards.
- Potential difficulty in operating kiln heat plants if moisture content of sawdust is too low.

8.5 Strategies to address sawlog moisture content

8.5.1 Log type and sacrifice

With time post-fire and increased within tree variation (Figure 16), it is possible that upper-stem logs could be sacrificed to lower value markets to address moisture content variation issues. In extreme cases, only butt logs would be recovered. While this would improve homogeneity of log supply, it has implications for resource availability and plantation revenues.

8.5.2 A staged approach to ultimate batching of fire-impacted logs

Analysis in South Africa concluded that boards sourced from fire-impacted logs intended for commercial use should be dried separately from green wood, with a milder drying schedule and over a longer time (Meincken et al, 2010, p.460). Segregation of storage (and subsequent processing) of fire-impacted logs in a wood-yard is a crude proxy to segregation by moisture content. One consideration is the issue is capacity to have multi-factorial log segregation. There are two broad approaches by industry:

- <u>Dilution</u>: Green and fire-impacted logs are processed together with the fire-effected logs diluted by green logs.
- <u>Batching</u>: Batch processing green and black logs separately, with sub-batching by length classes.

The choice of strategy will be set by the percentage of log intake that is fire impacted.

8.5.3 Measurement of individual log moisture content

A logical but difficult to implement strategy would be to measure log moisture content and crudely sort logs by moisture content and process batches on this basis. This would be difficult as logs usually dry from the ends, making it difficult to gain measurements by non-destructive sampling. As a result, most sawmills do not have good measurements of green log moisture content. It would be possible to undertake spot checks of log weight for volume as a proxy for moisture content.

8.5.4 Green mill board grading

Gamma radiation detectors control batching based on green density, but as moisture content decreases, homogeneity of batches is compromised.

A potential solution would be to combine gamma-based determination with a non-contact moisture meter to calibrate inferred density grading by the gamma tool; while possible this has not been implemented. A crude solution is to identify lower moisture content racks of boards by the weight during forklift handling in the mill. This can identify lighter packs, but it is possible that greater variation than usual will remain within racks creating issues during kiln drying.

8.5.5 Kiln type and operation

Addressing of differences in moisture content requires recalibration and management of drying schedules. Kilns with effective moisture and humidity control systems should have fewer issues in delivering quality dried sawn timber from fire-impacted logs (Malan, 2011, p.18). An alternative where a site has both types of kilns is to:

- Batch kiln: dry boards sourced from fire salvage logs.
- Continuous kiln: dry routine green log sourced boards that are more homogeneous.

South African experience suggests used of a moisture equalising treatment at the end of a drying cycle as a precaution to reduce excessive moisture differences within and between individual boards (Malan, 2011, p.18).

A two stage strategy has been applied in Western Australia (Barr, pers. comm). Low-density boards are segregated from sapwood, with such boards effectively free from corewood to run as a batch. Boards are then air dried for 2-4 weeks before steaming (reconditioning) and machining. Air drying allows higher moisture content boards to reduce rapidly during summer weather, while not over-drying the low moisture content boards. Winter conditions may reduce the effectiveness of this approach. After air drying and reconditioning, boards are held for another 5-7 days before running in the dry mill.

8.6 Pulp and paper

8.6.1 Impact of wood moisture content

Pulp and paper making requires homogeneous infeed stock: a key point is consistency of woodchip moisture content and that the percentage infeed from different sources remains consistent (industry information). For example, sawmill residue woodchips require segregation for controlled infeed into pulping. Cameron and Lodge (1924) first reported pulping of fire-impacted woodchips in 1924 (cited by Watson & Potter, 2004, p.475). They found: '*that for sulfite pulping of spruce, the optimum green spruce cooking conditions were too harsh for the fire-killed sample; hence, the conditions must match the chip sample in order to ensure adequate strength and bleachability.*' Canadian experience with fire-impacted logs concluded that the '*main areas of concern are low chip moisture content, chip carbon content and mechanical pulp brightness levels'* (Watson & Potter, 2004, p.476). When woodchip moisture content reaches FSP, woodchip rewetting is difficult (Watson & Potter, 2004: p.476). Tolerances to moisture content vary with technology and whether pulping is on a batch or continuous basis; batch pulping has greater tolerance than continuous pulping. Dry woodchips can take up more pulping liquor than usual and get over-cooked (impacting the chemical wood ratio). Alternatively, dry woodchips can float (particularly softwood woodchips in continuous pulping vessels) and fail to be cooked adequately to remove all lignin. It is suggested that even at 3% dry woodchips floating (e.g. not pulped effectively), under-cooked wood will clog screens and cause repairs and maintenance issues (e.g. damage, wear and blockages). Where variation in woodchip moisture content increases, pulpmills need to increase the rate of woodchip testing.

8.6.2 Solutions to low moisture content woodchips

It is suggested that '*careful metering of chips from burned wood into any pulping process is essential*' (Watson & Potter, 2004, p.473). There are neither methods to track woodchips of different origins in a single stockpile nor to determine the amount of carbon on woodchips (Erickson, 1998 cited by Watson & Potter, 2004, p.475). One option is to track the ratio of fire-impacted to green woodchips infeed to a stockpile. Experience suggests that '*regaining moisture by mixing with green chips is minimally effective and good pre-steaming is therefore essential for any operation*' (Pickrell 1998 cited by Watson & Potter, 2004, p.475). Tactics to address fire impacted woodchips into a pulpmill after addressing carbon are:

- Stage 1 Dilution: Dilution to 'shandy' fire-impacted with green woodchips to dilute over dry woodchips. This does not eliminate the issue (it may increase the probability that drier woodchips float to the surface) but keeps the level of subsequent impact to an acceptable level.
- Stage 2 Pre-treatment: Beyond a site and process specific level, shandying of fire-impacted material with green woodchips is not possible. Pre-steaming of woodchips prior to kraft cooking or a chemical pre-treatment for mechanical pulping may improve pulp quality (Watson & Potter, 2004, p.473).
- Stage 3: Batching: Where the percentage input of woodchips from fire-impacted logs, with associated low moisture content, reaches a site-specific trigger point, segregating and batch processing woodchips combined with a process of pre-steaming prior to kraft cooking or a chemical pre-treatment for mechanical pulping may improve pulp quality (Watson & Potter, 2004, p.473).

8.7 Panel products

8.7.1 Plywood manufacturing

A lower moisture content results in reduced strength in sheets. Logs are peeled to waste until sheets are 'fit for purpose'. It is product engineering that results in overall product strength. As trees dry, an enhanced radially differentiated moisture content profile can develop; from 43% DRY BASIS to 100% DRY BASIS across a log profile (akin to a donut with the mid-section of a log with the lowest moisture content). A differential moisture content affects peeling quality and product options. There is a need for a better understanding of log radial moisture content variation.

8.7.2 Particleboard

Issues with dry wood from fire-impacted trees commence with de-barking and log breakage in the log yard and continue into the manufacturing process. Particleboard manufacturing aims to create uniform (thin and flat) flakes. This is the most critical step in the process and where differences due to species and wood condition have an impact. Green wood readily slices in ring flakers. Dry wood is more difficult to flake to achieve the required quality as dry wood 'breaks' rather than flakes. This results in 'match sticks' with a different surface area to volume ratio to regular flakes, which requires increased resin to retain strength. Dry wood also wears out the ring flaker knives faster. A response strategy is to mix green and dry (fire-impacted) fibre. Sawmills processing the fire-impacted logs need to be able to identify the type of materials in residue chips when used by particleboard plants. This may be achieved by batch processing fire-impacted logs in sawmills supplying residue woodchips.

8.7.3 Medium density fibre board (MDF)

MDF production is more sensitive than particleboard to dry wood. Dry wood is defined as a moisture content of 43 to 54%$_{\text{DRY BASIS}}$. For MDF, some green materials always need to be included with fire-impacted and drier logs. A chip wash process will increase chip moisture content and this is undertaken when inputs contain greater than 10% dry wood.

8.8 Log moisture content monitoring

A testing program is required to monitor log moisture content and other properties relative to their intended use. The results of testing need to be the basis of manufacturing decisions. The process for sampling moisture content within a tree stem is well documented and includes destructive sampling (e.g. billets; whole stem; discs) and non-destructive methods (e.g. core samples and by instruments such as Pilodyn meters) (Downes et al., 1997, pp.10-12). Ideally, a sampling system should provide on-the-spot results rather than involving a return to a laboratory for analysis. There are several newer techniques and tools that can be used to measure tree and log conditions, although some require further testing and calibration.

- Core samples: A core sample removes a cross-sectional sample of a standing tree's wood from bark to bark. The sample requires laboratory analysis.
- RESI PowerDrill: The IML-RESI PowerDrill digitally presents wood quality by measuring a drill's needle resistance through the wood. Measurements are easy to capture, display and analyse. The WoodInspector software includes automatic, pre-set pass and fail values.[6]
- Near infrared radiation technology: Near-infrared (NIR) spectroscopy can be used to estimate physical and chemical properties of materials (e.g. wood) quickly and non-destructively (Eom et al., 2010, p.1). There are commercial instruments that make use of NIR to determine moisture content of grain products (e.g. wheat and corn) without of a need for sample grinding or preparation (Kandala, et al, 2008, p.1). NIR technology has been demonstrated to accurately estimate biomass moisture content (a range of 24% to 65% $_{\text{WET BASIS}}$) (Fridh et al., 2017, p.42). The technology has been demonstrated to be effective in predicting the moisture content of frozen wood. It is, however, necessary to take temperature into account (Thygesen & Lundqvist, 2000, p.183). A review of NIR technology concluded that it has potential to be used as a rapid tool for at-line measurement and monitoring of wood properties in the forest products industry (Leblon et al. 2013, p.596).

8.9 Recommended best practices

8.9.1 Salvage planning – triage, harvesting and logistics

Best practice 29: Reduce log moisture content variation by sacrificing upper crown logs once management is confident of adverse log moisture content issues.

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[6] http://www.iml-na.com/en/wood-inspection-products/wood-testing-drills/iml-resi-pd-series-wood-testing-drill/ downloaded from the 06/03/2020.

8.9.2 Processing – wood yard management / de-barking, sawing, drying

Best practice 30: Consider benefits from batching logs of similar moisture content for processing.

Best practice 31: Address variation in board moisture content during kiln drying by adopting a less aggressive schedule and including an equalisation process post kiln drying and prior to pre-reconditioning.

Best practice 32: Address issues with kiln drying of boards sourced from fire-impacted logs by use of batch rather than continuous kilns.

Best practice 33: Up to site- and process-specific percentages, address moisture content variation by dilution with green logs, after which batching is required.

8.10 Observations

Observation 18: An understanding of the cross sectional moisture content and impacts on log peeling and plywood manufacture is required.

Observation 19: A number of techniques and tools exist that could be used to measure tree and log condition and these may require further testing and calibration.

Observation 20: A non-destructive method to determine absolute tree and log moisture content radially and longitudinally is required. Ideally the technique would provide immediate data and be independent of laboratory analysis.

Observation 21: Based on a fire impact classification, there is a need to document patterns of stem drying in standing trees over time from a fire event.

Observation 22: Technology is required to address board moisture content variation as part of effective board batching based on green density.

Observation 23: Develop a 'fit for purpose' kiln-drying regime for reduced homogeneity populations of boards. This should include consideration of equalisation stages as an option.

Observation 24: Define trigger points between dilution and batch strategies to address variation in moisture content of fire-impacted logs.

9 Fire impacts – post-fire condition – biological damage agents

9.1 Summary

After a fire and with changes in tree moisture content, a range of biological damage agents can be active in dead and dying trees, or trees stressed as a result of fire, and in and recovered logs. Insects can attack standing trees, logs and logs under wet storage. Insect pheromones and/or emissions from stressed trees, harvest residues or decaying logs under water (e.g. emissions of ethanol) will attract insects. Ips will attack standing trees and logs depending on timing of a fire and subsequent weather conditions. Ips cannot complete life cycles and survive under effective log watering, but once removed, logs are readily attacked. Pinhole borers bore perpendicular to the log surface. A failure to maintain a film of water on the surface of logs will facilitate this species to attack (allowing ethanol emissions and physical access by insects). In cases noted in the literature, superficial consideration of the information suggested failure to effectively water logs under sprinklers allowed insect attack. Decay fungi can function in aerobic and anaerobic conditions and physically damage the mechanical properties of logs and boards. Historically, bluestain fungi impacts were the primary concern of post-fire salvage triage in softwoods. Bluestain in wood tissue results from fungi hyphae infestation. Bluestain infestation commences with inoculation by spores with Ips as a vector or with Diplodia via wounds or in stressed/damaged trees. The fungi spreads through conductive and storage tissues consuming carbohydrates (the tissue content). Initially, the fungal disruption of vessels and liquid transmission causes pit aspirations. Hyphae then explore the vessels and cross between passages via pits and, in the process, damage pit structure and they remain open causing the wood to become more porous and increase permeability to liquids. Bluestain fungi do not damage cell mechanical structures. Bacteria operate under anaerobic conditions within wet storage stockpiles. Bacteria enter log ends and, similar to bluestain, damage conductive and storage tissues, and cell pits, increasing wood porosity and permeability.

9.2 Introduction

Changes in tree and log moisture content result in indirect fire impact by facilitating biological agents. Issues of biological impacts and difficulties with detecting decay and wood soundness have long been recognised, with detection in standing trees more difficult that for logs (Fisher, 1896, p.78). Changes in wood fitness for purpose include changes in mechanical properties and movement of water through wood (see Box 8). This chapter addresses post-fire biological damage to trees and wood.

Box 8: Definitions of key terms linked to water movement in to and within wood.

Porosity: The state of being porous.[7]

Porous: Something that is porous has many small holes, so liquid or air can pass through, especially slowly.[8]

Permeability: The ability of a substance to allow gases or liquids to go through it.[9]

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[7] Downloaded from https://dictionary.cambridge.org/dictionary/english/porosity?q=Porosity on the 01/05/2020.
[8] Downloaded from https://dictionary.cambridge.org/dictionary/english/porous on the 01/05/2020.
[9] Downloaded from https://dictionary.cambridge.org/dictionary/english/permeability on the 01/05/2020.

9.3 Insects: Ips grandicollis

9.3.1 A snapshot history

Box 9 gives a snapshot of the five-spined bark beetle (*Ips grandicollis* Eichoff) or Ips. In Victoria and South Australia, Ips impacts to large numbers of healthy (but drought-stressed) trees have been recorded (Neumann, 1987, p.169). In Queensland, it has attacked recently felled trees, logging debris, and standing trees damaged by lightning, wind, fire or drought with only a few cases of attack on apparently healthy trees (Wylie et al, 1999, p.148). *P. radiata* is believed to be especially susceptible to damage: Ips can cause tree mortality and contribute to bluestain in sapwood (Neumann, 1987, p.166). Monitoring of plantations include detection of early symptoms of Ips attack: small quantities of dry, resin-free, reddish-brown borer dust (frass) around scattered entrance holes in tree bark (Wylie et al, 1999, p.148). After the 1994 fires in south-east Queensland, all species of *Pinus* damaged by fire *(P. elliottii* var. *elliottii, P. caribaea* var. *hondurensis, P. caribaea* var. *caribaea* and *P. taeda)* were attacked by Ips and appeared to be equally susceptible (Wylie et al, 1999, p.150).

Box 9: A snapshot history of the five-spined bark beetle (*I. grandicollis*) in Australia (taken from Wylie et al, 1999, p.148).

'The five-spined bark beetle (Ips grandicollis) is native to north America and was accidentally introduced into South Australia in 1943 and into Western Australia in 1952 via importation of pine logs with bark on from the United States (Morgan, 1967). It was found in Victoria and Queensland in 1982 and northern New South Wales in 1983 (Wylie & Peters 1987; Eldridge & Simpson 1987). While it disperses naturally by flight, movement of logs and timber with bark attached and of bark chip has assisted its spread. It is widely established in exotic pine plantations in south-east Queensland, where a quarantine on northward movement of susceptible material has been in force since 1982. It has just recently (November 1994) been found in the Byfield plantations in central Queensland.'

9.3.2 Mechanism of insect aggregation

Insect attack results from an aggregation of individuals. Cardé & Millar (2009) noted that *'bark and ambrosia beetles (Scolytidae) use pheromones to facilitate colonization of host trees (aggregation) and to attract mates. Many scolytid species must attack a tree en masse if they are to overwhelm the tree's defence, which consists of exuding sap into the tunnel that each beetle bores'*. A tree affected by fire may have reduced natural defences. Attack commences with the first beetles potentially identifying *'the host by means of chemicals emitted by the host tree itself'* (Cardé & Millar, 2009). Under specific conditions, ethanol is a product of fermentation of wood, which attracts beetles (Elliott et al. 1983, p.299; Moeck, 1970, p.985). Experience in New Zealand suggests that fungal and bacterial impacts on the sapwood of logs greatly modify the characteristics of 'host' log volatiles, which attract attacking males (Milligan, 1982, p.240). During colonisation by boring into a tree, insects *'release pheromones and increase emission of tree chemicals that together attract both male and female beetles'* (Cardé & Millar, 2009, p.766). Frass ejected from Ips tunnels contains *'an aggregating pheromone produced by the male, which attracts both females and males to the tree or log'* (Wylie et al, 1999, p.148).

9.3.3 Damage to a tree and rate of infestation

Adults and larvae tunnel in the cambial region and '*engrave the surface of the wood*' (Wylie et al, 1999, p.148). Trees infested by Ips will eventually die, regardless of apparent health of their crown, although degrade is slower to develop in green-topped trees (Hood & Ramsden 1996, p.13; Wylie et al, 1999, p.152). The rate of Ips infestation of fire-damaged trees in Queensland in 1994 was most rapid in the first few weeks following initial attack and begun to plateau at about 16 weeks; attack began six weeks after the 1994 fire in one plot and exceeded 10% of trees by eight weeks (Wylie et al, 1999, p.149). Ips was significant in most areas at 10 weeks (Wylie et al, 1999, p.148). In one plot, by 12 weeks 100% of trees were infested and incidence in all the other plots (except one) approached this level by 20 weeks. One year after the fire, 80% of trees in the remaining plot had been infested (Wylie et al, 1999, p.149).

9.3.4 Fire impact and sources of Ips infestation

The degree of crown scorch assessed four weeks after a fire was not a reliable guide to fire damage and the likelihood of attack by Ips (Wylie et al, 1999, p.149). Trees '*apparently only slightly affected by fire and still with a full green crown*' were attacked while trees of similar age and crown appearance in adjacent unburnt stands suffered nil attack (Wylie et al, 1999, p.149). It is suggested that this '*probably relate[s] to localised occurrences of a slower but more intense burn, such as may occur at night, in areas with considerable fuel load on the ground resulting in severe stem burn but no crown damage*' (Wylie et al, 1999, p.149). An improved method of assessing the likely degree of damage would incorporate factors such as the fuel loads prior to fire and speed of a burn (Wylie et al, 1999, p.152). Such information would be held by proxy in fire and stand histories. Reservoirs for Ips attack can remain in unburnt harvest residues. A trend that emerged from post-fire surveys in Queensland was a possible link between the timing of attack by Ips in a fire-damaged compartment and the previous logging history of the area. Fire-affected compartments near where thinning or other harvesting operations had taken place within eight months prior to a fire, could be at higher risk, which has been noted in 2020 in the Tumut area (Wylie et al, 1999, p.152). Harvesting debris may harbour Ips for up to eight months and may have survived the fire (thorough burning is required to destroy infestations) and could have provided a reservoir for the pest. Other sources of infestation can come from drought-stressed or lightning-struck trees (Wylie et al, 1999, p.150).

9.3.5 Water storage of salvage logs and Ips

As part of the 1994 Queensland fire salvage log storage, a trial tested the ability of Ips to colonise logs in water storage (Wylie et al, 1999). Ten billets infested by Ips were collected from salvage areas and five were placed in a stack under water spray and five were left in the open (controls). One treatment and one control billet were destructively sampled each week to determine insect mortality. After one week, all stages of Ips in the billet from the watered stack were dead while those in the control were alive. This remained the pattern throughout the experiment (Wylie et al, 1999, p.151). Another trial tested whether logs with and without bluestain that were removed from the watered stockpiles and left un-watered would be subject to attack by Ips. Stored logs were segregated by condition entering the facility; 'bluewood' logs had bluestain at entry and 'whitewood' was free of bluestain. Whitewood, bluewood and fresh-harvested green control logs were included. Figure 22 presents the outcomes. Logs remained attractive to Ips after 10 months of storage under water spray, and Ips were then able to complete a life cycle in such logs (Wylie et al, 1999, p.153). Green (fresh) logs had limited attack. Ips attacked the logs within a few days (potentially attracted by the emission of decay volatiles?), and at the first count all logs had been attacked. There was an initial difference in attack between logs with bluestain and those without ('white wood' stored in separate piles under watering) (Wylie et al, 1999, p.150). Queensland experience found that provided logs are processed rapidly after removal from storage, there should not be time for development of serious bluestain (Wylie et al, 1999, p.153). A key point is that while watering kills Ips, logs removed from watering can be colonised by Ips from other sources.

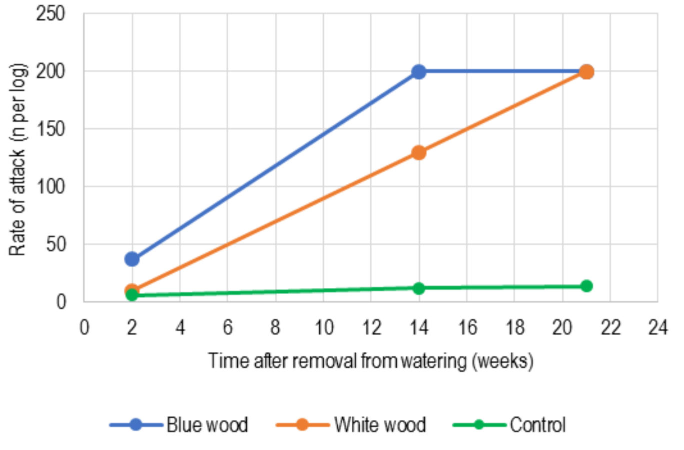

Figure 22: Rate of Ips attack of fresh logs and after storage; the rate at 21 weeks was 'several hundred' (based on Wylie et al, 1999, p.150).

9.3.6 Recommended management strategies for Ips

Strategies to reduce impacts from Ips include (Neumann, 1987, pp.173&174):

- Harvest residue management: Control of habitat of Ips includes chopper rolling where soil moisture capacity allows decay and, if not, broadcast burning.
- Salvage: Ensuring early salvage of high-quality trees killed or damaged by fire, lightning or windstorms, including burning of large diameter residues and slashing.
- Season: Restrict clearfelling between spring and autumn to compartments that are adjacent to thinned stands older than 17 years; due to a risk that Ips will build-up in harvest slash and then attack younger trees in adjacent stands.
- Quarantine: While with no legal basis, between October and May transport logs from plantations within two days of felling if the destination mill is outside an outbreak area.

These strategies have implications for log storage and transport, particularly given that the periods of concern are the fire danger period. While quarantine is an option, there is unlikely to be a mechanism to enforce it. Therefore, these remain as guides to industry.

9.4 Insects: Pin hole borers (Ambrosia beetles)

9.4.1 Pin hole borer damage to logs

Subsequent to Ips, other genera of Scolytids beetles will begin colonising, boring deep into the logs. Pin-hole borers drill into a log at right angles to the direction of the grain. The borer introduces fungal spores that, on germination, navigate the created passages and provide food for hatched larva. A blackish discolouration results from the fungal lining of the created passage walls. Experience with fire impacts has shown that pin-hole borers will attack logs in log stockpiles and some attack will occur in standing trees in the tropics. For example, in Queensland the Island pinhole borer (*Xyleborus perforans*) was first noticed in standing trees eight weeks after the 1994 fire and was most common in trees that had been severely burnt. It did not become a serious problem during the six-month salvage period, but heavy infestations occurred in trees remaining unharvested (Wylie et al, 1999, p.150).

9.4.2 Markets and wood utility

Logs with pin-hole borers can become a phytosanitary issue for log exports and there have been cases of rejection. The drilling process creates a serious weakening of the strength of wood. There are limitations on pin-hole borer infestation in boards under Australian Standards (Bootle, 1996, pp.32, 180&181). There are no remedial actions available against the pest as it is only detected once frass is visible below an entry hole.

9.4.3 Logs under water storage

The root causes of published observations need to be understood. New Zealand experience with salvaged log storage noted that '*conditions provided by stockpiling logs under water sprays were evidently peculiarly suitable*' for the breeding of pinhole borer, *Platypus apicalis* White (Milligan, 1982, p.238). Attacks were initiated soon after the stockpile was completed while logs were still fresh and in those that had been stored for up to three years. As a result, it was suggested that the borer imposed a constraint on sprinkler storage of logs (Milligan 1982, p.236). Rather than due to log storage *per se*, this event was associated with a failure of the watering system (N.C. Clifton, pers. comm. cited in Wylie et al, 1999, p.152). A trial of long-term storage of logs under sprinklers in the United States supports the finding that: '*all logs in the two decks with intermittent sprinkling schedules had heavy levels of ambrosia beetle damage, while there was no indication of ambrosia beetle damage in the logs in the two decks with continuous sprinkling schedules*' (Syme & Saucier, 1995, p.3).

Queensland experience with log storage after the 1994 fire provided the same insight. The log stockpile watering regime was altered in November 1995, in order to reduce pump maintenance and electricity costs, to watering during daylight hours unless conditions were windy or humidity was low. Tests of this altered regime in two bays showed that moisture content of logs and moisture content did not alter, and subsequent monitoring confirmed that result (Wylie et al, 1999, p.150). By January 1996, two species of *Xyleborus* pinhole borers were identified in sampled wood; *X. perfoans* (Wollaston) and *X. ferrugineus* (Fabricius) (Wylie et al, 1999, p.148). It was proposed that the beetles would have originated from debris throughout fire-damaged areas (Wylie et al, 1999, p.151). The borers were present in less than 1% of 'whitewood' logs and in about 6% of 'bluewood' logs. In almost all cases, attack occurred in dry patches on logs, usually on the underside where water did not appear to be reaching. Attack mostly seemed to be on ends of logs but in some cases extended to the centre of stacks. The 24-hour watering regime was reinstated and monitoring identified that not all parts of stockpiles were fully rewetting and new attacks occurred in drier patches. The cause of dry patches was sprinkler failure, low water pressure toward ends of long watering lines from pumps, and windy conditions. Repair and redeployment of sprinklers, adding new watering lines and boosting pressure with additional pumps rectified the situation (Wylie et al, 1999, p.152).

It was concluded that it was an absence of free-flowing surface water rather than a lowering of moisture content of the logs that allowed attack (Wylie et al, 1999, pp.151&152). A similar experience was noted in Germany during a log salvage and storage operation (Liese, 1984, p.128). Borer insect egg deposition was thought to have occurred either on wind-thrown trees in the forest prior to salvage or stockpiles where water application was insufficiently complete. On '*well-sprinkled logs*' no insect attack was observed during storage. In Queensland, after addressing the watering regime, no new attacks were observed on log surfaces that had a film of free-flowing water, and insect activity stopped after restoration of the film over surfaces with existing attack, generally within a few weeks (Wylie et al, 1999, p.151). Wylie et al (1999, p.152) proposed that it is possible that a water film reduces the emission of ethanol as a decay volatile and insect attractant.

9.4.4 Future log stockpile management

A point of caution from the Queensland salvage stockpile experience is that *'the development of dry patches, and consequently ambrosia beetle attack, would have occurred in time as a result of the settling of the stacks, the filling of crevices with debris from decomposing bark, and the proliferation of algal growth. This would have blocked the free passage of water and may account in part for the slow rewetting of the stacks following restoration of full watering'* (Wylie et al., 1999, p.153).

9.5 Insects: Other insect species

Other minor insect pests were identified during salvage operations during the 1994 Queensland fire salvage event.

- Termites: Termite galleries *(Coptotermes* sp.) were first noticed on the stems of some burnt trees in Queensland at c.12 weeks after a fire but did not cause any significant damage during the salvage period.
- Pine bark weevil: Infestations of pine bark weevil (*Aesiotes notabilis* Pascoe) occurred in some burnt stems in Queensland at c.12 weeks (Wylie et al, 1999, p.150)

9.6 Fungal impact: fungi classification

Fungi that degrade wood are classified as a) mould; b) decay fungi[10]; b) and c) staining fungi (Malan, 2011, p.10). There is a need to delineate between fungal stain and decay. A fungal stain is a change in appearance (discolouration) whereas decay events change the mechanical properties of wood (SFPA, 2002). Moulds and decay fungi are addressed in the following section. Staining fungi, specifically bluestain, is addressed in a separate section given the significance of this agent.

9.6.1 Moulds

Slime moulds and other organisms that are less common in dry-stored logs develop extensively in water-sprayed logs (Carpenter & Toole, 1963). Superficial black or dirty green-coloured moulds can develop on surfaces of timber with a moisture content above $20\%_{\text{DRY BASIS}}$. Mould feeds on carbohydrates within surface cells of wood and do not destroy wood tissue. The resulting stains are superficial and can be addressed by later stages of processing (Bootle, 1996, p.25). Industry observations suggest that while logs with mould are not yet affected by bluestain, the presence of mould suggests that a log is one step closer to bluestain.

9.6.2 Decay fungi

The appearance of fungal decay depends on the species of fungus, the timber attacked and stage of attack; and is defined as: a change of colour, softening, change of density and a change in odour (Cartright & Findlay, 1946, p.8). Box 10 provides details of decay fungi types (Goodell, et al, 2008, p.9).

Wet stored logs in Queensland (after the 1994 fire) were subject to a high incidence of decay with fungi identified as *Rigidoporus lineatus* (Pers.) Ryvarden (Wylie et al, 1999, p.148). Attack was identified in January 1996, c.2 months after a change in the watering regime. Approximately 48% of the 196 log bays were sampled

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[10] Malan (2011) separated out soft rot fungi from decay fungi, whereas Goodell et al (2008) included soft rot as a decay fungi.

(Hood et al, 1997, p.139) and by March 1996, logs with fungal fruiting bodies varied from 5% to 100% per bay (Hood et al, 1997, p.129). Growing conditions were tested and isolates of *R. lineatus* showed optimum radial growth over a temperature range 22–30°C. Growth rates decreased only slightly as atmospheric oxygen was reduced to trace levels, suggesting that among wood decay fungi, this species may be better adapted to maintaining growth in a reduced oxygen regime created by wet stored logs. The survey found that colony growth was minimal in logs with bark removed, but extension in undisturbed logs during storage may occur through development of the mycelial fans beneath intact bark and radial growth into the sapwood (Hood et al, 1997, p.139). Annotations to a commissioned report suggest a range of opinions as to the behaviour of this fungus (Johnson, 1996, p.2). The research surmised that partially dried logs become colonised from large numbers of spores of *R. lineatus* while being harvested and stored during the summer-autumn fruiting period of 1994-95 (Hood et al, 1997, p.139).

Box 10: Wood decay by fungi is typically classified into three types: soft rot, brown rot and white rot (Goodell, et al, 2008, p.9).
'Brown rot fungi are the most prevalent with regard to attack on coniferous, structural wood products in North America. The wood decayed by brown rot fungi is typically brown and crumbly and it is degraded via both non-enzymatic and enzymatic systems. A series of celluloytic enzymes are employed in the degradation process by brown rot fungi, but no lignin degrading enzymes are typically involved.'
'White rot fungi are typically associated with hardwood decay and their wood decay patterns can take on different forms. White rotted wood normally has a bleached appearance and this may either occur uniformly, leaving the wood a spongy or stringy mass, or it may appear as a selective decay or a pocket rot. White rot fungi possess both cellulolytic and lignin degrading enzymes and these fungi therefore have the potential to degrade the entirety of the wood structure under the correct environmental conditions.'
'Soft rot fungi typically attack higher moisture and lower lignin content wood and can create unique cavities in the wood cell wall. Less is known about the soft rot degradative enzyme systems, but their degradative mechanisms are reviewed along with the degradative enzymatic and non-enzymatic systems known to exist in the brown rot and white rot fungi. As we learn more about the non-enzymatic systems involved in both brown and white rot degradative systems, it changes our perspective on the role of enzymes in the decay process. This in turn is affecting the way we think about controlling decay in wood preservation and wood protection schemes, as well as how we may apply fungal decay mechanisms in bioindustrial processes.'

9.7 Fungal impact: Bluestain

9.7.1 Overview, vectors and mechanisms resulting in bluestain

Bluestain has been a subject of interest due to its widespread and common occurrence in the sapwood of logs and sawn timber with early studies, between the years 1897 and 1911 (Chapman & Scheffer, 1940, p.125). Development of bluestain fungi in softwood logs is well documented in Australia and was regarded as the main imposition following widespread damage to stands of *P. radiata* (Lewis & Ferguson, 1993, p.147). This premise is challenged by current industry information providing several caveats. Infection with *Ophiostoma ips* (Rumb) Nannf is one cause of bluestain and can kill trees (Neumann, 1987, p.166). The most widespread species of bluestain fungi are *Diplodia* and *Ohiostoma* spp. with *Ohiostoma* spp. vectored by Ips (Lewis & Ferguson, 1993, p.147). Wright & Grose (1970, p.155) noted that *Diplodia* species were the main fungi responsible for bluestain. Bluestain can occur in log ends and Diplodia can enter branch stubs that have been burnt. Diplodia can establish in trees after fires; it attacks the growth tips of trees and enters through cracks in the bark. Diplodia can result in bluestain in the wood of an infected tree. A tree may have Diplodia-generated bluestain in the upper crown (e.g. entering via branch stubs) and Ohiostoma bluestain in the lower stem. At the time of the 1994 Queensland fires, the contribution of Ips in distributing bluestain fungi was uncertain (Hood & Ramsden, 1997, p.7). After the fire, bluestain was associated with attack by Ips and was initially greatest in plots where the earliest insect attack occurred (Hood & Ramsden, 1997, p.7). It was concluded that Ips carried *O. ips. Diplodia sapinea* was not isolated from stems, but was present in dry branches and remains a potential agent of bluestain under suitable conditions (Hood & Ramsden, 1997, p.7). Diplodia is of greater significance in temperate areas, where Ips could be slower to build-up, hence early bluestain development is likely to be from DIplodia.

9.7.2 Impact of bluestain

Experience in WA suggests that sapwood greater than 80% bluestain (e.g. no clear patches) is 'too far gone'. Bluestain fungal development in sapwood is rapid once wood dries to a favourable moisture content (Lewis & Ferguson, 1993, p.147). Bluestain fungi do not attack cell walls, so the impact on strength properties is minimal but there is wood discolouration (Bootle, 1996, pp.24&32; Malan 2011, p.10). Although bluestain has no effect on strength there is considerable prejudice against stained wood and it must be regarded as an important defect (Wright & Grose, 1970, p.155). The blue discolouration results from '*fine dark threads of fungal hyphae in the cells, especially the ray cells'* (Bootle, 1996, p.24). Bluestain fungi grow either on the wood surface or within cell lumens (conductive and storage tissues, living on sugars and starch found within the lumen (Malan 2011, p.10) of freshly fallen trees (Bootle, 1996, pp.24&32). A North American study of bluestain in *P. contorta* var. *latifolia* (lodgepole pine) sapwood provided the following narrative (Ballard et al, 1984, p.1724): '*Fungi are initially confined to the sapwood rays. Hyphae readily penetrate the primary cell walls of ray parenchyma cells and proliferate within. Hyphae also grow freely in the region of the middle lamella of the rays. Host cell walls are breeched mechanically by a penetration peg originating from an appressorium like structure. Eventually, hyphae enter tracheids by penetrating the primary cell walls of pinoid, half-bordered pit pairs. Within the tracheid, fungal hyphae grow in a longitudinal fashion, branching infrequently. Hyphae may pass from tracheid to tracheid via bordered pit pairs.'* Ray parenchyma destruction by bluestain fungi is a possible mechanism for transpiration stream dysfunction (Ballard et al, 1984, p.1729).

Bluestain fungi can affect the sapwood and outer heartwood of softwood and hardwood logs and sawn timbers (Bootle, 1996, p.24). Softwood species with wide sapwood are particularly more susceptible (Bootle, 1996, p.24). Sapwood tracheids of bluestained southern pines have a high percentage of aspirated bordered pits (Nelson, 1934; Basham, 1970 cited in Ballard et al, 1984, pp.1725&1726). Bordered pit aspiration caused water conduction to cease, whereas trees that were not attacked showed a much lower percentage of aspirated bordered pits (Ballard et al, 1984, pp.1725&1726). Sapwood with bluestain was more permeable than sound sapwood, and sound heartwood was more permeable than the infested heartwood (Woo et al, 2005, p.112). Heartwood contained '*an abundant number*' of aspirated pits and supporting the observed lower permeability. However, for the bluestain heartwood, unaspirated pits were undetectable, which has been attributed to rapid removal of water from the onset of infestation (Woo et al, 2005, p.113). Changes in permeability during drying are directly related to the condition of the bordered pits based on electron microscopic studies that. When aspiration occurs, permeability is low; if aspiration is prevented, permeability is maintained at a high level. (Comstock & Côté, 1968, p.290). Subsequent microscopic analysis found that fungal hyphae are present in infested sapwood, which is likely the primary reason for increased permeability in infested sapwood (degraded pit membranes) (Woo et al, 2005, p.124).

9.7.3 Timing of bluestain and moisture content tolerances

The onset of bluestain can be rapid. Timelines of bluestain and decay development in standing trees after a 1965 fire in c.31 and 38 years old *P. radiata* plantation (see Table 16) are based on French & Keirle (1969, p.175). Bluestain associated with Diplodia was present within one month after the fire and increased with time. Queensland experience suggests that serious bluestain degrade of wood began to occur c.4-5 weeks after attack by Ips (Wylie et al, 1999, p.149). In another trial, bluestain associated with Diplodia affecting more than 10% of stems wood per plot was first observed 10-13 weeks after fire (Hood & Ramsden 1997, p.7). In another example, bluestain appeared c.10 months after a 1966 fire in crown-scorched *P. radiata* trees, extending very rapidly. By the end of the summer following the fire, bluestain levels were similar in complete crown-scorched and killed outright trees. By the second year after the fire, bluestain became extensive in lower stems with incipient decay in the upper stem (Wright & Grose, 1970, p.155). After the 2006 fires near Tumut, a series of plots were established to monitor tree impacts. Fire impacts were classified as in Table 11 and tree moisture content change is presented in Figure 17. Figure 23 presents data on timing of bluestain (associated with Ips) presence from the trial. Bluestain was identified after eight weeks (Joe, 2007, p.14).

Table 16: Timelines of bluestain and decay fungi post fire in *P. radiata* trees (c.31 and 38 years old) following a March 1965 fire (French & Keirle, 1969, p.176).

Year	Month	Season	Narrative
1965	March	Autumn	A fire event.
	April		Bluestain found in three of plots within three weeks of the fire in the north-west side of the trees where bark had been burnt thin.
	May		Bluestain penetrated from branch stubs to the centre of trees in severely burnt plots.
	June	Winter	Fungal activity decreased markedly during cold winter months.
	July		Typical wedges of stain were present in all trees sampled.
	August		
	September	Spring	Warm spring weather resulted in a rapid spread of bluestain through affected trees.
	October		Bluestain a major problem.
	November		Bluestain increased rapidly when it was found in the butts and centres of trees.
1966	December	Summer	
	January		
	February		Sporophores of *Schizophyllum commune* Fries were identified from stumps exposed to the fire.
	March	Autumn	
	April		Wood decay hyphae were found in orange-stained sections of boards sawn from salvaged logs. Finding decay in such areas of boards led to the examination of logs with clearly defined orange zones at their centres. No fungi were present in these areas.

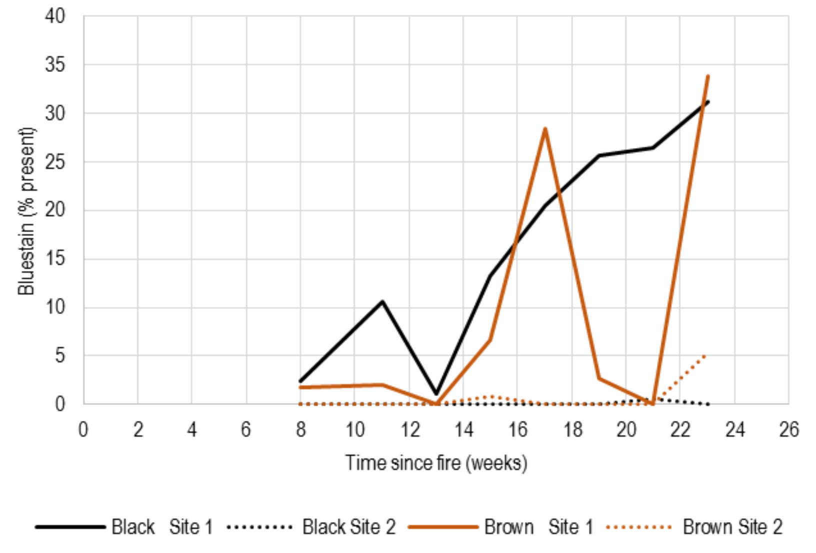

Figure 23: Time since fire and development of bluestain after the 2006 Tumut fires (based on Joe, 2007, Table 3, p.11&12)

Research on bluestain development in standing fire killed trees has found:

- Following a 1965 fire, bluestain developed in *P. radiata* stems with moisture contents between 40 and 70% $_{\text{DRY BASIS}}$ (Wright & Grose, 1970, p.156).
- Following the 1983 Ash Wednesday fires, Atyeo (1985 p.7, Table 3) determined the upper limit of *P. radiata* sapwood moisture content for each section of trees below which bluestain can develop (Table 17). *P. radiata* log storage initially adopted a target of 120% $_{\text{DRY BASIS}}$ as a safe minimum moisture content (Thomas, 1985, p.11).
- In Queensland, bluestain in Southern pines was significant where mean moisture content fell below 100 – 110% $_{\text{DRY BASIS}}$ as drying occurred particularly in the outer sapwood (Hood & Ramsden 1997, p.7).

Stem moisture content data from the Tumut trial is presented in Figure 24. At moisture contents of c.100-110% $_{\text{DRY BASIS}}$ bluestain increased dramatically (>10%). During the trial, bluestain went from 2.4% to 31.2% for black trees and from 1.8% to 33.8% for brown trees on site 1. On the other hand, there was little or no bluestain in site 2 while the average tree moisture content remained relatively high (Joe, 2007, p.11). Of interest is the difference between the two sites with site 1 drying to a greater degree than site 2. A whole stem average moisture content suggests that some sections of stems will have higher or lower actual moisture content. Figure 25 presents log moisture content data and bluestain levels for *P. radiata* logs supplied to a Western Australian sawmill: an increase in bluestain is evident once log moisture content drops below c.110% $_{\text{DRY BASIS}}$. Once timber moisture content has reached 20% $_{\text{DRY BASIS}}$ bluestain is not an issue (Bootle, 1996, p.25).

Published information suggests that development of bluestain in standing trees occurs within upper and lower limit moisture content. When wood moisture content reduces, voids that held water can hold air, increasing risk of bluestain as it is an oxygen-requiring process (Olsson, 2005, p.5; Malan, 2011, p.2). Rather than an absolute moisture content threshold below which bluestain commences, it is a reduction in moisture content which is key.

Table 17: Standing P. radiata pine trees bluestain limiting moisture content base on 1983 Ash Wednesday experience (Atyeo, 1985 p.7, Table 3).

Tree section	Moisture content (% $_{\text{DRY BASIS}}$)
Butt	90% – 100%
Mid	100% – 120%
Top	100% – 120%

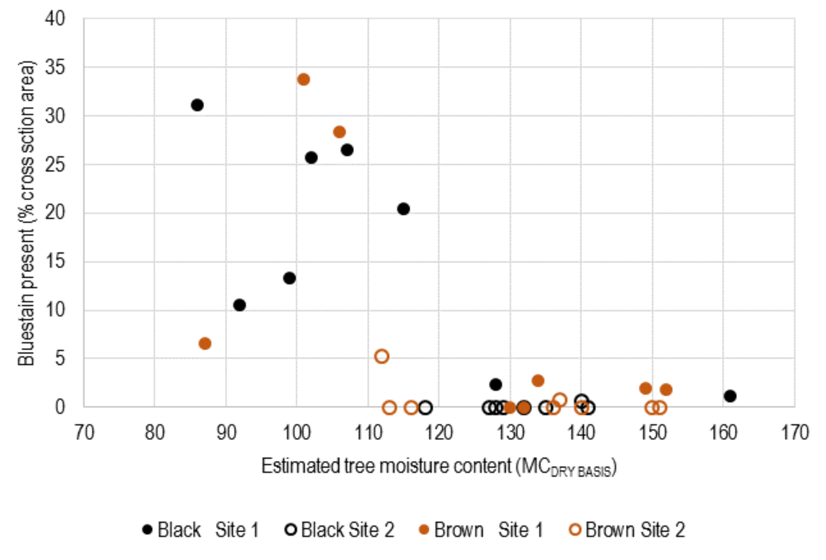

Figure 24: Tree drying (whole-tree moisture content) and the development of bluestain after the 2006 Tumut fires (based on Joe, 2007, Table 3, p.11&12)

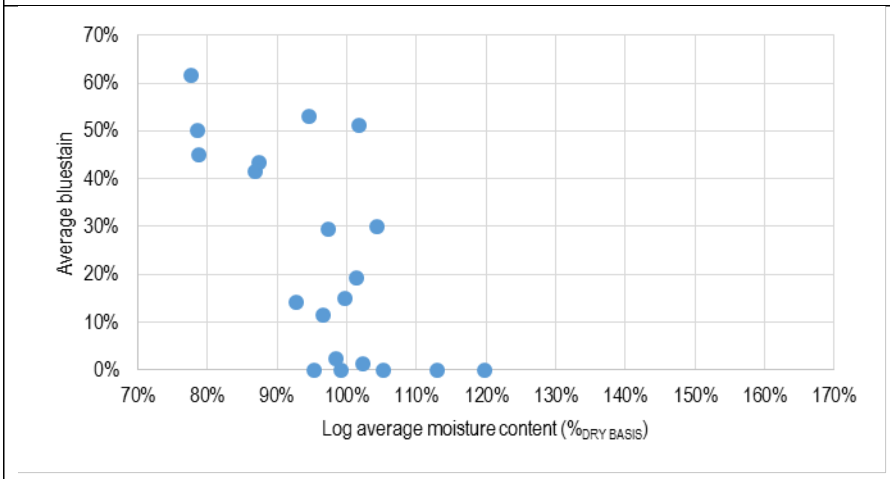

Figure 25: Average log moisture content and detected bluestain (based on WESPINE, Barr, pers. comm.)

9.7.4 Within stem variation in bluestain

After a January 1966 fire in a c.35 year old *P. radiata* plantation, bluestain development was monitored (see Table 18) (Wright & Grose, 1970, p.154). In defoliated trees, bluestain associated with Diplodia first appeared in sapwood of the upper stem about one month after the fire. Bluestain first appeared around knots and cone holes and extended in the outer sapwood, usually in longitudinal ribbons. It extended rapidly in small trees (less than c.25 cm DBHOB) and in the upper bole of larger trees. In the lower stem of larger trees, it was limited to occasional ribbons in the outer sapwood. After a year, bluestain was very extensive in log sections smaller than c. 25 cm diameter but was still relatively unimportant in large logs (Wright & Grose, 1970, p.155).

Table 18: Incidence and severity of bluestain in the sapwood of standing fire-killed P. radiata trees at various cross-sections within stems (based on Wright & Grose, 1970, p.156, Table 3).

Position in stem	Height (m)	Approximate depth of bluestain (cm)		Bluestain severity	
Time since fire (y)		0.5	1.0	0.5	1.0
Upper stem	15.2	5.0	To heartwood	Severe	Severe
Middle stem	8.5	2.5	5.0	Moderate	Moderate
Lower stem	2.1	1.2	2.5	Slight	Slight

Note: Severity of bluestain:

- <u>Slight</u>: Occasional narrow ribbons of stain in outer sapwood.

- Moderate: Approximately 25% of sapwood stained.
- Severe: More than 50% of sapwood stained.

While not possible for the data presented (Figure 23 to Figure 25), it would be significant to understand within-tree moisture content variation with height and the associated level of bluestain. In Queensland (Hood & Ramsden, 1997) and NSW (Joe, 2007) fire impact, Ips and bluestain analysis presented whole tree moisture content data. These data are based on aggregated data for discs taken from within sample trees at known heights within stems. Therefore, while bluestain may have been 'present' it would be helpful to revisit individual tree data sets to determine timelines of tree drying with height, actual moisture content of sample discs and corresponding levels of bluestain.

9.7.5 Impact of fire season and weather on bluestain development

Spores of fungal species are omnipresent and infestation will result under the right conditions (Bootle, 1996, p.24). Fungal attack has been shown to be related to weather conditions (French & Keirle, 1969, p.176) (see Table 16). The speed of bluestain attack increases in warmer months (Bootle, 1996, p.24). After a 1965 fire that damaged *P. radiata* plantations in NSW, the weather was drier than usual, with a rainfall of 580 mm compared with an average of 1020 mm (Anon 1948, cited in French & Keirle, 1969, p.176). In October 1966, 200 mm was recorded over an 11 day period. Mean maximum temperatures rose from 10°C (50°F) in July to 23°C (73°F) in December. The mean maximum temperature for March 1965 was the highest recorded for any month during the study (French & Keirle, 1969, p.176). If there had been a period of higher rainfall and temperatures immediately after the fire, bluestain in standing tree could have become widespread within an estimated 4-6 weeks. This estimate, made in 1966, was partially confirmed by experience following fires in late November 1968 in *P. elliottii* and *P. taeda* plantations near Casino, NSW. By January 1969, bluestain associated with Diplodia was found in standing trees and was widespread by the end of summer (Gardiner, personal communication cited by French & Keirle, 1969, p.179). A point of caution was that *'salvage operations should be completed as soon as possible, for the period when trees remain free of bluestain depends on unpredictable climatic factors*' (French & Keirle, 1969, p.179).

9.7.6 Management of bluestain risk during log storage

Observations in the US of log storage noted that the *'cool water reduced temperatures in and around the log piles. By itself, this amount of cooling would favour rather than hinder the development of stain and decay, because most of the fungi that cause such deterioration grow best at 24 to 32°C (75-90°F). It is the wetting, and not the cooling that protects the logs'* (Carpenter & Toole, 1963). A conclusion from experience in Germany suggests that correct storage results in logs attaining and retaining the required sapwood moisture content to not develop bluestain or wood-destroying fungi during storage for periods of up to five years (Liese, 1984, p.125).

9.7.7 Detection and management for bluestain

A key issue is the length of time wood remains merchantable before having 'too much' bluestain (as defined by markets). Observations in Victoria suggest that bluestain will first appear as dark rings in a log: a brown stain that can turn blue overnight. In some cases, while not actually bluestain fungi, mould on the side of a log is an indicator of bluestain. Management of bluestain risk during fire salvage should include a monitoring program to inform harvest scheduling. Monitoring for bluestain development has been a key element of salvage log management after all recent fires. Monitoring has been by destructive sampling, visual assessment of cut stems or simply seeking feedback from harvesting contractors. A non-destructive test is unavailable. However, Ips infestation is an indication of impending bluestain development. Possible indicators include: colour, acoustic properties, odour and visual assessment. To minimise the risk of bluestain development, the following is suggested:

- Monitoring: Monitor stands for Ips infestation and Diplodia.
- Log moisture content: Harvest logs prior to reaching threshold moisture contents of bluestain development.
- In forest storage: Logs stored in roadside landings can development bluestain if left too long. A site where harvest will make use of a landing for an extended period is at greatest risk due to the bottom logs being kept as the base with the log pile above replaced many times.
- Time until processing: A key is to process (saw or chip) logs prior to bluestain formation.
- Time until under sprinklers: Minimise the time from harvest to storage under sprinklers.
- Time under sprinklers: Once under sprinklers with 'fit for purpose' coverage, Ips will be killed and sapwood will remain at above the threshold tolerance for bluestain development.

9.8 Bacteria

Bacteria are early colonisers of wood in wet environments (e.g. Ellwood & Ecklund, 1959; Banks, 1970; Dunleavy & McQuire, 1970 cited in Maun & Webber, 1996, p.33). The role of bacteria in wood decay is minor compared to fungal decay, but it changes wood properties. A South African review of log storage under sprinklers concluded that '*the only changes to the wood of practical significance are caused by the activity of anaerobic bacteria during the storage period*' (Malan, 2004, p.77). '*No other signs of fungal decay or any other forms of biological damage could be detected, apart from soft-rot decay, which initially only affected the outer layers of some logs slightly'* (Malan, 2011, p.23). These changes were *'without any significant change in the strength characteristics of the wood in the short to medium term*' (Malan, 2004, p.81).

Greaves (1971, p.6) segregated bacteria impacts on wood:

- Bacteria affecting permeability of wood to liquids but with no significant effect on strength properties.
- Bacteria that attack wood structure.
- Bacteria that only function as integral members of a total microflora and are associated with the breakdown of wood.
- 'Passive' colonisers that have no effect on wood but influence other biological agents by their antagonistic activities.

Knuth (1960, p.82) researched bacterial impacts on wood, and laboratory tests indicated that *Bacillus polymyxa* could increase porosity of softwood sapwood like that resulting from log-pond storage. Bacterial action ferments wood components: cellulose, hemicellulose, pectin or xylan (Knuth, 1960, p.82) and results in a foul odour (Malan, 2011, p.23). Wood-living bacteria selectively attacked sapwood ray parenchyma, epithelial cells lining resin ducts and pits (Jonsson, 2004 cited by Olsson, 2005, p.6; Malan, 2011, p.26), in particular pit membranes of ray parenchyma and bordered pits between longitudinal tracheids (Liese, 1984, pp.126&127). After 3-4 years storage, alteration of tracheid cell walls may commence (Liese, 1984, p.126). Bacteria or a succession of bacteria penetrates bordered pits and S3 of wood cell walls (Clausen, 1996, p.105). Optical and electron microscope studies of softwood wood structure after storage in log ponds confirmed that tori and bordered-pit membranes had been destroyed, facilitating longitudinal and tangential flow. Increased radial permeability was attributed primarily to partial breakdown of the cross-field pit membranes of ray-parenchyma cells. At that time, bacterial action was suspected and yet to be confirmed (Dunleavy & McQuire, 1970, Abstract). Subsequent research has confirmed the action of bacteria.

There are three distinct forms of cell wall damage attributable to bacteria: erosion of lysis troughs, wall pitting, and attack of the crystalline cellulose structure in the secondary wall (Greaves, 1971, p.9). Optical and electron microscope studies of softwood wood structure after storage in log ponds found no evidence of cell-wall degradation and testing did not indicate any deterioration of strength properties (Dunleavy & McQuire, 1970, Abstract). Subsequent electron microscopic examination of logs after wet storage found no sign of cell wall degradation (apart damage to pits) (Malan, 2011, p.35). The result was no measurable loss in strength as only soft tissue was destroyed.

Wet-stored logs with attack by bacteria resulting in changes in porosity of wood are well recognised (Ellwood & Ecklund, 1959; Banks, 1970; Dunleavy & McQuire, 1970 cited in Maun & Webber, 1996, p.33). Under anaerobic storage conditions, permeability of wood increased faster than under aerobic conditions, explaining why development of bacterial damage can still occur when the roundwood is stored in water compared with under sprinklers (Banks & Dearling, 1973 cited in Olsson, 2005, p.6). Degradation of pit membranes increases timber porosity; an increase in porosity indicates an expansion of voids within wood. Increased porosity can increase wood permeability – the capability of wood to allow passage of fluids under pressure (Koch, 1972, p.307). Bacterial action increasing porosity in *E. regnans* and *P. radiata* wood has been documented, noting *P. radiata* as a highly refractory species (Greaves, 1971, p.7). A refractory species has wood with anatomical properties (e.g. pore size and structure) and chemical composition (e.g. pit membrane components or presence of wood extractives) (Civardi, et al, 2016, p.1) that reduce permeability. Pre-treatment by fungal action has been used to reduce heartwood refractory attributes by spraying a suspension of fungal spores in a nutrient solution onto non-decontaminated wood (Messner et al, 2003, p.389).

9.9 Impacts on log processing and products

Any biological agent impact (specifically decay) is defined against the intended use and '*whether by proper treatment the wood may not still be fit for use as timber'* (Fisher, 1896, p.77). Greaves et al (1965, p.161) found that less than 5% of defects in merchantable wood was due solely to fire; termites and fungal decay caused most degrade, although fire damage had allowed their entry. Historically, bluestain has been the most important defect in *P. radiata*, with insect damage and decay developing subsequently (Wright & Grose, 1970, p.149). Published information suggests that mechanical properties of bluestain wood remain unimpaired for some time in standing trees and logs (Lewis & Ferguson, 1993, p.147). In the absence of decay, fungi resulting in bluestain and bacteria affect wood porosity by damage to pits rather than wood mechanical properties. This changes wood drying behaviours and preservative uptakes.

9.9.1 Sawn timber

Historically, bluestain was noted as an issue with sawn timber, as consumers were less likely to buy discoloured wood (Lewis & Ferguson, 1993, p.147; Bootle, 1996, p.24), but this is less the case today. Industry comments varied. Bluestain was a major issue in sawn timber due to appearance; in other cases, sawn timbers could include bluestain with minimal market push back. It is possible that changes in building from stick-built to truss and frame plants may explain this change. In other cases, blue envelope treatment of boards can mask bluestain. Softwood logs stored under sprinklers in Queensland included 25% with some level of bluestain fungi prior to harvest and the logs were supplied to the market at the end of storage (DPI, 1995, p.5). Industry comments suggested that bluestain does not in itself indicate a loss of structural wood properties, unless it is of a 'long' duration. Based on published information, it is unlikely that bluestain causes changes in wood mechanical properties. A key point is that there is a need to understand concerns of timber in regards to bluestain and provide appropriate information and education.

9.9.2 Timber treatment

Bluestain and bacteria impacts affect wood preservative treatments, due to changes in porosity and permeability. Bluestain causes cell pits to remain open, increasing loss of wood moisture. If treated with preservative chemicals, uptake can be to three times the normal rates. Regarding light organic solvent (LOS) treatments, chemical consumption can increase by c.15%/m^3 of boards. Given that bluestain does not attack softwood corewood, and therefore corewood remains difficult to treat with preservative.

9.9.3 Export woodchips, pulp and paper

Pulp brightness is a key issue for product acceptance. Softwood pulp can be used in the manufacture of packaging grade paper, which can require quality surfaces for printing. Bluestain fibres can result in a whole reel of paper being rejected. For example, a run of paper can be rejected due to 20 logs affected by bluestain in 2000 t of woodchips. Bluestain fibres remain after pulping and cannot be detected or removed by usual pulping processes (Smook, 2002, p.57). It is possible to add dyes and optical brighteners with limited effectiveness and extra cost. Bluestain limits suitability of softwood logs as pulpwood (Lewis & Ferguson, 1993, p.147) and this remains the case with one major pulp and paper facility indicating that bluestain was the most significant issue with fire salvage logs. Other sites and export woodchips were less focused on bluestain as an issue depending on the proportion of logs affected. Once a log is chipped, it is less likely to develop bluestain in well-managed woodchip piles. However, bluestain will become more evident in stockpiles as they dry when logs already contained bluestain when chipped. Domestic pulp and export customers have different tolerances to bluestain. The Hume Region routine (non-salvage) log specification states that '*pulplogs must be reasonably free of bluestain'* (Forests NSW, 2007, p.8).

9.9.4 Panels

Cosmetic impacts of bluestain were regarded as less of an issue for some panel products (Lewis & Ferguson, 1993, p.147). While this remains broadly the case, it depends on the product. Where a product such as particleboard is intended for appearance-grade products, bluestain creates discolouration that can be visible through laminated resinated papers. Where particleboard is intended for flooring, bluestain is not an issue. Conversely, it was reported by a plywood manufacturer that structural plywood is more sensitive to 'appearance' whereas for form ply, bluestain was not an issue. Particleboard manufacturers suggest that bluestain-impacted wood tended to not flake as well. Industry trials demonstrated that wood with high bluestain (harvest greater than six weeks prior) increased manufacturing costs (e.g. resin use). It is possible that this related to wood dryness rather than bluestain. Bluestain was not identified as an issue with glue bonds in plywood.

9.10 Recommended best practices

Best practice 34: Develop operational plans informed by changes in standing trees post-fire, beginning with application of a robust fire impact classification system. Harvesting schedules require a degree of plasticity to take account of identified Ips issues and change harvest operations. There is likely to be a degree of 'stopping the Titanic' in ability and agility to swap harvesting around limited by markets, contractor capacity and pre-harvest road construction and maintenance.

Best practice 35: Determine timelines for operations after a fire, based on the fire's timing and expected subsequent weather. This will drive options and triage decisions and ultimately the rate of salvage and a need for dedicated storage.

9.11 Observation

Observation 25: Define the thresholds of bluestain in logs at which processing by various operations experience issues to determine decision points for a change from dilution to batching or rejection of bluestained logs.

Observation 26: Model to predict the onset of bluestain based on stem damage, crown damage, season of fire and expected subsequent weather conditions.

Observation 27: A simple non-destructive test is required to identify presence of bluestain development within stems. Currently Ips infestation is a proxy. Possible strategies include: colour, acoustic technology, odour as well as visual.

Observation 28: Predict (by indicators) the onset of impending Ips infestations. This could include field sampling for pheromones.

Observation 29: Define determinates of timelines and drying profile of fire-impacted trees (radially as well as vertically).

Observation 30: Revisit data collected after fire events. For example, where data presented was based on aggregated data for discs taken from within sample trees at known heights within stems. Therefore, while bluestain may have been 'present' it would be important to revisit the individual tree data sets to determine the timeline of tree drying, actual moisture content of sample discs and the corresponding level of bluestain.

Observation 31: There is a need to better understand the mechanisms and nuances of Ips and bluestain. This should address actual moisture content and/or timelines for Ips and bluestain and the conditions which determine timelines and moisture contents.

Observation 32: Understand Ips population dynamics in relation to harvest residues associated with a plantation and in surroundings areas. This would then link to population build up in fire killed trees that remain standing, and impact on surrounding trees.

Observation 33: Understand the potential for pheromone and ethanol as attractants of insects to logs in wet storage and whether both compounds could be used in tools to control potential insect pests.

Observation 34: Understand rate of penetration of bacteria into logs during wet storage and the impact of a failure for bacterial to completely colonise a log. There is potential that incomplete or uneven changes in log porosity could impact drying outcomes for sawn timber.

Observation 35: Determine whether softwood logs entering wet storage should be de-barked or not based on storage outcomes and any effect on biological degrade.

10 Fire impacts: post-fire conditions – wood yards, de-barking and log segregation

10.1 Summary

Carbon can be inherent within a log (e.g. burnt into wood) or superficially attached as passenger carbon (e.g. soot). The aim of de-barking is to remove log bark and with it as much carbon and other impurities as possible. Softwood logs are generally delivered bark-on and hardwood logs are de-barked in the forest. Fire impact direct to a stem can bake bark on, making it more difficult to remove. To assist in bark removal, log specifications can be amended to reduce risk of impediments to de-barking (e.g. stem straightness or branch stubs). De-barking technology varies between processing systems. Sawmills generally have ring de-barkers and pulpmills make use of drum de-barkers. Flail de-barkers have specific use in eucalypt plantation in-field chipping. Generally, a site will make use of the equipment already available, with adjustment to operations as necessary. There is a trade-off between maximising bark removal and minimising fibre loss; but to effect removal of carbon, some wood may be lost.

10.2 Introduction

There are three broad measures of de-barking efficacy: 1) wood fibre volume loss; 2) percentage of wood in bark residues; and 3) percentage of bark remaining on log surfaces (Laganière & Hernández, 2005, p.44). A primary aim of de-barking of fire-impacted logs is to reduce the risk of introducing carbon into a supply chain while reducing any compromise of the logs supplied. A broad classification of carbon from a fire is:

- Inherent: The actual bark is burnt or in more severe cases, wood is burnt.
- Passenger carbon: Loose carbon attached to bark or wood surface either as soot, flecks or nodules of carbon.

Because softwood logs are usually delivered with the bark on, harvest processor heads are generally set at pressures that retain bark. An operation may increase bark removal at harvest, but this requires a trade-off between bark removal and retained carbon on the log surface. To ensure maximum bark removal (with carbon contamination) is achieved, aggressive de-barking with fibre loss can be used (Watson & Potter, 2004, p.473). This can be achieved by the de-barker operation and/or by modified tip configuration on de-barkers (Dyson, 1999a, cited by Watson & Potter, 2004, p.475). This section addresses the topic of log de-barking technology, issues and outcomes.

10.3 Log segregation as a principle strategy to address fire-impacted logs

Processing systems rely on homogeneous log inputs to varying degrees. An ability to batch material with similar attributes with a degree of confidence will assist subsequent processing. Fire-salvage logs affect processing by creating a less homogenous feedstock. Plywood manufacturing has a high degree of tolerance, with some sites commenting that there is no difference between processing of fire-impacted and green logs. Sawmilling, and pulp and paper making, has a lower tolerance of change to log homogeneity. This problem can be exacerbated where continuous processing technology is used, as this requires a higher level of uniformity. Sawmills and pulp mills apply a two-stage strategy to handle fire-impacted logs. The first stage is to dilute them with green resources up to a tolerance threshold. After the threshold is reached, batching of fire-affected logs is implemented.

Segregation of fire-impacted logs is a critical first step. Logs should be sorted in plantations into nil burnt (green), lightly burnt and heavily burnt (down to wood-fibre) (Watson & Potter, 2004, p.476). In a sawmill, segregation by diameter and/or length facilitates batch processing of logs. The addition of fire-impacted logs will increase log yard complexity. For example, on a site receiving green and fire-impacted logs grouped by log length and extent of damage, logs were classified as from burnt or not burnt plantations, with no consideration of the amount of char or time since fire. In extreme cases where all logs are affected, segregation is not an issue. In a pulp mill, segregation is by wood type and/or process (where multiple pulping operations are on a site). Segregation is a first step, allowing introduction of impacted logs via chipping at a controlled rate with green logs to dilute fire-impacted logs. Particleboard and MDF manufacturing require a minimum level of green log input to dilute fire-impacted logs, but cannot handle 100% fire-impacted logs.

10.4 Drivers of bark adhesion

Fire damage to a tree includes combustion of bark (a direct impact) and drying when killed by fire. Recent Australian experience has identified issues associated with de-barking fire-impacted softwood logs. With bark combustion, bark can become bonded or glued to a tree by heat. In some cases, bark seems to be more strongly bonded to wood and ‘hangs on more’ to the stem around branch stubs. The impact is due to lowering of moisture content as a tree dries out. Importantly, with nil fire-affected logs, ‘*re-wetting was found to reduce the bond strength of dried material to the expected value for green material for E. obliqua and P. radiata but did not reduce the bond strength for an E. viminalis – E. rubida mixture*’ (Moore, 1987, p.73).

Wood-bark bond strength affects the effectiveness and efficiency of de-barking technology. Under external load, wood and bark usually separate at the cambium region, where thin cell walls readily shear when external load is applied (Chahal & Ciolkosz, 2019, p.9). Factors affecting wood-bark bond strength include moisture content, harvest season, wood species and direction of applied load (Chahal & Ciolkosz, 2019, p.1). Log moisture content is a good predictor for bark-wood bond strength (Moore, 1987, p.73). Published information suggests that adhesion strength of wood-bark is negatively correlated to moisture content (Moore, 1987, p.76; Chahal & Ciolkosz, 2019, p.6 citing Rowell 1984; Duchesne & Nylinder, 1996; Baroth, 2005). More specifically, there is a negative correlation of cambium tissue hydration with bark-wood adhesion strength (Chahal & Ciolkosz, 2019, p.6 citing Gurusinghe, 1994). The typical relationship observed between shear strength of wood to bark and moisture content of sapwood is nonlinear, with most variation occurring at moisture contents between 20 and 40% (Chahal & Ciolkosz, 2019, p.6 citing Duchesne & Nylinder, 1996). North American research tested the impact of steaming and herbicides, and changing moisture-content, on bark-wood bond strength, and found a 4-5-fold increase in bond strength when logs were dried from green to air-dry state (Moore, 1987, p.74 citing Miller, 1975). The likely reason why moisture content affects wood-bark adhesion strength is that constituent elements of plant cell walls (e.g. cellulose, hemicellulose, and pectin) behave differently when exposed to water molecules (Chahal & Ciolkosz, 2019, p.1; Chahal & Ciolkosz, 2019, p.6 citing Gurusinghe & Shackel, 1995). It was proposed that observed non-linear change in shear strength of wood-bark bonds with moisture content might be due to the evolution of pore topography, in which the structure of polymers evolved in such a way that average pore size increases and may merge (Chahal & Ciolkosz, 2019, p.6 citing Kulasinski, 2016).

10.5 Tolerance of bark and associated issues

10.5.1 Sawlogs

Where a log has been poorly de-barked, retained bark (with or without carbon) will have an adverse impact on sawmilling equipment, increasing repairs and maintenance. A further impact of retained bark is that bark may become loose and fall from logs during processing, creating a hygiene issue in green mills, and can obscure horizontal photo-eyes, creating production halts to clean these sensors. This can be addressed by changing the position of photo-eyes and pneumatic blasts to clean these sensors. Sawmill managers seek to maximise returns from logs delivered and processed. While actual burnt wood in a log may be an issue for sawn boards containing the actual burnt wood, carbon is more an issue for sales of processing residues. The risk of contamination of sawmill residue woodchips increases with increased difficulty of de-barking. Poor de-barking will affect the ability to supply processing residue to other markets including pulp and export woodchip markets. In the absence of effectively de-barking logs, fall-down and more tolerant markets are required for residues.

10.5.2 Domestic pulping

Pulp mills utilise material from logs and processed woodchips. Logs are sourced from thinning and clearfall operations, and woodchips come from either sawmill residues or in-field chipping operations. A pulp mill may only take plantation-grown softwood fibre, or accept plantation grown softwoods and hardwood fibre from native forest as residual logs, sawmill residues and plantation grown material (either as logs or in-field chipped materials). De-barking aims to maximise bark removal and limit stowaway bark. Residual bark is a critical issue and when de-barking is inadequate, contaminated woodchips can cause problems with pulping processes. For example, kraft pulping requires less than $0.5\%_{w/w}$ bark content in woodchips and tissue manufacturing requires $0.05\%_{w/w}$ bark or less. With fire-impacted logs, increased vigilance seeks to maintain this level of bark with rigorous inspection and enforcement.

10.5.3 Export woodchips

Export woodchips include fibre from a range of sources and markets for each have different tolerances to carbon (Table 19). Generally, export woodchips require less than 0.5% bark content.

Table 19: A snap-shot of export woodchip inputs and market tolerances based on public company information (WAPRES, 2017; Midway Limited, undated).

Product	WAPRES	Midway Limited
Natural forest export woodchips	Some tolerances	A tolerance to a degree of carbon.
Plantation eucalypt woodchips	Zero tolerance	Zero tolerance
Softwood plantation woodchips logs	Zero tolerance	Zero tolerance
Softwood plantation sawmill residues	Zero tolerance	Zero tolerance
Biomass for energy	Any product not accepted by the woodchip market but with lower level moisture content limits.	Not supplied

10.5.4 Panel production

Bark is not a major issue for plywood manufacturing. Embedded stones in bark are more likely to be a problem as they can damage peeler knives and increase maintenance. Particleboard manufacturing can accept up to 5%

bark content. Particleboard and MDF manufacturers focus on bark removal to ensure maximum panel uniformity as both bark and carbon are issues. De-barking is aggressive to reduce this risk and lost fibre is accepted as a trade-off for acceptable quality. This requirement flows through to any processing residue woodchips supplied, particularly by sawmills.

10.6 Wood yard

10.6.1 Capacity of storage at a processor's log-yard – management of a surge of supply

It is possible to store a surge in logs from fire-impacted plantation harvests, within the limits of log storage capacity. Log-yard capacity will be specific to a site. For example, a sawmill log-yard holding 13,000 m^3 of logs with a daily processing rate of 2 500 m^3/day holds 5.2 days production (2.2% of 598,000 m^3/y). Sawlogs are generally managed on a first-in – first-out principle with on-site tracking of stocks by size classes. For one site, sawlogs are segregated by length and are held in bays by length classes (3.0 to 6.0 m in 600 mm increments). Estimation of log stocks or area occupied requires an understanding of log stacking efficiency (e.g. the volume of space occupied by a volume of logs). Stacking efficacy is driven by log straightness and uniformity; and logs shorter than a maximum bay width will reduce stacking efficiency. Softwood sawmills avoid the need for log watering to maintain logs in a 'fit for purpose' condition by minimising the time from harvest to delivery to processing in green mills. Softwood sawmills hold minimal log inventory (e.g. 2 to 5 days) facilitated by year-round harvesting and scheduling of harvest between 'summer' and 'winter' coupes. In some examples, native forest hardwood sawmills are supplied on a seasonal basis and there is a need to hold log stocks (e.g. for continuous winter processing). Hardwood logs are usually watered due to sunk costs (e.g. harvest, haulage and storage), log value (e.g. stumpage, potential products and the cost of sourcing alternative logs from another site) and duration of storage. Any increase in on-site storage of fire-impacted logs for softwood sawmills would be a significant departure from business as usual. For pulp mills, while a site may have physical log storage capacity, log drying and bluestain are a risk with storage of logs prior to chipping. Log-stack management (e.g. stack heights and area) are also limitations. For example, a stockpile storing of 50,000 m^3 of 6 m long pulplogs stacked 6 m high would be c.2700 m in length and occupy 1.7 ha.

10.6.2 Log receival and handling

Fire-impacted logs can be difficult to identify, as damage may only be on one side or only at the end of a log. Logs not directly burnt can pick-up 'passenger' carbon contamination on their ends, in shattered ends or sides. Fire-impacted logs generate increased dust, including fine carbon particles.

Softwood logs are delivered with bark-on and de-barked prior to on-site stockpiling. Hardwood logs are delivered de-barked and are stockpiled directly.

Extra dust and grit as well as carbon may result from log-handling in plantations where surface soils are exposed due to burning of litter and humus. On-site handling and de-barking of softwood logs becomes a significant site hygiene risk. Some processors address this by washing equipment between handling fire impacted and green logs. In another example, a pulp mill de-barker was fully enclosed in a building to contain all dust (including carbon). De-barking of fire-impacted logs increases OHS issues for staff. During delivery, log-yards can be watered to suppress dust and to lubricate log-decks and conveyors. However, a carbon/water mixture is abrasive and results in increased wear on log decks and conveyors (Watson & Potter, 2004, p.476). Watering of softwood logs will increase bark moisture content, potentially assisting de-barking. Application of water can also ‘wash’ logs, which removes surface carbon (soot) but not embedded carbon. Increased watering can be an issue under drought conditions. Water can cause site run-off management issues, particularly as water will include carbon and dust.

10.6.3 De-barking technology

Softwood bark becomes more difficult to remove with increased fire intensity and decreased moisture content. Table 20 summarises de-barking technology. The technology will be based on specific site needs and circumstances. For example, a Canadian study noted that water blasting of bark allows production of woodchips with less than 1% dirt (Krilov & Ingate, 1984; cited in Watson & Potter, 2004, p.475), but this would be problematic under Australian conditions. A more obscure de-barking technique uses micro-organisms that weaken non-lignified cambium relatively faster than adjacent bark and wood. However, conditions favouring such techniques are also favourable for growth other micro-organisms or fungi (Kubler, 1990, cited by Chahal & Ciolkosz, 2019, p.4). Sawlogs can be de-barked with single ring de-barkers (e.g. Wespine and AKD, Tumut). However, a single ring de-barker may struggle with bark removal from fire-impacted logs. A particleboard manufacturer used small-scale ring de-barkers for smaller logs. Plywood logs are de-barked using a ring de-barker, which was reported as very effective. This is followed by peeling logs until they are round and all bark and carbon is removed. Peeling residues are used as boiler fuels. Australia’s two pulp and paper making sites use drum de-barkers for pulp logs. De-barked logs are fed straight into a chipper rather than being handled into a log stockpile. One site has a 5.5 m diameter log de-barker to make maintenance and operation simpler. Overall, fire-impacted logs can increase repairs and maintenance costs for de-barking equipment.

10.7 Tactics to address de-barking fire-impacted logs

10.7.1 Generic issues to address during de-barking

Sawmilling, pulp and paper production, and export woodchips have common tactics to address fire-impacted logs (see Box 11).

Box 11: Generic issues to address during de-barking.

- Log specifications: Modified log specifications aim to eliminate embedded carbon (e.g. burnt dry log sides or branch stubs with passenger carbon) and to increase efficacy of de-barking (particularly with ring and drum de-barkers). Log grade and defects that can carry carbon were identified for exclusion in a bespoke fire salvage log specification manual (Forests NSW, 2007).
- De-barking: Change to de-barking is limited by systems in place, with a trade-off possible between fibre loss due to more aggressive de-barking and ensuring bark removal.
- Log yard: Fire-impacted logs are segregated in log yards to allow application either a ‘dilution’ or a ‘batch’ strategy.
- Hygiene: Sprinklers are used to suppress dust (with a carbon particles), including wash-downs of de-barking equipment to remove loose carbon.

10.7.2 Issues to address carbon in woodchip operations

There is an issue with de-barking damage to fire-impacted logs beyond fibre loss. As the logs reduce in moisture content, they became brittle and break during ring de-barking. Similarly, over-dry logs can shatter during drum de-barking. In one example, fire-impacted logs were stored in piles separated by type of operation (e.g. thinnings or clearfelling) to narrow the diameter range. Logs are recovered by green or fire impacted and by diameter class and fed into the de-barker in batches to reduce log breakages. De-barked logs are then chipped and fed onto woodchip piles segregated by age to enhance woodchip homogeneity to ensure 'fit for purpose' pulping and resulting products. Box 12 presents points of an overall carbon management strategy.

Box 12: An overall carbon management strategy can include:

- Stand stratification: Map out impacted stands and define which can be safely harvested to address carbon issues.
- Delay harvest: Allow natural weather events to reduce the abundance of carbon on the surface soils of a site.
- Harvest systems: Make use of in-field chipping to reduce the risk of surface carbon on freshly cut eucalypt logs.
- Flail de-barking: Add an extra flail de-barking unit to increase de-barking certainty. Space the extra unit to allow monitoring of log outfeed and infeed to the main unit. Increase the aggressiveness of operation, potentially sacrificing fibre to ensure bark removal.
- Monitoring: Increase monitoring of log in-feeds and the resulting woodchips to detect carbon contamination.
- Downgrade: If carbon cannot be excluded from woodchips, there is an option to downgrade woodchips to a native forest grade product (if possible).

10.7.3 Sawmill tactics to address de-barkingof fire-impacted logs

A range of strategies to improve bark removal are possible as presented in Box 13.

Box 13: An overall carbon management strategy can include the following.

Plant and equipment:

- Knife type: Processors have tested use of knives designed to de-bark frozen logs.
- Ring de-barkers in series: Ring de-barkers in series can have rings rotating in opposite directions (Dyson, 1999b; cited in Watson & Potter 2004, p.475).

Operations:

- Knife pressures: Adjust ring de-barker knife pressures to remove more bark (Pickrell, 1998; cited in Watson & Potter 2004, p.475).
- Knife sharpness: Improve de-barker knife sharpness.
- Angle on cutting tips: Adjust the angle on cutting tips (Pickrell, 1998, cited in Watson & Potter 2004, p.475).
- Arm pressures: Increase arm pressures (Pickrell, 1998 cited in Watson & Potter, 2004, p.475).
- Feed speeds: Lower feed speeds (Pickrell, 1998, cited in Watson & Potter 2004, p.475).

Table 20: A summary of de-barking technology.

Technology	**Drum de-barking**	**Ring de-barking**	**Rosser-head de-barking**	**Cradle de-barking**	**Chain flail de-barking**	**High-pressure water jet de-barking,**	**Compression de-barking**
Description	A cylindrical drum fitted with slots, mounted at slight incline.	An array of swing arm knives mounted to a rotatable ring.	Rounded cutting teeth spaced in repeated rows running the length of a cylindrical surface.	Vertical conveyers raise and drop logs, inducing compression and shear forces, separating bark and stem	Hard chains mounted on a rotating shaft shred small branches and bark off tree trunks.	High-pressure water jets scrape the bark off from logs.	Suitable method to remove bark from chipped wood
Mode	Tumbling action by logs inside abrade logs against other logs and against drum surface.	Scrapes the bark off logs as fed through the ring.	Logs revolve on their axis while being fed longitudinally with shear action between log and teeth removing bark	Abrasive action is produced between logs and between logs and conveyors, resulting in removal of bark.			Woodchips with bark are compressed between closely spaced steel rollers rotating in opposite directions. Pinching action induces stresses cause bark to delaminate from wood
Operation	Logs fed in the higher side and are discharged as de-barked wood from the other end.	Force applied to logs based on species, log diameter, and log-condition (frozen or non-frozen)				A trunnion wheel supports and rotates individual logs.	A screening step then separates the wood from the bark.
Issues	If de-barking time is too short, logs are partially de-barked; if for too long, it leads to wood loss	Processing speed is inversely related to diameter. Soaking the logs in warm water improves de-barking performance significantly.			They tend to damage more wood than is preferable, hence often restricted to whole tree chipping and pulpwood production.	Potential use on wide logs; small to large logs and easy to difficult to de-bark species. A downside is the use of water, which might be reduced by filtration and recirculation	
Reference	Chahal & Ciolkosz, (2019, pp.2&3) citing Isokangas et al, (2006); Oman (2000).	Laganiere & Hernandez (2005); Ding et al (2012); Bassler (1987); Koch (1983).	Chahal & Ciolkosz (2019, p.3).	Chahal & Ciolkosz (2019, p.3) citing Gupta et al (2015)	Chahal & Ciolkosz, (2019, pp.3&4) citing Thompson & Sturos (1991); Hartsough et al, (2000); Watson et al, (1993); McEwan et al, (2017)	Chahal & Ciolkosz (2019, p.4) citing Gupta et al (2015); Grobbelaar & Manyuchi (2000)	Chahal & Ciolkosz (2019, p.4) citing Sturos & Erickson (1977); Mattson (1974)

10.7.4 *Addressing fire-impacted softwood pulplogs*

Logs are de-barked by logs abrading against each other in drum de-barkers. A range of tactics can be put in place to maximise the efficacy of such operations. (Note: there was a degree of tolerance to smearing's of soot on logs.) See Box 14.

Box 14: Addressing carbon on softwood pulplogs.

Log specifications:

- Small end diameter: Softwood log SED increased (e.g. to 120 mm) to reduce breakage risks.
- Straightness: Drum de-barking efficacy increased by excluding crooked or poor form logs allowing logs to better rub against each other.
- Log defects: Specific defects are excluded:
  - broken-end or split end logs (carbon could be on broken ends)
  - nil double leaders to increasing de-barking efficacy.

Operations of drum de-barkers.

- Stockpile management: Logs are stockpiled by broad diameter class and log source to increase uniformity.
- Log batching: Process logs batched by diameter to ensure that small logs can be processed for longer to facilitate efficient bark removal. When 'big' and 'small' logs are mixed, this increases the risk of breaking smaller logs.
- Duration: Logs are de-barked for longer to ensure that bark is removed.
- Water and dust management: Water is used as a lubricant of feed systems rather than as a cleaning agent of logs. It also assists as a dust suppressant.

10.7.5 *Addressing fire-impacted hardwood pulplogs*

Australian Paper has a long-history of addressing fire-impacted native forest logs and noted that there are fewer issues with fire-killed native forest eucalypts. To reduce the risk of carbon contamination, log specifications exclude logs with burnt bark attached, burnt knots and branches, and burnt dry scars (Australian Paper, undated). Exclusion of carbon-impacted logs is managed by the supplying state agency to provide a consistent product. This is built on cooperation between the company and the agency. All native forest eucalypt logs are managed in a single pile. Burnt plantation-grown hardwoods can have issues with small and retained branches. Dead branches are burnt back into stems and under the bark. This creates nodules of carbon within the tree wood. This results in burnt 'young' plantation hardwood trees generally not being salvaged.

10.8 Export woodchips as a specific example

10.8.1 *Objectives*

The objective is to provide 'fit for purpose' materials to markets and to maximise returns by supplying the highest value products (where fall-down markets exist). There is variation in tolerances to carbon impurities between different products, which allows downgrading to take account of carbon if it cannot be excluded from a supply chain (see Table 19).

10.8.2 *Stand stratification*

Eucalypt plantations harvested for export woodchips generally produce a single product. To maximise value recovery, the first step is to stratify stands based on level of fire impact and to focus on stands that are likely to de-bark efficiently and completely remove carbon. A key point is the degree to which fire has burnt through the bark into the actual wood. Where fire damage affects wood, logs are downgraded to 'natural forest woodchips' within limits of defined tolerances.

10.8.3 *Cut to length and static chipping*

Cut-to-length (CTL) logs are produced from trees processed at the stump, including de-barking. This provides an opportunity for logs to accumulate passenger carbon. For this reason, such stands are more likely to be chipped in-field. One strategy to reduce carbon contamination in CTL operations is to delay harvest until rainfall has reduced soil surface carbon (charcoal). While soil surface carbon can be addressed (or washed-off but at an extra cost); carbon from wood combustion cannot. In this case, logs would be downgraded to natural forest export woodchips. To manage this delineation, log inspection and monitoring is increased in the wood-yard.

10.8.4 *In-field chipping and flail de-barking*

Fire-impacted hardwood plantation logs can be processed on-site (in-field chipping). In-field chipping makes use of flail de-barking systems where whole trees are bunched and presented to the infeed. Trees are extracted with grapple skidders that keep one stem-end off the ground, minimising accumulation of passenger carbon on cut stem ends. Carbon can accumulate on bark and foliage. To maximise removal of carbon, an additional flail de-barking system can be added to the system infeed. If this approach is used, adequate spacing is required to allow monitoring of the quality of bark and foliage removal, and to identify any carbon embedded in the wood surfaces. To increase efficacy, system pressures are increased, making de-barking and de-limbing more aggressive, accepting a trade-off between wood-fibre losses and achieving maximum bark removal. Once produced, woodchips are delivered to an export facility with samples taken to verify carbon-free status.

10.9 Recommended best practices

10.9.1 *Pre-event planning*

Best practice 36: Define trigger thresholds for transition from dilution to batch strategies for log-yard and de-barking strategies.

Best practice 37: Understand fall-down market options for materials where adequate/effective bark management is not possible.

10.9.2 *Processing – wood yard management/de-barking, sawing, drying*

Best practice 38: Understand the potential for effective surge storage capacity on routine processing sites.

Best practice 39: Understand the best financial outcomes in a trade-off between more aggressive de-barking and fibre loss.

Best practice 40: Manage hygiene strategies in processing centres, including consideration/identification of all positions where bark may obscure sensors.

Best practice 41: Apply a light watering system to supress dust and particulate carbon from migrating from wood yards to other sections of a processing site. This should include management of site water run-off.

Best practice 42: Process fire-impacted logs differently to routine green logs due to heat baked on bark, carbon and reduced stem moisture content.

Best practice 43: Subject fire-salvage logs to an enhanced log specification to minimise risk of carbon contamination and to maximise de-barking efficacy. This should be included in routine log specifications to be triggered by a fire event, as agreed between parties.

Best practice 44: Segregate fire-impacted logs from fresh green logs to allow management of carbon risk, de-barking and blending onto stockpiles via chipping. This may include segregation based on diameter class to facilitate de-barking. If the scale of fire-impacted logs is beyond what is possible to blend in such resources, batching will be required and this is an individual site decision.

Best practice 45: Reduce the risk of carbon entering a woodchip pile by more aggressive management of de-barking equipment. This is facilitated by changes in log specifications and batching of logs into de-barkers.

Best practice 46: Determine the level (percentage) of fire-impacted logs processed and when a dilution strategy should be replaced with a batching strategy.

Best practice 47: Sacrifice some logs to increase log homogeneity for processing to address a range of fire impacts to trees and therefore logs.

Best practice 48: Segregate logs and batch process as a fundamental strategy to address issues associated with sawing of fire-impacted logs.

Best practice 49: Assess log moisture content and, if possible, determine whether logs contain compression fracture or fractures caused during harvesting. Include this information as an element of a log batching strategy.

10.10 Observations

Observation 36: Logs with lower moisture content may cause increased friction during drying and heat up saws. Such logs may have cracks and checking which can divert saws causing damage to saw blades.

Observation 37: Success in de-barking and removal of potential carbon contamination will impact market options where carbon sensitivity is a barrier to supply.

Observation 38: Determine and understand the impact of micro-organisms on bark adhesion.

Observation 39: Debarking is a critical factor when processing fire affected logs.

Observation 40: Develop a better understanding of MC and de-barking effort.

Observation 41: To assist planning for fire events develop a difficulty of de-barking index for standing trees and stored by species: fire impact X stand pre condition X time since fire X de-barking methods.

Observation 42: Bark adhesion variation with the different levels of fire impact to tree stems as defined by the fire impact classification system. This would then allow planning for salvage logging.

Observation 43: Impact of log wet-storage on bark adhesion and log de-barking strategies.

Observation 44: Trade-off between bark removal and fibre loss with more aggressive de-barking. This would include quantification of losses.

Observation 45: Log specifications to address passenger bark risk and to maximise de-barking efficacy. These should be agreed in advance of fire seasons.

Observation 46: Methods to detect and address carbon in woodchips.

11 Storage strategies – as standing trees (storage on the stump)

11.1 Summary

Storage on the stump allows direct delivery of harvested trees to processors; it is the simplest approach to fire salvage. Duration of storage on the stump combined with expected woodflows will determine whether dedicated log storage is required.

This strategy has been successfully applied throughout the long history of wildfire salvage. A critical point is to determine how long such storage is possible. Fire-impacted and killed trees dry from the top down, and become susceptible to bluestain development and subject to Ips attack. This can be used to define when to harvest. A starting point is to define stand damage and understand the effect of climate (temperate or tropical) and tree species following the initial fire impacts.

Harvesting of fire-impacted stands involves more risks, which can be compounded by any requirement to bring in outside contractors to undertake harvest and haulage. Harvesting costs can increase and there is a need for salvage premiums to address these increases. A fire-impacted forest can also create a workplace that can have an adverse impact on operators' mental health.

11.2 Introduction

A need to store logs can result from routine operations (e.g. in Finland; Whitehead, et al 2008, p. iii), fire events (e.g. as a result of the 1983 Ash Wednesday fire in Australia; Thomas, 1985), significant wind-throw (e.g. major storms in Europe from the 1990s to 2010; Lutze, 2014) or following salvage of insect-killed trees (e.g. mountain pine beetle attack in Canada; Whitehead, et al 2008). Storage methods vary with local conditions and experience. For example, in Finland, 3.5 million m^3/y of logs are stored under snow (Whitehead, et al 2008, p. iii); a North American operation included log storage under snow to prevent infestation of mountain pine beetle in green logs (Whitehead, et al, 2008, p.iv); and in parts of Europe, storm-damaged logs are stored in wrapping film to create a low oxygen environment (see Box 15).

More routine methods of longer-duration log storage include storage under sprinklers or submerged in bodies of water. A fibre storage strategy will seek to conserve resources at risk of deterioration by damage (e.g. bluestain and drying) for later when there is adequate processing capacity and willing markets. The primary aim is to store logs '*under conditions that minimize defects associated with shrinkage, end-checking, and attacks by fungi, bacteria, and insects*' (Forest Products Laboratory, 2004); to preserve wood quality; and maximise value recovery (Whitehead, et al 2008, p. iii). Taking a broader view, it was proposed that '*where there is an opportunity to store large volumes of quality logs, doing so for an extended period (more than one year) may help defer or moderate anticipated social, environmental and economic impacts in the areas most affected .....*' (Whitehead, et al, 2008, p. iii).

Timber can be stored for later use on the stump, as logs or as processed woodchips. The efficacy of each system is determined by a range of factors. Regardless of eventual strategies, all begin with a period of storage on the stump and this section addresses this element of fire salvage including harvesting and haulage considerations.

Box 15: Novel approaches to storm=damaged salvage log storage in Europe (Lutze, 2014, p.1).

Storage by wrapping in film**:** Storage by film-wrapping is based on the principle of air exclusion. For this the logs are wrapped in an air-tight film, usually, UV-resistant polythene film that is also commonly used in agriculture to wrap silage. There are currently two methods used – the Baden-Württemberg method and the Swiss method.

- The Baden-Württemberg method**:** With this method the timber is wrapped in hermetically sealed plastic film and stored in an atmosphere that is as free of oxygen as possible. Natural processes such as breathing and fermentation reduce the oxygen level under the film to almost zero.
- The Swiss method**:** The Swiss method dispenses with the plastic film on the ground under the stack. The wrapped timber is kept permanently moist by the exclusion of air, thus preventing deterioration in the quality of the timber.

11.3 Principle and strategy

There is no single or simple solution to a fire salvage. Maintenance of trees standing on the stump and delivery direct to a processor is the simplest and cheapest method. Storage on the stump can be a standalone strategy or be part of a more complex storage strategy. United Kingdom experience with harvest and water storage of wind-blown trees concluded that: *'... although the technique worked well with softwoods and hardwoods, storage of windblown trees 'on their roots' is likely to be the most logical option in most circumstances for timber other than pine* (Webber & Gibbs, 1996, p.X). Industry notes that water storage of fire-killed timber should only be undertaken where necessary due to cost and the risk of further log degrade. The aim of a combined strategy is to increase the salvage period; for example, fire killed *E. regnans* from the 1939 fire could be stored as logs under water sprays or in ponds as well as on the stump (Wright & Grose, 1970, p.149). Storage on the stump prior to entry into a longer-term storage under water sprinklers provides time to harvest and deliver logs to a storage facility. There is a need to determine at what point it is too late to harvest, based on market requirements, but there is a lack of clear evidence as to how to define this point. After the 1983 Ash Wednesday fires in south-east South Australia and the 1994 Beerburrum fires, 960,000 m^3 (50.5%) and 200,000 m^3 (33.3%) respectively of logs salvaged were delivered directly to processors (Table 21). After Ash Wednesday in the Mount Lofty Ranges. 125,000 m^3 (69%) were processed by local mills. Following the December 2006 Billo Road fire, the bulk of sawlogs were harvested by August 2007 with local domestic processors able to absorb the salvage material without the need to store logs, other than on the stump.

11.4 Duration of storage on the stump

11.4.1 Determining when to harvest

Salvage harvest schedules can be complicated, with an interaction of burn severity, crop value, markets, equipment and seasonality (Box 16). Duration of storage on the stump is a matching of:

- Markets and capacity: Agreement on the maximum rate of processor acceptance of fire-impacted logs and availability of contractor capacity to deliver logs:
- Biological limits: How long resources remain 'fit for purpose' on the stump. This can include recognition of top-down stem degrade and potential to downgrade upper stem logs or sacrifice of these logs to extent the biological limits.

When plantations are affected by fire, the prospect of preventing loss depends largely on the industry's ability to utilise the trees before they deteriorate beyond 'fit for purpose'. This depends on the size of trees, the volume of wood affected, and the rate at which wood degrades, balanced with processing capacity. A fundamental question is the length of time trees can be stored on the stump. Industry recognises when it is too late (e.g. reduction in log quality) but the challenge is how to define when it will become too late. Once carbon issues have been addressed (e.g. by log grades and de-barking), all other issues relate to moisture content, which is the driver of secondary impacts of insect attack, fungi discolouration and bacterial degrade. In simple terms, there is no standard timing or single simple method to determine when to cease storage on the stump. Trees need to be monitored for moisture content and bluestain development.

Box 16: A snapshot of issues to address in determining how long to store stems on the stump.

There is a sequence of events and deterioration of standing trees post fire:

1. Expected woodflows to take account of potential reductions in resource due to fire impacts.
2. Market willingness and capability to accept the expected woodflows.
3. A switch from processing green un-impacted trees to impacted trees.
4. A change to log grade system to improve de-barking efficacy and reduce risk of carbon contamination.
5. A triage system based on fire outcomes.
6. With time a potential to sacrifice of upper stem logs that have dried too much

11.4.2 Past events

The outcomes of past fire events are the result of interaction between fire intensity and impact, timing, tree size and biological damage agents. The following are examples:

- *P. radiata* (1965): After a 1965 fire, little sawlog volume was lost in the first year after the fire, but after this period rapidly increasing defects seriously affected yields (Wright & Grose, 1970, p.157). Defects developed as the wood dried. In the first two years after a fire, bluestain was the most important defect with insect damage and decay subsequently developing (Wright & Grose, 1970, p.149).
- *P. radiata* (1983): After the Ash Wednesday fire, logs were harvested and processed after two years of storage on the stump. Deterioration in wood quality of standing trees commenced one and two years after the fire (Atyeo, 1985, p.1).
- Southern pines (1994): The 1994 Beerburrum fire experience suggested a maximum six month windowfor of harvest and storage on the stump.
- *P. radiata* (2006): Nine months after the Billo road fire, sawlogs were viably processed; the onset of cooler weather late in the salvage period would have assisted in this.
- South African softwoods (2007): Based on this experience it can be safely assumed that larger trees killed by fire will retain relatively high moisture levels for at least 4-6 months, provided the bark layer remains intact. Deterioration will start primarily in the stem tops (Malan, 2011, p.7).
- *P. radiata* (2019): 12 months after a fire in south-west WA sawlogs were viably processed.

An important consideration is that while a log can be processed adequately after a period, the key issue is change in timber strength grade recovered. Observations can be the perceptions of an individual and may not include all evidence (e.g. while a log may appear sound and process into clean boards, timber grade recovery is a critical issue). Box 16 presents a snapshot of degrade in a tree over time since a fire. Experience in South Africa suggested that, despite marked moisture-loss, moisture content remained too high for many months after the fire to allow serious deterioration. Deterioration due to bluestain and surface checking began in parts of the stem where moisture content was below FSP (e.g. near some branch bases and where bark has been damaged) (Malan, 2011, p.7). While each situation is different, after the 2006 Tumut fires, bluestain began at c.110% to 120% $_{\text{DRY BASIS}}$ whole tree moisture content (see Figure 24). This occurred after 10 weeks for one site and 14 weeks for two sites and for three sites by 23 weeks (one site did not fall below c.130% $_{\text{DRY BASIS}}$ by 23 weeks). After a fire in Western Australia, bluestain was present in logs with a log moisture content of c.100% to 105% $_{\text{DRY BASIS}}$ (see Figure 25) which occurred 8-10 weeks after a fire (see Table 21).

Box 17: A snapshot of the sequence of degrade over time of trees standing on the stump (indicative time lines are presented).

There is a sequence of events and deterioration of standing trees after a fire:

1. Trees commence to dry from the upper stem downwards.
2. Ips attack can commence within days.
3. Bluestain can be present within one month of a fire.
4. The upper stem can be too dry to recover by 12 months after a fire.

11.4.3 Impact of season

The timing of a fire relative to the seasonal variation in access for harvesting will drive development of a fire salvage strategy and harvest plans. A fire at the start of summer will allow a longer period of harvest than a fire at the end of summer or in autumn, when winter closures and/or restrictions may affect harvesting.

This helps define the period of storage on the stump. The timing of a fire and subsequent seasonal conditions will affect the rate of tree drying (deterioration) and therefore duration of storage on the stump. For example, in South Australia while a fire in March or April may limit harvest over wetter months, cooler winter conditions will slow the rate of moisture losses. Winter rains will also reduce the amount of free carbon on a site reducing the risk of passenger carbon.

11.5 Tools to help classify fire impact and temporal change

11.5.1 Initial fire mapping and impact classification

Initial mapping and classification of fire impacts creates a start point for salvage planning and decision making (Box 18). Fire-caused tree mortality results from events before, during and after a fire (Hood et al, 2019, p.1). Mechanisms include fundamental biophysical processes linking fire behaviour and tree mortality (Michaletz & Johnson, 2007, pp.500-501). Tree mortality is a result of multiple stressors: competition, pest and pathogen activity, and short- and long-term weather fluctuations (Das et al., 2016 cited in Hood et al 2018, p.6). Tree mortality from surface fires results from several complex and coupled processes (Ryan & Reinhardt, 1988 cited in Michaletz & Johnson, 2007, p.506; Parker et al, 2006, cited in Michaletz & Johnson, 2007, p.506), which can be direct (e.g. heat transfer and resulting tissue necrosis) or indirect (e.g. altered physiology, insect attack and pathogenic infection) (Michaletz & Johnson, 2007, p.506). Fire intensity (see Table 6) will result in an immediate visually apparent impact that can be used as a proxy for intensity, and a range of fire impact classification systems have been developed (see Table 10 to Table 13).

There are two components to impact: individual tree impact and a collective impact to a stand or compartment of trees. Impact mapping is generally undertaken soon after a fire and will classify impact to a stand. Tree death can occur in trees with minimal impact (e.g. class 2 for Queensland with light to moderate damage, see Table 10). Such trees still lose moisture and dry out (see Figure 18). There can be variation in subsequent moisture loss, even with the same tree impact classification, driven by site (see Figure 17). Fire classification, while useful, does not provide a foolproof metric to determine whether or not to store on the stump.

Box 18: A proposed approach to initial fire mapping and ongoing monitoring.

There is a sequence of events and deterioration of standing trees post-fire:

1. Initial fire impact statement:
    a) Fire impact classification: Fire impact is classified as per
    b) , considering crown and stem damage to better predict fire outcomes.
    c) Fire impact mapping: Fire impact mapping should consider a broader range of attributes (see Figure 13).
2. Temporal changes:
    a) Moisture content change: Stems drying from the top down and where bark damaged.
    b) Ips attack: Beetles bore into tree bark.
    c) Bluestain: Once tree moisture content reaches threshold levels.

11.5.2 Temporal changes: tree moisture content, Ips attack and bluestain

Patterns of standing tree moisture content loss are discussed in Section 8, and presented in Figure 16 to Figure 20. Stem moisture loss commences with tree death and when the outer layers of stem-wood reach FSP numerous surface checks form. The rate of deterioration becomes '*a vicious interplay between further moisture loss, accelerated by the rapidly expanding surface area (caused by the radial extension of some of the checks into the wood), combined with further invasions by wood degrading organisms such as beetles, termites, staining and decay fungi*' (Malan, 2011, p.2). The effect of retained bark in curbing moisture loss from the wood was demonstrated by Stöhr (1982) (cited by Malan, 2011, p.8). Patterns of standing tree impacts by insects and bluestain fungi have been discussed (see Figure 22 to Figure 25). As stem moisture content reduces insect attack and bluestain increase.

Given the biology of bluestain and Ips as a vector, monitoring of Ips levels can help determine when to harvest. A harvest trigger point was set for plantations burnt during the Beerburrum fire at 10% of trees infested with Ips. Once stands reached this level they were scheduled for harvest (Wylie et al, 1999, pp.149&150). Ips attack began six weeks after the fire and in one plot exceeded 10% of trees by eight weeks, and in all other plots by 10 weeks (Wylie et al, 1999, p.149). However, development of bluestain is driven by stem moisture content (see Figure 24 and Figure 25). Tree moisture content will change over time since a fire (Figure 17 to Figure 20) and with position in the stem, deceasing from the top down (see Figure 16). Data on bluestain development with wood moisture content can be based on whole tree averages (see Figure 24) but this masks a variation with tree height. As yet there is no simple solution to determining tree moisture content variation with height. Apart from Ips issues, tree and log moisture content will drive impacts and use of logs by processors and this needs to be addressed. The outcome is an initial fire impact map updated with information from an ongoing monitoring program.

11.6 Harvest and haulage

11.6.1 Log-handling and management

Log-handling during storage requires broadly the same steps as routine wood-yard management. A key difference is that there is an imperative to deliver logs to processors and enter them into stockpiles and under sprinklers as soon as possible. A second consideration is management of log stocks within stockpiles (e.g. first in first out, aggregation by fire impact matrix classification, aggregation by size classes). Issues to consider include.

- Core requirements regardless of intent:
    - Logs to site gate: Felling, extraction and haulage, including any price premiums.
    - Log receivals at site gate: Truck unloading, extra log inspections and log stacking (including inventory management).
- Additional requirements of log storage:
    - Operating costs: Water, insurance, staff, contractors, maintenance, fuel and electricity costs.
    - Log recovery: The cost of log recovery and loading on trucks, which may include some form of wash down.
    - Log transport: Log transport from the site to a processing centre.

Workforce capacity and training will be a key success factor towards safe and efficient operation of a site. Health, safety and environmental concerns (e.g. erosion and water management) must be addressed.

11.6.2 Harvest planning

Fire salvage harvesting includes additional risks to routine harvesting and specific risk assessment is required to address issues such as hot stump holes, trees broken in fire storms, effect of carbon on operators (e.g. respiratory tract impacts).

Whole-of-industry engagement and collaboration is critical to planning fire salvage. This can be facilitated by pre-planned response scenarios and strategies to assist all parties to understand the needs of all other parties. Development of an integrated approach to managing fire-impacted sawlogs, pulpwood, sawmill chip and bark sales is required, given the interdependence of the industry. Planning should include an understanding and quantification of log types by markets to allow development of product schedules for log storage or supply direct to processors. Once woodflows are understood, harvest and haulage capacity is required to deliver logs to processors or storage sites. A key decision is which trees to salvage and in what order. It is prudent to consider the cost of re-establishment of sites post-harvest and if it is more cost effective to salvage a marginal site to free up a site for re-establishment or to conduct a stand-alone clean-up operation.

Past fire salvage experience suggests that a key limiting factor is access to contractors to undertake works if expected woodflows are well beyond business as usual.

A first step is to make use of existing well-established contractors and customers to their full capacity (e.g. increased shifts). Supplementary contractor capacity may need to be transferred from unburnt areas or interstate. For example, after the 1994 Beerburrum fire, an unprecedented ‘armada’ of log harvesting and haulage machinery was assembled and deployed. An emergency tendering process was implemented, with funding managed at short notice. Tenders were assessed and logging contractors were appointed from Tasmania, NSW, South Australia and (mostly) Queensland. Guidelines for direct employment of logging contractors for this type of operation had to be developed and implemented, as well as systems for monitoring of contractor performance, recording of salvage inventories and organisation of contractor payments (DPI, 1995, p.4). Development and implementation requires:

- Rapid ramp-up harvesting capacity in a measured manner to match capacity in all other aspects of a salvage operation (e.g. make sure that processors and/or storage capacity is ready to receive and manage logs).
- To avoid log degrade due to moisture loss, insect attack and bluestain, logs are better stored on the stump until all harvest aspects are in place.
- Recognition of changes in wear and tear on all equipment (e.g. blunting of cutting equipment) is required in contractual arrangements. This may include a requirement for equipment modification.
- There is a need for a consistent approach to managing contractor payments.
- Appropriate harvest strategies are required to minimise log contact with the ground and the possibility of passenger carbon. For example, eucalypt plantations can be harvested with in-field chipping systems after whole tree extraction (to eliminate de-barked logs onto the ground). Use skidders to elevate one end of fallen trees off the ground during extraction.
- It is possible for harvest crews to undertake selected long-butting to reduce carbon impacts.

11.6.3 Log specifications and making

NSW has developed a fire-impact specific set of log specifications, which allows acceptable logs to be identified, maximising de-barking and reducing carbon contamination risk (Forests NSW, 2007). Canadian experience suggested that tree length logs rather than cut-to-length product reduced log drying (Watson & Potter, 2004, p.476). In contrast, experience from Ash Wednesday strongly recommended that logs intended for storage should be cut to common customer lengths rather than storing stems for later processing (Thomas, 1985, Appendix A). Logs should be sorted prior to transport into ‘heavily’ burnt (down to the wood fibre), and ‘lightly’ burnt. An option is that butt logs damaged by ground fires can be long-butted to improve value recovery; if not, stems can be treated as routine.

11.6.4 Increased costs and cost premiums

Salvage harvesting can increase wear and tear on harvest machines due to soil and carbon affecting components such as machine tracks, felling head bars, dust filters. Fuel consumption is increased and there is an overall loss of productivity. Experience suggests that an increased cost of harvest is compensated by salvage premiums. A range of basis and values were noted: \$2/m^3 evolved to a 5% premium on standard harvest costs, with recent examples of a 7% to 12% premium (industry insights). Each situation will be different (e.g. scale, breadth, and market and operating environments) so increased cost elements, such as on-costs associated with shifting (floats), machine re-tooling, accommodation or travel allowances, need to be defined. A higher cost of salvage can affect the value of a plantation, and strategies and plans should be tested by benefit-cost analysis.

11.6.5 Issues with harvesting

Log recovery from fire-impacted trees can be reduced due to mechanical damage to stems. German experience with windstorms found trees that had undergone severe stress may have internal failures that are ‘*sometimes difficult to recognise (slip planes in secondary tracheid walls)*.’ Short fractures and transverse compression failures in logs from windblown trees are well known (Liese, 1984, p.129). Evidence from South Africa indicated compression failures in logs most likely developed from strong winds during fire storms (Malan, 2011, p.31). With time and lowering tree moisture content, there can be an increase in stem shattering and compression failures on felling due to nil sail area to slow down a tree as it falls (Malan, 2011, p.31). For example, felling *P. radiata* one year after a 1966 fire shattered about 5% of merchantable volume, with most of the affected wood in the upper bole of larger trees (Wright & Grose, 1970, p.156). This result was with harvesting techniques at that time (e.g. hand felling). Upper stem loss is suspected to be due to stem drying.

11.6.6 Storage at the roadside: Softwood sawlog and pulpwood systems

Any logs stored on a roadside are likely to be damaged by a fire. Post-fire there is an option to store salvage logs on the roadside. This is a short-term tactic, due to drying and rapid biological degrade (e.g. bluestain). The actual harvest combines tree felling and log processing at the stump (under a CTL system). At any time there may be logs remaining in the forest/plantation at the stump. Processed logs are extracted to roadside for storage prior to log cartage and/or for loading directly onto trucks. There will also be a proportion of log stocks held on log trucks. There are many variations and combinations based on the specific systems used.

An indicative sawmilling operation may take deliveries for c. 235 days per year, depending on site licences etc. Delivery days may be affected by fire restrictions and season wet weather issues. Contractor supervision seeks to limit storage prior to receival at processors, although it can happen from time to time. The softwood industry suggests that in general 1-3 days deliveries of sawlogs remain in this transient state. This accounted for 0.5% to 1.0% of mill annual intakes in one example. In another example, a large-scale plantation manager suggested that 1% of log annual outputs be held at roadside and 3% in the forest (a total of 4%). In regards to roadside stocks, log stack height and length will dictate the volume able to be stored: at normal 2 m height with 6 m logs, a 100 lineal metre log dump would hold 600 m^3 of logs (assuming a stacking efficacy of 0.5 m^3/m^3). This suggests that while there is capacity to increase such stocks, the ability to cope with a significant surge is limited.

11.6.7 Road construction and maintenance, and haulage

Road access into fire-impacted areas must be adequate for safe log-truck use. The time taken to complete road upgrades will be defined by required regulatory approvals prior to roadworks and the time to undertake the works. This can be expedited by pre-planning of contingency processes to seek such approvals and access road construction and maintenance plant, equipment and materials. Road construction and maintenance will require rock, gravel and culverts. As an example, salvage of logs and delivery to the Beerburrum fire storage area commenced 2-3 months after the fire (DPI, 1995, p.5). Post-fire increased truck movements can cause road congestion and stress to other road users (particularly in local communities). In the case of the Beerburrum operations, at the peak (beginning of February 1994), 320 truckloads carrying more than 8000 t of logs were arriving each day (one truck every 2-3 minutes). A total 400,000 m^3 of logs were stored (DPI, 1995, p.5). Management of haulage must control of potential overloading on roads.

11.7 Occupation, health and safety associated with harvest and haulage

11.7.1 Initial occupation, health and safety considerations

A salvage plan must address OHS issues for the workforce. Harvesting of fire-impacted stands will be different to harvesting routine (green) plantations. For example, a burnt tree may lack the sail area created by green foliage with different behaviours during felling (e.g. much faster). All operators will require orientation to such changes. A harvesting of fire-impacted trees manual is required. A burnt forest may also affect staff mental health; it could be considered as a depressing workplace, particularly where operators become reluctant to exit machines during lunch times and social interaction with colleagues is reduced. Increased hours of operations must be within legal limits and fatigue management will be an issue. This can be compounded where contractors have lost plant and equipment.

11.7.2 Managing high intensity harvesting

Additional shifts with existing equipment will include new operators, which creates familiarity issues (e.g. with the specific machines and operating environment). A recruitment strategy can partly address issues and risks, but there is likely to be a need for intensive and effective training programs to orientate new staff.

It is possible that generic machine operator skills could be added to (e.g. from the mining sector) but the nuances of forestry operations will still need to be addressed. Addition of contractors who are new to an area brings a broad range of challenges and risks to address. While staff are highly skilled in their own environment, changes in topography and ground condition (including fire impacts) and potentially tree species will create unfamiliar territory.

There is potential for concentrated harvesting in a location and safe spacing will be required. This issue presents a greater risk with truck movements and log transport where drivers may lack local knowledge (e.g. of road conditions) and experience in local environments (e.g. weather conditions). Log truck movements create a significant risk where roads are shared with local communities and other road users.

11.7.3 Specific risks

There are a range of specific risks associated with harvesting fire-impacted trees. Initial considerations are presented in Box 19.

11.8 Environmental considerations associated with harvest and haulage

Harvest of plantations is controlled by State-based regulations, including codes of practice that include requirements to protect environmental values. Depending on fire type (Box 6) and intensity (Table 6), a plantation will be changed from a routine site. For example, all ground cover and duff layers may be removed by fire, exposing mineral soils to erosion and making machinery less stable. To address operational requirements, harvesting prescriptions need to be modified. Water quality maintenance is a risk, with increased risk where a fire occurs prior to winter without adequate time to allow germination of ground covers. Remedial works associated with roads adjacent to areas to be harvested requires recognition of increased run-off associated with denuded landscapes. Machine movements and harvesting set-backs from drainage lines are considerations. Harvest planning at the coupe level requires a detailed strategic risk assessment focusing on high risk areas, such as steeper sections and erodible soils.

Box 19: A summary of specific risks associated with fire salvage harvesting.

1. Health impacts: There can be impacts of carbon on operators (e.g. respiratory tract impacts) and increased overall dust (e.g. impacts on eyes).
2. Ground conditions: Depending on fire type (see Box 6) loss of ground cover, dust and charcoal management for machines and operators is required.
3. Residual fire activity: Depending on the time since a fire, hot stump holes can remain and there can be a risk of re-ignition.
4. Increased activity: Increased activity in a concentrated area will increase interactions between contractors and local communities.
5. Infrastructure impacts: A fire impacted area will have damage to infrastructure and while initial repairs will have addressed strategic bridges and crossing, it is possible that not all bridges and crossings have been addressed. This limits access and egress options and all parties need to be made aware.
6. Familiarity: It is highly likely that out-of-town operators and truck drivers will be required and they will need induction, awareness and coaching on local conditions.
7. Tree conditions: Trees can be broken in fire storms, creating a tangle of stems to address. With time after a fire, trees lose moisture and become brittle, changing behaviour during felling.

11.9 Recommended best practices

11.9.1 Pre-event planning

Best practice 50: Prepare a contractor capacity plan and strategy that can be shared between industry parties as part of pre-summer fire pre-preparation planning.

Best practice 51: Establish a memorandum of cooperation between parties defining processes / protocols to plan fire event responses.

Best practice 52: Develop specific plans, e.g. Workforce capacity and training; Health, safety and environmental concerns (e.g. erosion risk and management); Community support.

Best practice 53: Develop a portfolio of pre-planned administrative systems to support a fire salvage operation.

11.9.2 Fire Impacts (classification, physical, biological)

Best practice 54: Develop standard monitoring protocols for plantations post-fire to feed information into ongoing management of fire salvage operations. Monitoring of insect and fungal attack, and moisture content can support the scheduling process in order to prioritise susceptible stands. Care is needed to achieve an ‘agile’ and responsive process, and avoid a chaotic and reactionary one. Given the biology of bluestain and Ips as a vector, monitoring of Ips levels can be used to determine when to harvest.

11.9.3 Salvage planning – triage, harvesting and logistics

Best practice 55: Ensure that resource modelling systems used to develop fire response plans have the capacity to address expected losses due to fire impacts such as compression fractures, brittleness and butt log direct fire impacts.

Best practice 56: Address resource losses due to harvesting damage caused by brittle wood. This should include consideration of compression fractures created by fire storm winds and stem drying.

Best practice 57: Change scheduled/planned harvests are part of a salvage response plan. This will necessitate a review of road construction and maintenance, harvesting and haulage requirements.

Best practice 58: Assess may require regulatory approvals, access to materials and contractor capacity as part of the road construction and maintenance requirements. The protocols and requirements should be in place as part of pre-fire season planning and development of a response manual.

Best practice 59: Match the triaged change to harvesting schedules with upgrade and construction of roads, which will dictate the sequence of harvest and planning of operations.

Best practice 60: Re-allocate harvesting and haulage capacity from current green harvest operations, which will require a degree of negotiation. The next step is to increase harvesting hours of operation and/or bring in contractors from other locations. A high degree of coordination and cooperation will be required.

11.9.4 Storage

Best practice 61: Storage on the stump and direct delivery to market is the cheapest option.

Best practice 62: Monitor standing trees to assist with harvest planning to minimise deterioration below intended log grades.

11.9.5 Salvage harvesting and logistics, environmental and safety management

Best practice 63: Develop and include fire-impacted log specifications in all log specifications agree between parties to a wood supply agreement.

Best practice 64: Develop a harvesting manual as an agreed set of best practice processes and protocols to undertake fire salvage harvesting works.

Best practice 65: Develop a protocol to address road construction and maintenance requirements as part of a fire response plan. This should include linkages to regulatory authorities and their processes and protocols.

11.9.6 Processing – wood yard management / de-barking, sawing, drying

Best practice 66: Develop and include fire response clauses in all contracts associated with harvesting and supply of logs to processors to expedite the response processes to fire. Develop standard clauses in harvest contracts to take account of increased wear and tear.

11.10 Observations

Observation 47: Regional fire response plans should consider socio economic impacts in addition to salvage harvest planning.

12 Storage strategies – log stockpiles

12.1 Summary

Following catastrophic events (e.g. in Europe windstorms or in North America due to mountain pine beetle), a large volume of logs needs to be stored in dedicated wet storage areas. That experience can inform post-fire storage.

A log stockpile site should be 'fit for purpose' with adequate access, area and water supply. Australia has two recent experiences with storage of large volumes of softwood logs (after the 1983 Ash Wednesday fires and the Beerburrum fires in 1994). A point of caution is that successful regimes are specific to the conditions of a fire event and subsequent storage.

A key point is that with correct storage under sprinklers, Ambrosia beetles will be inhibited from infesting the logs, any Ips bark beetle activity will cease and bluestain can be maintained at the level present at the time of initiating watering. Storage under sprinklers should also protect the logs from fungal decay (especially low durability softwood species), being mindful that in specific circumstances some fungi can grow and cause decay in highly saturated logs, e.g. *Rigidoporus lineatus* at the Beerburrum log storage facility in 1994).

Logs should be segregated based on usual products/sizes rather than as stems to facilitate simpler recovery and supply to the market. Log stockpiles should be arranged to maximise protection from wind and to facilitate recovery. They should be stacked directly onto the ground. A base may be prepared using crushed rock or geotextiles to facilitate machine access, water management and to reduce logs sinking into the soil. Successful storage has been achieved with log stockpiles up to 6 m high with water applied at a rate of 100 to 150 mm/day (there is no basis for this rate, but it was successful). It is essential that water application is continuous to maintain a constant film of water across log surfaces, which will suppress ethanol release and ambrosia beetle attack (a mechanical barrier). Logs should be stacked with flush ends to reduce risk of eaves and logs beneath drying out (and to maintain a water film).

Irrigation systems require specific professional advice and must be robust and reliable with built-in redundancies. It is possible that advances in irrigation, monitoring and control systems can contribute significantly to storage success. Water quality is only an issue where it affects the watering system (e.g. minerals that can erode the system or impurities that can block sprinkler nozzles, as can algal growth). Logs can be watered with saline waters, waste waters or fresh water. The most important point is to have secure and reliable access to water.

There are also a range of regulatory issues that need to be addressed.

12.2 Introduction

Storage on the stump and direct delivery to processors is the cheapest response within time limits defined by log quality. If processor capacity and markets cannot consume the quantity of logs to be salvaged before they degrade, a storage strategy will be required. As a result of past catastrophic events, there is a significant body of knowledge about wet storage of salvaged logs. South African experience notes that '*water spraying and sprinkling was found far more effective to control stain, decay and drying defects, provided logs were kept completely wet all the time by ensuring that the wetting system is properly functioning all the time*' (Malan, 2011, p.21). While wet storage has been successful, UK experience provides a point of caution: '*In future, water storage should be considered a major option whenever and wherever large quantities of pine are* *rendered vulnerable to stain and decay. However, although the technique worked well with softwoods and hardwoods, storage of windblown trees 'on their roots' is likely to be the most logical option in most circumstances for timber other than pine'* (Webber, et al, 1996). A decision to wet store fire salvage logs requires a critical analysis of facts, costs and requirements. This section addresses storage of fire-impacted logs under wet (sprinkler) storage conditions.

12.3 Past experience with wet storage of log stockpiles following catastrophic events

European forest managers have experience with significant salvage events. For example, a large-scale multi-year storage event followed hurricane Gudrun (January 2005), which resulted in 75 million m^3 of wind-throw timber in southern Sweden (Jonsson, 2007, cited by Whitehead, et al 2008, p.12). The volume was approximately equal to a year of harvest for the entire country. In some areas, the equivalent of 20 years of harvest were felled in a single night (Donoghue et al, 2006b cited by Whitehead, et al 2008, p.12). The resource had an estimated gross value of more than €20 billion (Björheden, 2007 cited by Whitehead, et al 2008, p.12). Hurricane Gudrun was not a once-off, with storms Vivian, Wiebke and Lothar in the 1990s, and Kyrill, Klaus and Xynthia between 2007 and 2010 all affecting European forest and timber industries, resulting in several million cubic metres of wind-throw timber in each case (Lutze, 2014, p.1). Windstorm damage is inevitable and should be expected. In a similar manner, and based on increasing fire frequency (see Figure 4), fires are to be expected and responses to log storage should be planned in advance.

The following is a timeline of specific examples of Australian and overseas wet-storage of logs:

- <u>Germany (1972)</u>: Following a severe windstorm in 1972, wet storage of approximately 1.39 million m^3 of logs was the largest storage up to that time (Clifton, 1978; cited by Liese, 1984, p.119).
- <u>Ash Wednesday (1983)</u>: After the February 1993 fires, 16,000 ha of *P. radiata* plantations burnt, with 1.9 million m^3 of logs affected. A total of 960,000 m^3 was delivered direct to processors, 405,000 m^3 of logs were stored under sprinklers and 353,000 m^3 stored in a lake (Thomas, 1985, p.1).
- <u>The United Kingdom (1988)</u>: A gale in October 1987 resulted in 4 million m^3 of wind-throw in the south of England. Based of successful storage in Denmark and Germany, a decision was taken in early 1988 to store 70,000 m^3 of *P. sylvestris* (Scots pine) and *P. nigra* (Corsican pine) sawlogs under water sprinklers to protect them from fungal degrade (Webber & Gibbs, 1996, p.ix).
- <u>South Africa (1989)</u>: The first wet storage facility in South Africa was set up after a fire destroyed c.2000 ha of softwood plantations in October 1989. Salvage logs were cut into 6.3 m lengths and stacked in rows. An agricultural sprinkler system was installed on top of the stacks and water was continuously applied at 75 mm/day for nearly a year. In total, 9624 m^3 of timber was preserved this way (von dem Bussche, 1993 cited by Malan, 2011, p.21).
- <u>Queensland (1994)</u>**:** In September and November 1994, wildfires burnt 1200 ha and 3600 ha respectively through the Beerburrum area. The September fire damaged government pine plantations in the largest such occurrence in the 70-year history of softwood plantation management in Queensland. The November fire burnt through government plantations. A total volume of 650,000 m^3 was impacted (DPI 1995, p.2&6).
- <u>New Zealand (1995)</u>: On 1 August 1975, north-westerly winds (180 km/h) passed over parts of the South Island, affecting some 44,000 ha of plantations and shelterbelts in the Canterbury area (Wilson,

1976, p.136). Approximately 10,700 ha of merchantable *P. radiata* (age 40-45 years) were blown down, containing c. 2.2 million m^3 sawlog (Wilson, 1976, p.136). Storage of logs for up to 4½ years was based on favourable experience in similar situations (documented by Clifton, 1978).

- Sweden 2005 &2006: In response to catastrophic windstorms in 2005 and 2006, large stockpiles of the most valuable logs were stored for use up to four years later. Government, industry and landowners collaborated in implementation of these measures to further their diverse interests. (Whitehead, et al, 2008: p. iv).

Wet storage of logs has proved a reliable method of long-term protection of log quality for large quantities of logs resulting from catastrophic events. Of particular interest are successful processes implemented in other countries (Wilson, 1976, p.136; Webber & Gibbs, 1996, p.ix). Potential for post-fire storage has been noted by overseas authors (Liese, 1984, p.133). A point of caution is that experiences are not always transferrable (e.g. temperate Ash Wednesday to tropical Beerburrum) (Johnson, 1996, p.1). A further consideration is differences between fire-killed trees and those impacted by wind or beetles.

12.4 Storage in dedicated log storage facilities

After most fires in Australia in recent years, additional log storage has been avoided by balancing storage on the stump with direct delivery to processors. For example, in 2006, a fire near Tumut (NSW) burnt 8000 ha impacting 1.1 million m^3 with 550,000 m^3 of sawlog salvaged and delivered directly to processors. Australia has had few large-scale fire salvage events in the past 40 years requiring storage of logs (see Table 21 for two examples). Details of the storage sites are shown in Table 22. After the 1983 Ash Wednesday fires, 350,000 m^3 of *P. radiata* logs were recovered in the Mount Lofty Ranges near Adelaide with 45,000 m^3 put into two sprinkler storage areas, using waste water from sewage treatment plants. Some logs in stockpiles in the South East of SA were kept under sprinklers for 10 years to allow managers to spread out the impact of fire and to cover expected subsequent gaps in green log availability (industry information). Following 1994 wildfires in Beerburrum, 600,000 m^3 of southern pine logs were salvaged and 400,000 m^3 were stockpiled under sprinkler irrigation (Hood et al, 1997, p.139).

Table 21: Two examples of fire salvage volume in excess of what could be absorbed by local processing capacity (South Australia based on Thomas, 1985; Queensland based on DPI, 1995, p.5).

Fire event	Ash Wednesday, South Australia.	Beerburrum, Queensland
Total volume (m^3)	1,900,000	600,000
Direct to processors (m^3)	960,000	200,000
Sprinkler storage (m^3)	405,000	400,000
Lake storage (m^3)	535,000	0

12.5 Log stockpile management objective: moisture content and water

12.5.1 Sapwood moisture content objectives

The objective of wet storage is to maintain or increase moisture content in logs (Liukko, 1997 cited by Olsson, 2005, p.5) and, more specifically, to maintain sapwood moisture content (Whitehead, et al 2008, p. iv) for protection from insects and fungi (Syme & Saucier, 1995, p.2). A further consideration is maintenance of log mechanical and processing properties. This is regarded as the '*decisive factor for successful protection of logs in storage*' (Liese 1984, p.125). Application of water to log stockpiles creates an enhanced environment to reduce the rate of log moisture loss (Nolan *et al.* 2003, p.3-6): *'... spraying the whole log pile with water on a regular basis. In this way, the logs are kept wet and the water evaporating off the logs and surrounding area lowers the air temperature and raises the humidity.'* This avoids checking as a result of drying-out (Olsson, 2005, p.5) and infestation with bluestain fungi. Overseas experience aimed to maintain sapwood moisture content at 100-120%$_{\text{DRY BASIS}}$ (Nylinder, 1950 cited in Olsson, 2005, p.4; Syme & Saucier, 1995, p.2). In some examples, target sapwood moisture content was species specific: for *P. sylvestris* (basic density of 490 kg/m^3) a minimum sapwood moisture content of 108-120% $_{\text{DRY BASIS}}$ was required (Liese, 1984, p.125). Change in sapwood moisture content under sprinkler storage has been documented: in New Zealand, sapwood moisture content initially declined to 107% $_{\text{DRY BASIS}}$ in September 1976, then increased to 160% $_{\text{DRY BASIS}}$ by April 1978 (Clifton, 1978 cited in Milligan, 1982, p.236); log storage experience in the south-east of South Australia noted an increase in log sapwood moisture content from 104% $_{\text{DRY BASIS}}$ (May) to 138% $_{\text{DRY BASIS}}$ (October) (Thomas, 1985, p.11).

Table 22: A summary of recent large-scale Australian log wet storage responses; Ash Wednesday (based on Thomas, 1985) and Beerburrum (based on DPI, 1995 and Wylie et al, 1999).

Event	**Ash Wednesday**				**Beerburrum**
Site	Norman's	Lightbody's	Mount Schank Quarry	Heath	
Previous land use		Quarry	Quarry	Ex pasture	
Volume stored (m^3)	21,936	25,568	93,411	259,692	400,000
Duration (mths)	17	22	29	Min 11	
Log delivery rate (m^3/day)	1100	5100	N/A	N/A	8000
Size		N/A	N/A	400 m X 350 m = 14 ha	192 stacks on a 49 ha site
Log stockpile height (m)	2.5	N/A	6	5	4
Degrade		No deterioration	No deterioration	No deterioration	Significant decay fungi under continuous watering conditions. Ambrosia beetle attack to dry logs
		12% affected by bluestain. Could have been on logs before delivery.	No indication of bluestain during storage	Bluestain in smaller logs	Nil change in bluestain
Comments			Prolific development of algae on log ends.	Commence stacking 5 months after fire. Irrigation began 8 weeks later.	Change in watering regime created issues.

12.5.2 Maintenance of a film of water over log surfaces

A second objective of stockpile water management is to maintain a film of free water across all log surfaces. Dry logs can be attacked by Ambrosia beetle (pin-hole borer). Experience at Beerburrum concluded that a surface film of water over the logs, rather than log moisture content, influenced insect attack (Wylie et al, 1999, p.152). This is consistent with research findings (e.g. Syme & Saucier, 1995, p.4) and a general conclusion regarding watered logs in Germany where no insect attack was observed during storage (Liese, 1984, p.128). The Beerburrum experience concluded that development of dry patches, and consequently ambrosia beetle attack, would inevitably occur over time (Wylie et al, 1999, p.153) and this would determine the duration of successful log storage. Over time, log stockpiles will change (e.g. settling of stacks, filling of crevices with debris from decomposing bark, and a proliferation of algal growth), which can block the free passage of water. Insect attack can occur as ethanol from fermentation of wood acts as an attractant to beetles (Elliott et al. 1983, p.299; Moeck, 1970, p.985). A film of water reduces ethanol emissions and attraction of insects to a site.

12.6 Log attributes and segregation

12.6.1 Log quality and products entering a facility

Log quality entering a storage facility is a significant contributor to log quality after storage. A consistent observation has been that bluestain in logs post-storage was most likely because it was already present in logs entering storage.

- Bluestain prior to entry: After 22 months, Lightbody's storage (see Table 22); Ash Wednesday) had approximately 12% of logs with bluestain (none severely). It was suggested that: '*it is highly probable that the logs containing bluestain had been infected before irrigation commenced*' (Thomas, 1985, p.5). A similar conclusion was reached in South Africa, where bluestain in some smaller logs was attributed to development before logs were placed under water sprays (Malan, 2011, p.23).
- Bluestain after entry with delayed water application: On another site (Heath; see Table 22, Ash Wednesday) it was demonstrated that logs can be kept under sprinklers for up to 10 years apart from bluestain (in smaller logs). It was suggested that bluestain: '*was to be expected since, stacking did not start until July 1983 (5 months after fire) and irrigation commenced some 8 weeks later*' (Thomas, 1985, p.11).
- No change in bluestain: In the UK in 1988, less than 2% of logs were affected by bluestain and any bluestain present in logs prior to storage was prevented from developing further (Webber & Gibbs, 1996, p.ix).

Salvage triage will define the quality of log entering a storage site. Overseas experience noted that wet storage must be restricted to high-quality logs with a high moisture content and free of fungal infection (Liese, 1984, p.125) or to absolutely fresh logs suitable for storage (Whitehead, et al 2008, p. iv; Lutze, 2014, p.1). This is an important point as it will determine the maximum time logs can be stored on the stump. Logs destined for storage should be grouped on the basis of typical mill runs and specific processing lines (Whitehead, et al, 2008, p.iv). Ash Wednesday experience notes that logs should be cut to target specifications before entering storage (Thomas, 1985, Appendix A). A compromised log (e.g. bark damage with subsequent partial loss of moisture and incipient decay) will predispose a log to loss in value during storage (Liese, 1984, p.125) and the value pf storing of such logs should be carefully considered.

12.6.2 Log attributes and segregation

To maximise storage efficacy, logs should be of as uniform length as possible to avoid creation of hollow spaces (Lutze, 2014, p.1). European recommendations for wind throw damage say that it is '*damage to the bark and injuries to the surface of the trunk*' (Lutze, 2014, p.1). While experience with wind throw and beetle kill salvage is invaluable, a fire- impacted tree will produce logs with specific de-barking issues where directly impacted by fire (heat-fused bark) and challenges associated with reduced log moisture content. Log stockpiles should be segregated by attributes (products), and with or without burnt bark. Such segregation was recommended for pulpwood in Canada (Watson & Potter, 2004, p.476). The Beerburrum wildfires and salvage harvesting occurred over the seven months from December 1994 to July 1995. '*Logs stored during the first part of the salvage operation were mostly unstained ("whitewood" logs), but eventually a large proportion of "bluewood" logs stained by an Ophiostoma sp. were also included'* (Wylie et al., 1996; Hood & Ramsden, 1997). The majority of salvaged timber was classed as 'whitewood' (sawlog and plylog quality and free of serious degrade), some of logs recovered towards the end of the salvage period were classed as 'bluewood' (with degrade caused by insects and bluestain) (Wylie et al, 1999: p.148). Stockpile management segregated logs with bluestain and 'whitewood' into separate bays (Wylie et al, 1999: p.150).

Log moisture content is critical (e.g. to de-barkingand processing) and changes with storage on the stump. It is pertinent to consider log segregation by duration of storage on the stump and potentially log position within a stem as proxies for log moisture content, to facilitate of batching of homogeneous logs. A basis for log segregation includes the attributes listed in Box 21. There is a need to understand which of these have a material impact on overall outcomes. With the exception of bluestain, all items listed are a proxy for log moisture content. A means of accurately and simply measuring log moisture content would assist in rational log segregation. Segregation may also enhance the removal of log from storage.

Box 20: Log attributes as a potential basis of log segregation in a wet storage facility.

- Green logs: No fire-impacted logs harvested to create rational land management units.
- No impact: Logs with no signs of bark scorch or bluestain, but from fire-impacted trees.
- Bluestain: Logs with no signs of bark scorch but with bluestain.
- Both: Logs with bark scorch and bluestain.
- Length classes: Logs segregated by log length to maximise stockpile efficacy.
- Products: It may be necessary include products in a log classification system.
- Position within a stem: Segregate logs by location within tree.

12.7 Log stockpile site selection

Long-term storage requires secure access to a suitable site with specific attributes to develop required infrastructure. The primary and most critical requirement is access to uninterrupted supply of suitable volumes of water.

The Beerburrum fire storage site (49 ha) was selected within one week of the fire (DPI, 1995, p.3). The south-east South Australia Ash Wednesday fire salvage operations made use of four sites (Table 22). Storage site selection experiences are summarised below.

A UK site selection checklist developed in 1988 included obvious requirements of an adequate water supply; sufficient storage space on a reasonably level free-draining site with good bearing capacity in all weathers; good access from public roads. Subsequently, a facility to monitor and control haulage inputs and dispatch (e.g. a weighbridge and proximity of suitable staff to supervise and maintain the site) were added (Griggs, 1996, p. 4).

Given the objective to apply water to log stacks, site micro-climate, particularly wind exposure, was found to be an issue. With a focus on water-use efficacy, water availability and log quality, the direction of the prevailing wind must be considered (Carpenter & Toole, 1963). Advice to hardwood sawmills (Nolan et al, 2003, pp.3-10) suggested that if a log yard '*is in an open location and exposed to high or hot winds, the yard should be protected on the windward sides by tree wind breaks on natural ground or on earth berms'*. The south-east South Australia Ash Wednesday response included use of old quarry sites (Thomas, 1985; Table 22).

Appropriate infrastructure is required. The Beerburrum experience noted that *'design of the storage site, involving a network of roads, pump sites, drains, storage bays, irrigation lines, groundwater monitoring wells, a 110 megalitre dam, a weighbridge, an office and toilet facilities, also commenced immediately'* (DPI, 1995, p.3). After a period of c.4 weeks, *'enough of the dam, roads storage bays pumps, irrigation pipes and drains had been constructed or installed to commence receiving logs at the storage site'* (DPI, 1995, p.4).

Delivery of logs and truck movements will create a hygiene issue so adjacent and surrounding land-use should be considered when selecting a site. A key requirement of a suitable storage area is where logs can be placed in storage easily, and then later recovered. Box 21 summarises requirements for a wet-storage log facility.

Box 21: A summary of site requirements for a wet log storage facility.

General site requirements:

- Location: Well located in relation to salvage plantations and conversion plants (Liese 1984, p.122; Thomas, 1985, Appendix A; Griggs, 1996, p.4).
- Road access: Good public road access (Thomas, 1985, Appendix A).
- Area: Adequate area for the target log stocks with possibility for site extension (Liese, 1984, p.122; Griggs, 1996, p.4).
- Tenure: Ideally land owned by the forest owner to avoid rental (Thomas, 1985, Appendix A).
- Staff: Site should be within a reasonable travel distance to allow close monitoring by staff (Griggs, 1996, p.4).
- Social licence: Manage proximity, perceptions and impact to local communities by securing community support.
- Other enterprises: Consider proximity and impact on other enterprises and land-uses.

Site environment:

- Topography: Flat and firm ground conditions (Thomas, 1985, Appendix A). To operate specialist material handlers site slope must be less than 3%. For general safety requirements, maximum site slopes should be less than 5%.
- Soils: Soils with adequate mechanical properties (Liese 1984, p.122; Thomas, 1985, Appendix A; Griggs, 1996, p.4).
- Prevailing winds: Direction of prevailing winds must be considered (Carpenter & Toole, 1963). Dry, windy sites are unsuitable (Lutze, 2014, p.1).
- Shelter: Preferably sheltered (e.g. quarry, inside a forest, behind a shelter belt) (Thomas, 1985, Appendix A).

Services:

- Water: Water supply on or near the surface as deep bores require high energy inputs (Thomas, 1985, Appendix A). A secure water allocation is required to ensure that supply is not compromised during storage.
- Drainage: Adequate drainage and capture of water applied to log piles (Liese 1984, p.122).
- Electricity: Mains power supply (Thomas, 1985, Appendix A) and other required energy (Liese 1984, p.122).

12.8 Log stockpile management and attributes

12.8.1 Log stockpile spatial arrangements

A log stockpile site is defined by the total or gross area of the site and the area under log stockpiles (net area). Infrastructure such as roads is separate. Stockpiles should be orientated to take account of prevailing wind directions (Carpenter & Toole, 1963). A mega-stockpile in Sweden (1 million m^3 of logs, Whitehead et al, 2008, p.13) was developed on an abandoned airstrip with trees on both sides, with logs stacked perpendicular to and abutting the trees to minimise airflows. A wind-tunnel effect resulted after removing centrally placed log stacks from the Beerburrum site, exposing two new faces to ambrosia beetle attack. This was countered by deploying new water lines and sprinklers, and later by removing edge stacks or whole blocks (Wylie et al, 1999, p.153).

The use of shade is noted as a requirement for storing hardwood sawlogs. While not often observed, it is possible to reduce sawlog degrade by installing shade cloth structures or by use of natural shade in a coupe. For example, a best practice guide notes *'… covering the logs with shade cloth or a similar covering. This reduces the impact of direct sunlight and lowers the temperature and air velocity'* (Nolan et al. 2003, pp.3-6). Industry information suggests that overhead shade cloth has been used in some hardwood log yards.

12.8.2 Log stockpile base

Bearer logs at 90° to the stored log axis enhance handling but focuses airflow (a chimney effect) through stockpiles, facilitating drying (Liese, 1984, pp.123&124). This contrasts with advice provided to hardwood sawmills (Nolan et al., 2003, pp.3-10): *'Logs should be laid directly onto lines of bearers. Logs in storage need to be kept clean so should not be laid on the ground as mud; dirt and stones can cover the surface of the log'*. This demonstrates a need for situation-specific advice. Logs should be stacked on either a hardpan or sacrificial layer of logs (e.g. lower-grade logs). South Australian experience suggests that logs placed directly onto the ground in a stockpile with adequate watering do not deteriorate during storage (Thomas, 1985, p.1). While evidence suggests minimal risk, a sacrificial layer may or may not be recovered. Analysis of Swedish stockpiles suggested that water losses due to evaporation and ground infiltration are c.15-20% (Swedish environmental protection agency, 1992; cited by Olsson, 2005, p.4). In Sweden, it is common to store logs on asphalted sites (Olsson, 2005, p.1). A hardpan will add to the cost of establishing a log storage facility. Given identified issues with water management, consideration should also be given to whether some form of geotextile/membrane should be installed under a stockpile to catch and manage (recycle) water.

If logs are handled by a front-end loader, they will be placed in and recovered from stockpiles by machinery entering a stockpile bay and handling logs perpendicular to a machine. In such cases, a hard base is required to facilitate machine access. If logs are stacked by plant side onto a stockpile (e.g. using an excavator which pivots on its base and reaches across with an arm), the area outside of the stockpiles with require a base suitable for machine access. A hybrid option is where an excavator is on top of the log stockpiles. Stockpile base options include: a) nil – direct onto the ground (with or without geotextiles); b) crushed rock (with or without geotextiles); c) bitumen. A decision will be informed by the elements presented in Box 22.

Box 22: Issues to address in the decisions to the base of a log wet storage facility.

- Status quo: Currently available sites for use as log storage either at a processor or stand-alone site.
- Expectations: Single-event log storage duration and an ability to re-use a site.
- Plant access: The type of log-handling systems used and where these require access into log bays.
- Water: Water management requirements and water supply limitations (e.g. an ability to recycle water).
- Benefits: A benefit cost analysis of a dedicated site including any cost-savings due to reduced haulage and/or double handling costs.

12.8.3 Stockpile spatial arrangement and stockpile height

Industry comments suggest that the height of log stockpiles needs to ensure satisfactory water percolation and that stockpile layout needs to be designed to allow maximum use of a site. Stockpile log storage will be driven by the efficiency of packing logs together (a stowage factor) and effective utilisation of available area. There are two considerations: 1) spatial arrangement of the individual stockpiles; 2) log arrangements within the stockpiles.

Spatial arrangement of log stockpiles will determine the volume of logs stored and subsequent management (e.g. water application per cubic metre of logs stored). For example, rows of logs should be kept close together to reduce airflow (Nolan et al 2003: pp.3-10). Stockpile efficiency may be improved with segregated stockpiles to isolate and batch fire-burnt logs and fire-impacted but not burnt logs.

Stockpile height combined with stacking efficacy is a fundamental driver of log volume occupancy per square metre. A range of heights are documented in the literature but no guidelines have been found. Overseas experience noted that logs stockpiles were usually around 4.0 to 5.0 m in height (Liese, 1984, p.122; Nylinder, 1950 cited in Olsson, 2005, p.4) but an example in Sweden reported stacked logs 13 m high (Whitehead et al, 2008, p.13). Logs at the Beerburrum site were in 196 bays c.150 m long and 4 m high (Wylie et al., 1999, p.150). The height of the south-east South Australia Ash Wednesday stockpiles depended on equipment available and ranged from 2.5 m to 6.0 m (Table 23, Thomas, 1985); 6 m high log stacks preserved wood quality (Thomas, 1985: p.6). In a UK example, front-end loaders stacked logs up to 2 m and trucks equipped with cranes were able stockpile to 4 m (Griggs, 1996, p.6). Standard log forwarders typically stockpile to a maximum of 4 m but could be modified if required. Large 30 t excavators can comfortably stockpile to 6m in height. Specialist material handlers (e.g. Sennebogen units) move logs efficiently but require a good running surface. Therefore, there is a trade-off between the ability to stockpile logs to extra height and site civil engineering costs. A 5 m high stockpile with a stacking efficacy of 0.5 m^3/m^3 would hold 3.0 m^3/m^2 of logs per stockpile area (30,000 m^3/ha), assuming a perfectly vertical log stockpile end. The impact of stockpile height on storage volumes is demonstrated by Figure 26.

12.8.4 Enhanced stockpile height

Log stockpiles without some form of support (e.g. vertical piles) will not stockpile vertically. The stockpile tail will slope as a result of friction between the logs, as demonstrated in various photographs of log storage (e.g. Carpenter & Toole, 1963; Thomas, 1985; Forest Products Laboratory, 2004; Olsson, 2004; Whitehead et al, 2008; Lutze, 2014, p.1). Log stockpile volume estimating techniques recognise the uneven nature of stockpile height and tail end slopes. The tail slope of a log stockpile is set by the angle of repose, which varies between species (e.g. 35° with pine and 45° for spruce with straighter stems) (Liese, 1984, p.124). South Australian experience suggested that sloping stockpiles on the perimeter of a site prevented exposure of log ends and enabled ‘knocker sprinklers’ to be sited on the slope (Thomas, 1985, Appendix A). To maximise log storage, it is suggested that some form of pylons be installed to support log stockpile ends. In Germany, supports were inserted at the tail of log stockpiles (Liese, 1984, p.123). Images of large log stockpiles in Sweden show that log stockpiles are run first in one direction to form a backstop for subsequent stockpiles run perpendicular to the first row (Figure 27 from Forsman, 2016, p.7, Figure 2). An alternative strategy is to make log stockpiles are as long as possible; a Swedish log stockpile storing 1 million m^3 of logs for up to four years under sprinklers was 2.3 km in length, stacked up to 13 m high (Whitehead et al, 2008: p.13). An engineering solution is to manufacture certified ‘bookends’ to provide stable stockpile ends. These could be relocated for future use

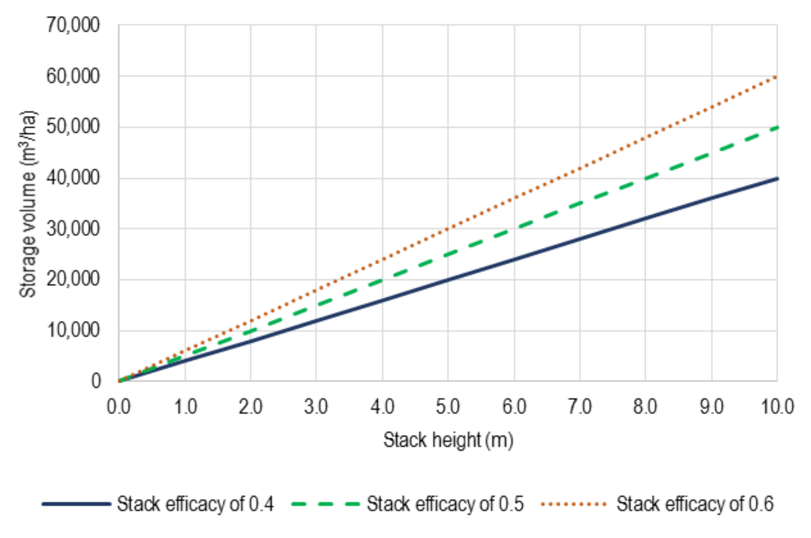

Figure 26: Theoretical change in log stockpile volume with stacking efficacy (m^3/m^3) and stockpile height.

Figure 27: An example of a large log stockpile (Forsman, 2016, p.7).

12.8.5 Log-stockpile sides

Where logs are poorly stacked or of un-even length, protruding log ends create eaves and a rain shadow for logs below, allowing logs to dry out (Carpenter & Toole, 1963; Thomas, 1985, Appendix A; Gibbs & Webber, 1996, p.42). At the Beerburrum site, this resulted in ambrosia beetle attack (Johnson, 1996, p.2). This suggests a need for length-specific log piles. In South Africa, a higher incidence of bluestain fungi was found in exposed end log ends that protruded from stockpile sides, as these were not adequately watered. This was addressed by taking greater care during stacking by placing log ends flush with one another, especially on the side of stacks that is more exposed to the sun (Malan, 2011, p.23). Uniform log length is critical for this and complements segregation of storage of logs by products in bays.

12.9 Watering regime

12.9.1 Water rates applied to log stockpiles

Under limited supply, water application must be as efficient as possible. presents examples of water application rates. Little information was available on how application rates were verified in practice. An example from Victoria indicated that water-use rates were based on metered bore drawdown data. Data from publications was converted from the reported units (shaded in grey) to millimetres/hour, litres/metre squared/day, megalitres/hectare/day and megalitres/hectare/year. One millimetre of rainfall per square metre has a volume of 1 litre, and an annual rainfall of 1000 mm/y would deposit 10 megalitres (ML) per hectare. To place water application rates for log storage into perspective, a land-based water effluent disposal system would irrigate c.2-3 ML/y.

12.9.2 Testing water application regimes

A log watering regime consists of water application rate (usually expressed as mm/day), continuity of application and duration of pauses between application (e.g. 1 hour on and 2 hours off). A US study (Carpenter & Toole, 1963) tested water application patterns: no watering; 30 minutes off and on; 12 hours off and on; and full-time application. This study resulted from consideration of water as a scarce or costly resource, and that intermittent watering was an option (Carpenter & Toole, 1963). The study included four species of logs and assessed bluestain penetration into the logs (Table 24). All three spray treatments provided more successful storage than no treatment, with continuous application achieving the least bluestain penetration. At the end of 16 weeks, watered logs of red oak, sweet gum and cottonwood were mostly free of bluestain. On average, bluestain did not penetrate more than 25 mm into logs-ends with watering, while unprotected logs were badly discoloured (Carpenter & Toole, 1963). After almost a year in storage, logs were processed into sawn timber and logs stored without water application were not worth processing as they had checked badly, had pinworm holes and a few insect larvae under the bark (Carpenter & Toole, 1963). Outcomes of another trial (Syme & Saucier, 1995) in the US suggest that continuous watering with 100 mm/day application was superior to a cycle of 60 minutes on and 120 minutes off and to a rate of 56 mm/day on a continuous basis.

Table 23: Examples of water application rates to log stockpiles for the countries listed.							
Site	**Stockpile height**	**Application rates**					**Reference**
	(m)	**(mm/hr)**	**(mm/day)**	**(L/m²/day)**	**(ML/ha/day)**	**(ML/ha/y)**	
South east South Australia	2.5–6.0	5.0	120	120	1.2	438.0	Thomas (1985)
	2.5–6.0	4.2	100	100	1.0	365.0	Thomas (1985)
Queensland	4.0	6.3	150	150	1.5		Wylie et al, (1999, p.150)
Victoria (hardwoods)	5.0	0.0		0	0.0	40.0	Confidential pers. comm.
New Zealand		6.0	144	144	1.4	525.6	Thomas (1985, p.2)
South Africa		3.1	75	75	0.8	273.8	von dem Bussche (1993) cited in Malan (2011, p.21)
USA	1.5	4.2	100	100	1.0	365.0	Syme & Saucier (1995, p.4).
UK	3.5 (3.2–3.6)	3.0	72	72	0.7	262.8	Griggs (1996, p.4)
Denmark		1.8	44	44	0.4	160.6	Moltesen, 1971 cited by Liese (1984 p.124)
Germany		1.9	40 -50	45	0.5	164.3	Liese (1984, p.124).
Nordic countries	4.0–5.0	2.8	60-75	67	0.7	244.6	Boutelje (1987) cited by Olsson (2005: p.4).
Norway (adequate)		1.7	40	40	0.4	146.0	Myhra, & Gjengedal (1998) cited by Olsson (2005, p.4).
Norway (applied)		3.5	70-100	85	0.9	310.3	Myhra, & Gjengedal (1998 cited) by Olsson, 2005: p.4.
Norway (maximum)		5.2	100-150	125	1.3	456.3	Myhra, & Gjengedal, 1998 cited by Olsson (2005, p.4).
Sweden		2.1	50	50	0.5	182.5	(Lutze, 2014).
	5	2.1	50	50	0.5	182.5	Nylinder (1950), cited in Olsson (2005: p.4).

Table 24: Depth of bluestain penetration into log ends after four months of storage (Carpenter & Toole, 1963).

	Red oak	Sweet gum	Hackberry	Cottonwood
Nil water	84	60	37	48
30 mins off and on	1	2	11	1
12 hours off and on	3	1	3	0
Full time	1	1	1	0

Table 25: Outcomes of a two year trial of water application rates in South Carolina US (Syme & Saucier, 1995, p.2).

Regime	Intermittent-light	Intermittent-heavy	Continuous-light	Continuous-heavy
Water rate (mm/day)	17.8	33.0	55.9	100.0
Cycle	60 minutes on and 120 minutes off	60 minutes on and 120 minutes off	100% on	100% on
Duration	24 hours/day	24 hours/day	24 hours/day	24 hours/day
Outcome - Ambrosia beetle damage	Heavy	Heavy	Nil	Nil
Outcome - Bluestain	Present	Present	Present	Nil

12.9.3 Operational results

A range of watering regimes have been documented and often watering rates are expressed simply in mm/day but with no consideration of continuity (). The basis of quoted rates of water application must be understood. For natural forest hardwood sawlogs, it is suggested that ‘*logs do not need to be sprayed continually but they do need to be kept wet. Spraying regimes of 15 minutes spraying every 3 hours have been shown to be as effective for regrowth jarrah and karri as spraying continuously*’ (Nolan *et al.* 2003, pp.3-7). In another example, a hardwood sawmill applied water on a cycle of 7 minutes on and 14 minutes off. Watering rates of softwood log stockpiles have been set based on the literature, considered opinions and operational experience. The South Australia Ash Wednesday experience noted best endeavours to determine water application rates (Box 23). Actual application rates were based on pumping capacity existing on-site. An important point is that the South Australia watering regimes were successful (see Table 22). Daily watering rates to protect log stockpiles at Beerburrum was determined by literature review and extensive consultation. The initial regime was 150 mm/day applied continuously. To reduce pump maintenance and electricity costs, watering was reduced in November 1995 to during daylight hours (unless conditions were windy or humidity was low). When this regime was trialled, moisture content of logs and percentage moisture saturation did not alter (Wylie et al, 1999, p.150), but other factors were ignored.

Box 23: The basis of the water rate applied to post Ash Wednesday log stockpile (Thomas, 1985, p.2).

‘The Woods and Forests Department examined the New Zealand experience with wind-blown radiata pine In North Canterbury (Clifton 1978) noting that the watering rate for 20,000 m^3 of logs was approximately 96,000 litres/hour over a 1.6 ha site i.e. 60,000 L/ha/hr or 144 mm of precipitation per 24 hours.

Mr Norman advised that his irrigation pump was capable of producing 200,000 L/hr. This volume of water could safely store 30,000 m^3 of logs based on the New Zealand operation.

Departmental officers reviewed other available literature on water spray storages and concluded that the minimum acceptable watering rate for the South East was 100 mm/24 hours.’

Table 26 presents a summary of south east South Australia and Beerburrum watering regimes and outcomes. The South Australia regimes were successful at preventing further degrade of log quality in storage. The

Beerburrum operational watering regimes (including intermittent watering) were effective in preventing Ips and bluestain fungi. However, intermittent watering did not prevent attack by ambrosia beetles and full watering did not suppress decay fungi (*R. lineatus*) (Wylie et al., 1999, p.153). This is consistent with US results (Table 25). In New Zealand, attack by ambrosia beetle occurred in 'well-watered' stored logs after 2-3 years (Milligan, 1982, p.236). This was associated with a failure of the watering system (N.C. Clifton, pers. comm. cited in Wylie et al, 1999, p.152). A South African review concluded that '*to reap full benefits of the approach it is of utmost importance that the entire surface of each and every log in the pile is kept wet continuously. The sprinkler system must function effectively at all times, as dry spots in the log piles normally become infected fairly quickly, resulting in irreversible damage (staining) to the wood*' (Malan, 2004, p.81).

Table 26: Outcomes of operational log stockpile watering regimes.

Site	**Nominal rate**	**Continuity**	**Outcome**	**Impact agent**			**Reference**
	(mm/day)			**Bluestain**	**Decay fungus**	**Ambrosia**	
Ash Wednesday South Australia	120	100%	Nil log degrade	Nil	Nil	Nil	Thomas (1985)
	100	Summer 100%; Winter 50%	Nil log degrade	Nil	Nil	Nil	Thomas (1985)
Beerburrum, Qld	150	100%	Nil log degrade	Nil	Nil	Nil	Wylie et al, (1999, p.150)
	75*	Daylight hours	Log degrade	Nil	Significant	Significant	Wylie et al, (1999, p.150)

* While not stated, it was assumed that reduced watering hours reduced the water rate by a *pro rata* amount.

12.9.4 Development of an operational regime

Water sprinkling has been demonstrated to effectively control log degrade, provided logs were kept completely wet at all times (Carpenter & Toole, 1963; Thomas, 1985; Simpson & Ward, 1991; Syme & Saucier, 1995; Wylie et al, 1999; Malan, 2011). This demands an uninterrupted water supply at a required flow rates. Water availability is the most significant determinant of an ability to store logs.

Under drought conditions, water supply is likely to be limited and additional planning will be needed to ensure adequate water to treat log stockpiles.

Log stockpile height must be considered in developing a log watering regime. Extrapolation of results from a US study (see Table 1) was cautioned: '*although the 4 inches [100 mm] of water per day was adequate to protect the logs in the test deck, larger sized commercial decks, where logs are typically stacked to heights of up to 30 feet [9.1 m], will require additional inches of water output to protect the stored logs. The amount of water required will vary with the height of the log deck and other conditions*' (Syme & Saucier, 1995, p.4). Analysis of a Swedish watering regime indicated that 50 mm/day applied to a 5 m high stockpile maintained log moisture content of 100-120% $_{\text{DRY BASIS}}$ (Nylinder, 1950 cited in Olsson, 2005, p.4). Continuous watering of 6 m high stacks at 100 mm/day in South Australia and 4 m high stacks with continuous watering at 150 mm/day at Beerburrum was shown to be successful. Figure 28 demonstrates the impact of log stockpile height (with a stacking efficiency of 0.5 m^3/m^3) on water use when applied at 200, 400 and 600 ML/ha/y (this equates to water application at 55, 110 and 164 mm/day respectively). Where water is limited, the importance of stockpile height increases. Up to a height of 5 to 6 m, watering rates is the main driver of water use per cubic metre of logs stored, beyond which stockpile height is the main driver.

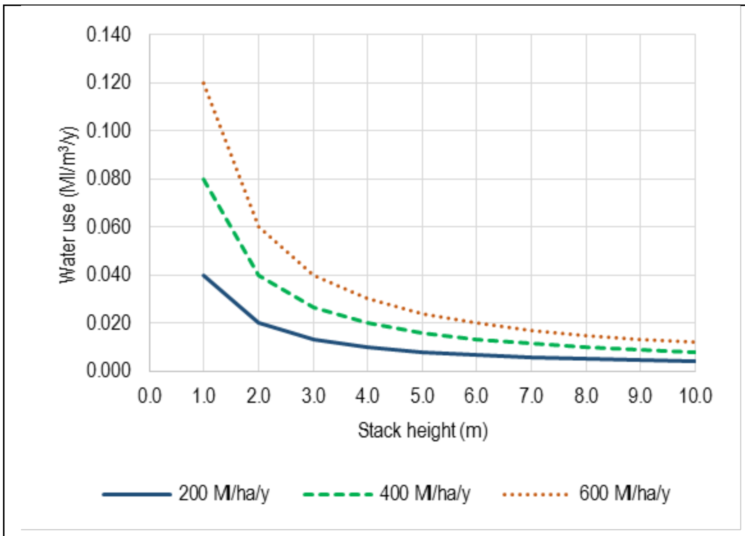

Figure 28: Theoretical change in water use per cubic metre of logs stored by stockpile height (with an assumed staking efficacy of 0.5 m³/m³).

12.9.5 Water source, quality and management

Water availability will determine the option and scale of potential log storage. Water sources include dams fed by a creek or a bore, estuarine waters, bore or recycled water. A key requirement is that a water supply needs to be reliable, with appropriate back-up systems. South Australian Ash Wednesday log storage sourced ground water from purpose sunk bores and limestone sinkholes (Thomas, 1985, p.3&7). While construction of dedicated water storage is an option, required capacity will be determined by the size of a log yard, rate of water flows feeding the dam, ground conditions and local climate (Nolan et al., 2003, pp.3-11). To service the Beerburrum log storage site, a 110 ML dam was designed and built (DPI, 1995, p.3). The dam was filled and topped-up in dry periods, from a nearby tidal creek, reaching a peak salt level of approximately one third that of seawater (Wylie et al, 1999, p.150). It is possible to use recycled water as done in Adelaide after Ash Wednesday (45,000 t of logs stored under sprinkler using waste water from sewage treatment plants but it caused issues with alga/slime growth and odour).

At an application rate of 100 mm/day of water, a site will receive 1 ML/ha/day of water. In the absence of a recycling system, this would consume 365 ML/y; equivalent to 36,500 mm/ha/y of rainfall. To place log watering-regime water-use into perspective, other rural industries were considered. It is noted that scale of manufacturing will drive water outputs, however the examples are to demonstrate scale of potential recycled water application to land: a cheese manufacturer produces 472 ML/y (1.3 ML/day) or a milk factory produces 550 ML/y (1.5 ML/day). Land reuse management of waste water applies 3 - 5 ML/ha/y limited by nutrient loads and individual site capacity to deal with such volumes. This highlights that while a factory may produce adequate water for log storage, addressing water management issues will be required. Swales or drains should run between lines of logs, and drain to a catch-dam. For erodible soils, the base and sides of swales should be protected (Nolan et al, 2003, pp.3-11). To achieve this goal:

- Roads, un-loading areas and storage areas should have adequate falls to drains.
- Drains should fall to sumps or other water storage areas.
- Drains, dams, bores and other irrigation equipment should comply with requirements of relevant state or local government authorities.

Water management could include use of an impermeable base membrane (as used to line municipal refuse pits) or treatment of soils with engineering solutions (e.g. cement stabilisation) or agricultural techniques (e.g. sub-surface drainage).

Water quality does not influence its preservative effect on wood (Liese, 1984, p.124). Past research has explored log storage using chemical sprays (Keirle & Johnstone, unpublished data cited by French & Keirle, 1969, p.178). In Queensland there was little difference between watering with salt-water or fresh water in effect on ambrosia beetle infestations (Wylie et al, 1999, p.153). Water quality is a mechanical issue for delivery systems (recall that reducing pump maintenance motivated reduced watering at Beerburrum; Wylie et al, 1999, p.150). Other impacts due to water quality include:

- Nozzle impacts: German experience noted that water must be clean enough to prevent blocking of sprinklers by iron contamination. In SA, sprinklers with 3 mm nozzles were blocked by limestone fragments, and insects in summer fouled the knocking action of some sprinklers (Thomas, 1985, p.10);
- Pipe damage: Water must be clean enough to prevent corrosion of piping (Liese 1984, p.124). In SA, iron salts created excessive wear. (Thomas, 1985, p.10);
- Pipe blockages: Clogging with slime or debris in the water (Carpenter & Toole, 1963) and in South Australia, pipes had flow restrictions due to black sludge and rusty iron deposits (Thomas, 1985, p.10).

Water quality issues will result from recycling water after spraying on logs. Water supply and control of run-off from a site is a regulatory and site environmental certification – an ISO14001 issue. Requirements of voluntary third party certification (e.g. forest management, chain of custody and controlled wood) need to be considered and addressed. There is potential to develop a capture and recycling system to ensure water re-use, but having adequate water supply, including a top-up amount to take account of losses, remains the key issue.

12.9.6 Water application equipment

Development of a watering system is a complex task involving many decisions (Thomas, 1985, p.1) so it is recommended that specific advice be sought. For example, (Lutze, 2014: p.2) suggests that '*the sprinkling plant must have the appropriate dimensions for the position and form of the storage area, as well as to cope with the type, quantity and pressure of the water*'. An irrigation system should include the ability to isolate sections to ensure continuous application across a site during works or log recovery, and the ability to quickly change lines or fittings. A water delivery system includes:

- Pumps: Pumps with sufficient capacity to service the number of sprinklers (Nolan et al., 2003, pp.3-11). A key point is that on-site pump redundancy is required, including back-up generators for electic pumps.
- Control mechanisms: Use of appropriate control mechanisms (combined with monitoring) allows a watering regime to be scheduled (Nolan et al. 2003, pp.3-11) and respond to microsite conditions.
- Piping: There is a trade-off between pipe diameter, length of piping, flows required and system pressures. Piping includes main trunks, side trunks and pipes to individual sprinklers.
- Fittings: Use appropriate connections and taps (e.g. Thomas, 1985 suggests use of ball valves).

Since Ash Wednesday and Beerburrum, considerable advances have been made in control systems, including smart systems, automation and sensors. With appropriate design, it would be possible to minimise disruption to water flows by using proximity sensors to turn sprinklers on or off when mobile plant approaches a stockpile to deliver or recover logs.

The final step in development and management of a log stockpile is delivery of water via sprinklers. Sprinkler efficacy will define log storage success. Degrade associated with log moisture content has been shown to be caused by a failure of sprinkler systems (Liese, 1984, p.126). One failure can be that sprinklers on the ground 'rob' water from sprinkler on top of stacks (Thomas, 1985, Appendix A). Sprinklers should be located to cover all exposed areas of a log stockpile, particularly the ends of logs exposed to prevailing winds (Nolan et al, 2003, pp.3-11). As a guide, all timber should lie within 75% of a calculated sprinkler radius (Liese 1984, p.124). This is generally achieved by positioning pipes and sprinklers over the top and along the sides of stockpiles (Wylie et al, 1999, p.150). While effective, experience has shown that sprinkler type (e.g. Thomas, 1985 suggested that part-circle sprinklers were unreliable) and nozzles are considerations for water pattern and duration of service planning. Expert advice can be obtained from specialist log stockpile irrigation equipment suppliers (for example Nelson Irrigation: http://nelsonirrigation.com/products/application/log-pile-irrigation). Table 27 presents a summary of sprinkler head configurations. A hardwood sawmilling operation makes use of part-circle agricultural (knocker) sprinklers, made of brass with a capacity to deliver 2 240 and 7 840 L/h, at pressures of 3.5–6.0 BAR with a coverage of 16–24 metres in diameter (extracted from https://www.vyrsa.com/en/catalogo/productos/vyr-65/ on 11/03/2020). This equates to 11.1 to 30.0 mm/h of water for a 16 m diameter coverage and 4.9 to 17.3 mm/h of water for 24 m diameter coverage. A circular pattern of the sprinkler delivery has additional complications when designing appropriate lay-out (e.g. a 25% sprinkler overlap).

Table 27: Recommended sprinkler configurations based on south-east South Australia experience (Thomas, 1985).

Sprinkler type	Objective	Stack element	Comments
Knocker sprinklers	General use around a site	General use around a site	Some allow changes to nozzles
	Adjust fittings to get best results	Traget the log stack ends	
Roto-frame sprinklers	Where saturation is required (extra water application).	Exposed stockpile edges	Applicable for northern and western faces
		On stockpile tops	

12.10 Removal from watering storage and insect attack

After storage under sprinklers, logs must be removed for transport to processors. A trial in Queensland found that logs remained attractive to Ips after 10 months storage under water sprays and this insect was able to complete a life cycle in logs removed from storage (Wylie et al, 1999, p.153). Ethanol is a likely driver in attracting insects. After a sample of segregated logs was removed from storage and allowed to dry. Ips attack was rapid (within a few days), and at first count all logs had been attacked. There were differences in attack rates between log segregation types (see Figure 22): bluewood was attacked faster than whitewood and by three weeks the rate of attack was the same. The rate of attack of fresh (control) logs was much lower (Wylie et al., 1999, p.150). Provided that logs are processed rapidly, it was suggested that there should not be time for development of serious bluestain degrade (Wylie et al, 1999, p.153). Ambrosia beetles attacked logs removed from storage but this was more of a problem in dry patches on logs in the watered stacks (Wylie et al, 1999, p.153). Therefore, to maintain log quality, log watering needs to be maintained and disruption during log recovery minimised for safe transport. This indicates a need for irrigation systems to be modular to allow control of watering with log stockpiles and a need for expediency in transport to processors and subsequent processing. As well, all-weather roads are needed to allow safe truck movements straight after watering stops rather than delayed while access dries.

12.11 Monitoring wood quality during storage

A monitoring program of stored logs is needed to identify any degrade, and to determine and address causes of degrade. This can be achieved by frequent inspections (Carpenter & Toole, 1963, p.2). Monitoring can take several formats (see Box 24). Logs stored under sprinklers in New Zealand were noted to have a strong odour, which seems indicative of decomposition of organic materials by anaerobic micro-organisms (Clifton, 1978). Degradation of stored *P. radiata* logs was reported to be minimal after two years and it was concluded that a satisfactory solution to long-term storage had been found (Clifton, 1978 cited by Milligan, 1982, p.236). Experience in Germany noted that although log-ends became covered with '*slime fungi of a striking yellow-red colour and later with algae and mosses*', a few millimetres beneath the surface was wood of original colour and appearance (Liese, 1984, p.125). Management of Ash Wednesday log stockpiles included log moisture content monitoring by taking core samples. To verify the procedure, a comparison of moisture content of blocks of sapwood cut from a disc adjacent to 'Pressler cores samples' indicated a 15% higher reading from the blocks compared to cores. This would indicate a squeezing effect by the core sampler with an implication that core moisture contents are likely to be conservative (Thomas, 1985, p.11) or that the core samples were not representative. A system of wood quality monitoring was implemented at the Beerburrum storage facility to establish critical moisture content targets, and the effect of using saline water on subsequent log utilisation (DPI, 1995: p.4). It was demonstrated that the quality of wood was being preserved (DPI, 1995, p.6). To reduce risk of dry patches, regular inspections should check logs (Johnson, 1996, p.2). A facility monitoring program is required (see Box 25). There are a range of sampling strategies (see Downes et al, 1997) and any program should seek qualified recommendations. This intent must commence with layout of log stockpiles to facilitate access and measurement of target parameters. There will be OHS issues with movements around log stockpiles. With advances in monitoring equipment (moisture censors, drones, etc), it is likely that monitoring can be automated rather than relying on people.

Box 24: A historic perspective of monitoring of log quality.

Fisher (1896, p.78) states:

'Striking the reverse of an axe against a stem at different places, from the clear or dull sound given out, leads to conclusions as to the soundness of the tree. At the same time the practice of one man striking at one end of a log and another placing his ear at the other end affords no certain test of soundness.'

'The colour of fresh sections of wood offers an excellent test of its soundness. Uniformity of colour, and for most species the lighter tints, are usually signs of soundness. Patches or stripes of darker colour in a wood prove the opposite.'

'*In many cases, the scent of the sawdust is an excellent guide to the soundness of the wood; thus sound oakwood possesses the well-known scent of tannic acid, whilst in the case of many diseases of coniferous wood, a strong' scent of turpentine is observed. Several other species have scents peculiar to themselves, but which cannot be described. Whenever the scent is unpleasant and mouldy, it is a proof of more or less advanced decay.'*

Box 25: A snapshot of elements of a log wet storage monitoring program.

- Watering system operation and efficacy.
- Log moisture content variation.
- Pest attack that may affect log quality (e.g. boring insects)
- Development of bluestain, decay and mould.
- Bacteria development in logs potentially detected by odour.

12.12 Duration and successful storage

Maximum duration time and successful log storage will be defined by the point in time where log condition begins to deteriorate. Successful storage results when logs attain and retain required sapwood moisture content with no insect attack, bluestain or wood-destroying fungi. A caveat is that while a log may appear to be sound and 'fit for purpose', there may be an impact on wood properties.

The first study carried out in South Africa on the effect of wet storage on timber showed that it had no adverse effect on the wood or any serious or long-lasting negative effects on the environment and water quality after 10 months of storage (von dem Bussche, 1993 cited in Malan, 2011, p.25).

A New Zealand example of log storage post wind throw had successful storage of up to five years (Liese, 1984, p.125). Following the Ash Wednesday fires, log storage was successful up to 29 months (Table 22). A report on the Beerburrum log storage documents a less successful outcome: '*In January 1996, a potentially serious decay problem was discovered in the stored logs and urgent research was initiated to determine the nature of the causal agent and if possible to find a means of containing it. The distribution and development of the decay fungus Rigidoporus lineatus (Pers.) Ryvarden were studied in the sprinkled logs in the log store'* (Hood et al, 1997, p.139). Subsequent recommendations were to salvage all material within three months and store under water sprinklers for periods no longer than six months (Wylie et al, 1999, p.153). However, some issues with the Beerburrum site relate to a change in the water application regime from 24 hr/day to application only during daylight hours. It is not known whether maintenance of 24 hr/day watering would have increased the length of successful storage. To make defendable recommendations of best-practice methods requires an understanding of failure mechanisms; key insights and lessons are possible from causal analysis of less successful operations to determine what not to do and what is important.

- Prevailing winds: Ambrosia beetle attack at Beerburrum was highest in zones at the end of the irrigation system that were the most exposed to the prevailing winds, and therefore more prone to drying out (Wylie et al., 1999, p.153).
- Air movements and drying: After removal of centrally placed log stacks from the Beerburrum site, a wind tunnel effect resulted, exposing two new faces to ambrosia beetle attack.
- Not 'fit for purpose': In response to fire salvage in 2009, 20,000 t of softwood sawlogs were recovered and stored in the log yard of a hardwood sawmill (which had ceased operation). The site had existing log watering infrastructure, with water supplied from a bore. Due to poor sprinkler coverage, the logs experienced drying and wetting with degrade due to fungi and discolouration. Logs were supplied into an export market on a fall-down basis, providing a lower return. This highlights the need for care in irrigation system design and potentially different needs for softwood and hardwood sawlogs.
- Equipment failure: Sprinkler watering in South Africa was successful, if logs were kept completely wet all the time. Areas that dried as a result of blocked spray nozzles or sprinklers that stopped oscillating were usually infected with bluestain very quickly (Malan, 2011, p.21). In New Zealand, attack by ambrosia beetle occurred in well-watered stored logs after 2-3 years (Milligan, 1982, p.236) associated with a failure of the watering system (N.C. Clifton, pers. comm. cited in Wylie et al, 1999: p.152).
- Log overhangs rain-shadows: Poorly stacked logs of uneven length with protruding log ends created eaves and a rain shadow for logs below (Carpenter & Toole, 1963, p.1 of reprint; Thomas, 1985, Appendix A; Webber & Gibbs, 1996, p.42) allowing logs to dry out. In Queensland, this resulted in ambrosia beetle attack (Johnson, 1996, p.2) and bluestain in South Africa (Malan, 2011, p.23).

- Change of watering regime: Issues with the Beerburrum site related to a change in water application from 24 hr/day to application during daylight hours. It is not known whether maintenance of 24 hr/day watering would have increased this efficacy and duration of storage.

12.13 Regulatory and social licence considerations

12.13.1 Environmental management

Watering of log stockpiles creates a potential pollution issue and acceptable past practices may no longer be acceptable (Box 26). Development of large log storage sites in Germany in 1972 required authorisation often linked with a requirement to monitor site runoff water quality, due to a lack of information on possible effects on the environment. Several hundred water samples were taken (at different locations and intervals) during initial months of operation. Chemical oxygen demand (COD) of run-off water increased from c.50 mg COD/L to 350 mg COD/L due to carbohydrates leached from bark and wood. With ongoing watering, organic solutes contributing to COD decreased to c.70 mg COD/L after three months (Liese, 1984, pp.130&131). Research in Sweden documented environmental outcomes of log storage under sprinklers and noted that it '*gives rise to large amounts of polluted leach-water. The leach-water is able to cause damage to both surface and groundwater in the surroundings if no measures are take*n' (Olsson, 2005: p.ii). In another example, it was reported that *'relatively high sprinkling intensity has resulted in large amounts of wastewater and sometimes to an undesirable influence on the environment resulting from the leaching of hazardous substances from the timber'* (Schuytema & Schankland, 1976, cited in Olsson, 2005, p.4). The specific water quality issues were '*mainly by increased concentrations of BOD, COD, nitrogen, phosphorus and phenols*' (Olsson, 2005, p.ii).

Box 26: Examples of operations during the Ash Wednesday log stockpile water management reflecting conditions at that time.
Lightbody's: *'Water quality at the source was good until it was contaminated with used water that had percolated through the log stacks. While draining back into the cave across the quarry floor it picked up bark fragments, silt, frogs and insects. This was overcome initially by placing a levee of 20 mm gravel across the cave entrance to screen out the solids. However this was soon blocked with silt and the final solution was to fit a 'spillway' made from a 1.8 m sheet of perforated galvanised iron in the levee. The solids which collected at the bottom of the spillway were cleaned out once or twice a day. The water system at this site was "closed' i.e. all used water drained back to the source.'* (Thomas, 1985, p.5).
Heath: *'To protect the underground water resource the Engineering and Water Supply Department requested that all water should remain within the confines of the storage site. Therefore an earthen levee bank was constructed outside the road network to prevent surface run-off away from the site. Manipulation of the reclaim pump ensured there was no overflow and also provided more efficient use of the total water supply'.* (Thomas, 1985, p.6).

Management of the Beerburrum site implemented measures to ensure that the facility did not have a negative environmental impact (e.g. to the nearby Pumicestone Passage) (DPI 1995, pp.4-6). An interim Environmental Management Plan (EMP) was drafted in December 1994 after which a full and comprehensive EMP was completed. Remedial and preventative measures were taken to eliminate or reduce impacts of engineering works. Surface water was sampled at the intake pumps on Elimbah Creek, in the dam and downstream from the dam in Glass Mountain Creek. Deep and shallow groundwater wells were established on-site and around the perimeter of the facility.

12.13.2 *Coordination and cooperation*

Experience with the Beerburrum site demonstrates a need for pre-planning and an understanding of requirements. To develop the site, '*urgent consultation with ... South East Queensland Electricity Board, Telecom, the Caloundra City and Caboolture Shire Councils, and the Departments of Environment and Heritage, Treasury and Transport, was held within two weeks of the November fire to explain what salvage work was to be undertaken and to obtain the necessary approvals'* (DPI, 1995, p.4). Operational implementation required industry co-operation. Under usual circumstances, harvest and haulage was arranged by log buyers. As a result of the fire, arrangements were agreed by all parties to allow purchasers from outside the Beerburrum area to draw their log resource from burnt plantations to conserve unburnt areas. This included most parties in the '*exotic pine industry*' south of Bundaberg in salvage operations for at least a short period. This concentrated harvesting in a reduced area to normal operations, with different parties in adjacent compartments (DPI, 1995, p.5).

Hours of operation, dust, noise and light will dictate log storage operations directly or indirectly. Each site will require a range of local and state government approvals and granting of approval is not guaranteed. Community support (social licence) is critical, as is management of communications. A public relations effort was part of the Beerburrum salvage plan to explain that there was a clear plan to recover from the fires. Most local and Brisbane television stations and newspapers carried positive feature reports of commencement of the salvage operations (DPI, 1995, p.4).

12.14 Cost profile considerations

12.14.1 *Basis of financial analysis of log storage strategies*

The financial impact of salvaged log storage is well understood: *'the most significant factor impeding long-term log storage in British Columbia is the requirement to carry costs of development, stumpage, harvest, transportation, storage and silviculture without any return until the stored timber is manufactured into products and sold in the market'* (Whitehead, et al, 2008, p.v). Canadian experience suggests that a *'shift [of] paradigms from minimising delivered wood cost to maximising overall profit margin, inertia will be a major impediment to adoption of storage to improve value return from beetle-killed wood'* (Whitehead, et al, 2008, p. iv). An analysis should include cost of re-establishment with and without a salvage operation. Linking back to development of a salvage strategy, storage on the stump is the cheapest option until the point of log downgrade (e.g. due to moisture content and bluestain). With full costing of a log storage proposal (stump to processor via storage) compared to direct supply after storage on the stump, it is possible that extending storage on the stump by sacrificing upper stem logs that are too dry may be a viable option.

12.14.2 *A cost profile*

Given that every site and situation will be different, development of specific cost profiles are not possible. Documented costs from Ash Wednesday salvage suggests that (in 1985 dollars) stockpiles and sprinklers cost \$1/m^3 compared to Lake Bonney storage cost at \$2.60/m^3. The Beerburrum fire salvage operation cost a total of \$12 million (\$30/m^3) of which \$3 million (7.50/m^3) were capital costs (DPI, 1995, p.5). The cost of storage should include consideration of the working capital held, and where storage is greater than 12 months, consideration of creation of an asset. Specific accounting advice will be required. Elements of a cost profile required for wet storage of logs is presented in Box 27.

Box 27: Elements of a cost profile to undertake wet storage of fire salvage logs.

Site costs:

- Site selection: Identifying and securing a suitable site and the cost of such access.
- Regulatory approvals: The cost of application preparation and submission and any subsequent fees.
- Civil works: Development of a storage site will include seeking expert advice, equipment (hire or purchase), road construction and maintenance, and connection to water and power.
- Irrigation systems: Design and installation of as effective a system as possible.

Operating costs:

- Logs to site gate: Felling, extraction and haulage including any price premiums.
- Log receivals at site gate: Truck unloading, extra log inspections and log stacking (including inventory management).
- Operating costs: Water, insurances, staff, contractors, and maintenance, fuel and electricity costs.
- Log recovery: The cost of log recovery and loading on-truck which may include some form of wash down.
- Log transport: Log transport from the site to a processing centre.
- Log receivals at customer gate: Truck unloading, extra de-barking efforts and extra log inspections. Log stacking after de-barking.

12.15 Expert advice

Development and management of a compliant wet log storage facility requires a range of expert inputs as presented in Box 28.

Box 28: A summary of the expert advice and input required to develop and manage a wet log storage facility.

- OHS advisers: Advice on site design and management (e.g. maximum log stockpile heights).
- Civil engineer: Advice on site design and management.
- Environmental engineer: Advice on site management.
- Irrigation expert: Advice on design and installation log sprinkler systems (Certified Irrigation Designer- CIC-Irrigation Australia Limited https://www.irrigationaustralia.com.au/
- Agricultural experts: Advice on site management.

12.16 Recommended best practices

12.16.1 Salvage harvesting and logistics, environmental and safety management

Best practice 67: Determine, on best available information, whether a log wet storage facility can be developed on-site at a processors. This must be informed by water input requirements and an ability to recycle water. This would be the next cheapest option to storage on the stump.

Best practice 68: Develop a dedicated facility, if development of on-site log wet storage facility is not an option.

12.16.2 Storage

Best practice 69: Review efficacy of the watering system and impact of settling of log stockpiles on overall storage.

Best practice 70: Ensure log storage facility is ready to receive and water logs before beginning deliveries to prevent log degrade once on-site.

Best practice 71: Implement the different requirements for wet storage of hardwood and softwood logs. Softwood logs require a free water film to be maintained across log surfaces to prevent insect attack and decay fungi infestation.

Best practice 72: Consider adverse impacts of prevailing winds on the spatial arrangement of the individual log stockpiles within a log wet storage facility. Logs stockpile should minimise wind impacts that would affect water application and drying rates.

Best practice 73: Design log stockpiles to maximise watering efficiency and effectiveness. Store logs directly on the ground rather than on bearer logs. Consider use of membrane or other material to assist with water management. Stack logs as uniformly as possible to create a flush-sided stockpile to prevent rain shadows.

Best practice 74: Segregate log stockpiles to contain one type of log. Segregation should be based on dimensions (length and/or diameter), processor-specific log grade, fire impact and bluestain status. Understand which attributes are of the greatest importance to inform log segregation.

Best practice 75: Begin water application as soon as logs are delivered to a storage area. Water applied at a rate of 100 mm/day (temperate conditions) and 150 mm/day (tropical conditions) with continuous application will maintain log quality. This was for log stockpiles 6 m and 4 m high under temperate and tropical conditions respectively.

Best practice 76: Monitor quality of logs entering a stockpile. This will determine the maximum log quality after storage. To prevent development of bluestain, maintain sapwood moisture content above $110\%_{\text{DRY BASIS}}$. To prevent ambrosia beetle (pin-hole borer) and fungus attack, maintain a film of water on log surfaces. Attention should also be paid to anaerobic decay fungi which can operate under watered conditions.

Best practice 77: Ensure watering infrastructure can maintain an appropriate watering regime. Water quality can be a management issue for blockages to equipment. Failures of watering application (e.g. due to mechanical faults), even for a short time, can be catastrophic. Water management should include retention within the site with recycling and cleaning.

Best practice 78: Plan removal of logs from a stockpile to minimise interruption to the watering regime.

Best practice 79: A wet storage area must have ‘fit for purpose’ irrigation infrastructure (e.g. pumps with adequate capacity and redundancies), back-up systems (e.g. electricity) and robust irrigation pipes and sprinklers. It is suggested that circular sprinklers should overlap by 25%. The irrigation system should be designed in modules to allow isolation of trunk-lines to move logs in and out and to effect repairs and maintenance of hardware.

Best practice 80: Consider that ability for water capture and recycling to prevent run-off, maintenance of water quality by appropriate filtration systems, and adequate equipment redundancies to ensure nil gaps in watering.

Best practice 81: Include development and implementation of a monitoring program to ensure effective management and maintenance of log quality.

Best practice 82: Seek specific expert advice on design and development of a wet log storage facility.

Best practice 83: Select a suitable site that allows development and operation of a log wet storage facility.

Best practice 84: Establish a development (capital) and operational budget. Unless developed as a service provider, a log wet storage facility is an expense against future revenues.

Best practice 85: Analysis the financial implications of all possible scenarios (e.g. is it a better proposition to sacrifice upper stem logs due to drying, to maintain logs on the stump or harvest and store in a wet storage facility). Analysis must consider risk and uncertainty.

Best practice 86: Define the point in time where log condition is expected to begin deteriorating.

Best practice 87: Operational experience in New Zealand and South East South Australia had success in storage of P. radiata logs for 24 and 29 months respectively.

Best practice 88: Softwood log storage was recommended to be no longer than 6 months and required a continuously operating watering system.

12.16.3 Processing – wood yard management / de-barking, sawing, drying, etc

Best practice 89: Batch and manage logs separately, particularly after a period of wet storage that will have changed log porosity and permeability.

12.17 Observations

Observation 48: Investigate the relationship between log stockpile height, water application rates and maintaining supply of ‘fit for purpose’ log. Stockpile height will determine site capacity and water application rate will determine the amount of water used.

Observation 49: Determine what factors are important for log segregation during storage and recovery of logs.

Observation 50: Consider management options including site engineering, base materials, log stack design, watering, log delivery and removal when selecting log storage sites.

Observation 51: Explore options for base materials (e.g. bitumen, crushed rock, pasture) in a log storage area and the role of geotextiles. Issues to consider include soil properties, mechanical strength, machine-access and water management.

Observation 52: Determine the most effective watering regime for logs in wet storage. This should include consideration of advances in watering technology and monitoring and control systems.

Observation 53: Determine the rate of bluestain development once logs are removed from wet storage to inform log management and processing and its impact on wood properties.

Observation 54: Document potential environmental impacts of wet storage facilities for logs under local site conditions and for the species of woodchips stored.

Observation 55: Investigate the impact of species, operating environment and equipment on the management of wet storage facilities.

13 Storage strategies – water storage of logs

13.1 Summary

Storage of logs immersed in water is a traditional approach to log stock management in Europe and North America. However, due to environmental concerns (e.g. impacts on water quality) and practicalities (e.g. log delivery into a water body and their subsequent recovery) this approach is of lesser importance. This approach has been successfully applied in Australia (after Ash Wednesday in Lake Bonney in SA) and the same logistical issues were noted.

13.2 Introduction

This section addresses the option of log immersion in water as a log storage method. Water storage has been routine practice in Scandinavia and North America (Fisher, 1896, p.430; Koch, 1972, Vol 2, p.738; Lutze, 2014) and it is a reliable and effective means of wet storage (Simpson & Ward, 1991, p.223). An Australian example of storage of logs in a water body occurred in the early 1970s as part of the Gordon/Pedder hydro-electric scheme.[11] Huon pine trees (*Lagarostrobos franklinii*) in the flood zone were felled. Some were supplied to sawmills; others remained on-site and were floated with flooding of the river systems. Some trees that had been submerged in a lake for 15 years were severely attacked by ambrosia beetles (*Platypus subgranosus* Schedl) when the lake level dropped exposing the logs (H.J. Elliott, pers. comm. cited in Wylie et al., 1999, p.153).

13.3 Log pond storage

13.3.1 Log pond storage as a historic option

An 1800s observation is *'Wherever logs are to be stored for a number of years, it is best to keep them under water, provided that they are completely immersed, and there is a moderate inlet and outlet of the water to prevent its becoming stagnant. Logs are then most securely preserved for several years from decay and from cracking, and can be readily converted into planks, scantling, etc.'* (Fisher, 1896, p.430). Prior to World War II in the US southern pine logs were commonly protected against fungal decay and drying defects by storing them in log-ponds (Koch, 1972 Vol 2, p.738). While storage of logs in water bodies '*was once a regular practice, it is now rare in North American mills*' (Simpson & Ward, 1991, p.223).

Of the 1.9 million m^3 of salvage logs from the Ash Wednesday fires in south-east SA, 535,000 m^3 (28.2%) were stored in Lake Bonney (see Table 21; Thomas, 1985: p.1). Log recovery from Lake Bonney ceased in June 1994 (Box 29). This was the last significant in water storage of logs in Australia.

13.3.2 Description of water storage of logs

Storage of fire-impacted logs in a water body is an alternative to sprinkler application of water to a log stockpile. The objective of log storage in water is to slow the rate of degrade due to drying and associated

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[11] Sourced from https://www.huonpine.com/lake-gordon-salvage-operations/ on 11/03/2020.

impacts such as insect attack and bluestain. Logs can be stored in stagnant or slow-moving water bodies (Lutze, 2014, p.2) such as lakes, rivers and salt-water estuaries (Simpson & Ward, 1991, p.223). Log ponds at US sawmills can be 14-16 ha in surface area and as deep as 3 m (Knuth, 1960, p.4). Logs are usually banded together as floating rafts to increase the holding capacity of a pond and to prevent wet wood-logs from sinking (Simpson & Ward, 1991). European experience suggests that logs strapped into bundles hold c.10-20 m^3/bundle. While such bundles occupy a small area, they are at least 2-3 m 'deep' (Lutze, 2014, p.2). The aim is to submerge logs to maximise water coverage (Simpson & Ward, 1991, p.223).

Box 29: A snapshot of the history of log storage in Lake Bonney (Lake Bonney Management Committee, 1996, p.21).

Following the disastrous bush fires of February 1983, salvaged pine logs were stored in Lake Bonney to preserve them for milling at a later date. A fenced area was constructed in the lake to retain the logs but due to rough weather during the construction phase and the urgency with which logs were stored the fence was breached and a number of logs escaped into the vast expanse of the lake. These logs have been found over the full extent of the lake. Following removal of the logs within the fenced area, accessible logs from the remainder of the lake have been collected and removed. There are still some isolated logs in inaccessible areas well above the normal operating level of the lake. These logs are in poor condition due to rot. Where they are within the Canunda National Park, the National Parks and Wildlife service have agreed that they can remain in situ.

During the log storage operation logs either sank or floated. A number of the logs that sunk were not found during the recovery operation. These logs are likely to remain on the bottom but may be visible depending upon the level of the lake.

The Forestry Division of Primary Industries has stated that although all log removal operations ceased by 30 June 1994, it cannot be guaranteed that all logs have been removed. Some logs can be expected to remain submerged and will move about the lake according to changing wind direction and will present an ongoing hazard to boating. All of the fence infrastructure has been removed.

13.4 Issues with log storage in a water body

13.4.1 Operational issues with storage of logs in a water body

Operational experience with water body storage of logs identified a range of considerations and insights (see Box 30). Firstly a suitable water body must be available. Site suitability includes scale, the ability to develop a log marshalling area and road infrastructure. When logs float, the surface of the logs is exposed to drying and may develop drying defects (e.g. end checking) (Simpson & Ward, 1991, p.223). A European prescription suggests that '*at least two thirds of the cross-section of the trunk must be constantly under water'* and if not logs may require application of water by sprinklers (Lutze, 2014, p.2). US log pond management includes removal of floating logs to avoid fungal infection in sections floating above the water surface (Koch, 1972 Vol 2, p.738). Logs stored in fresh water are exposed to attack by insects and fungi if stored too long during warm weather (Simpson & Ward, 1991, pp.220&235). Logs stored in ocean water can be attacked by marine borers and saltwater micro-organisms (Simpson & Ward, 1991, p.224). Logistical drawbacks (e.g. transport and drying of saturated logs) were noted as issues of log storage in water bodies in Canada (Whitehead, et al, 2008, p.4). Overall, difficulty with keeping logs wet throughout, and the expenses of log-pond maintenance, recovery of sunken logs, and withdrawal of logs from storage, has contributed to a decline in this approach (Koch, 1972 Vol 2, p.738). Experience gained during Lake Bonney operations were consistent with overseas experience, finding that lake storage has problems in both getting logs into storage and recovering logs for supply to processors (Pers. comm. David Geddes).

Box 30: Issues identified with lake storage of logs in Germany (Liese, 1984, p.120&121).

1. They are limited in availability.
2. They can hold approximately 1000 m^3/ha compared with approximately 10,000 m^3 under sprinklers.
3. Loading and unloading involve technical problems.
4. Loss due to ‘sinkers’ may occur.
5. Moisture content in some logs may not become sufficiently high for protection, particularly if stored in bundles.
6. Water pollution due to removal of bark and leaching of extractives may affect fish and sometimes leads to unpleasant odours.

13.4.2 Pollution issues

Knuth (1960: p.4) conducted research into water quality issues and bacterial impacts on wood during storage of log in log-ponds with water conditions described as varying from cold flowing to stagnant. Log storage is known to adversely impact water quality. (Hoffbuhr, 1969, Abstract) concluded that ‘*factors such as log storage time and overflow rate were found to affect the chemical nature of the log ponds*’. A later study concluded that ‘*storage in lakes cause a change of the bottom sediments, an addition of organic substances to the water and, sometimes, to increased acidity. The breakdown of organic substances leads to oxygen demand at the same time as the supply of oxygen and sunlight irradiation into the lake is reduced by the stored timber’* (Olsson, 2005, p.4). Environmental impacts noted in the study of log ponds in Sweden (Björkhem et al 1977 cited by Olsson, 2005, p.8) included eutrophication, oxygen deficiency, sedimentation, decrease in transmittance, acidification, acute toxicity and leaching of metals. In the US, water body storage of logs has largely ceased due to the negative impact on water quality as well as deterioration of wood quality (Simpson & Ward, 1991). In Canada, storage of logs from mountain pine beetle salvage in lakes or reservoirs was considered (Rogers Consulting, 2001 cited by Whitehead, et al 2008, p.4; MacDougall 2005 cited by Whitehead, et al, 2008, p.4). However, environmental concerns (e.g. riparian zone damage; raised BOD in lakes or reservoirs; leaching of toxic substances Whitehead, et al. 2008, p.4) terminated this option.

Prior to use of Lake Bonney as a log storage pond, it had been ‘damaged by the discharge of large amounts of nutrients and contaminants from pulp and paper mills for over 70 years, and smaller volumes have also entered the lake from the Millicent wastewater treatment plant for over 45 years’[12]. In 1939, approval was given for pulp mill effluent to be discharged into the lake and an effluent high in pulp solids was discharged from 1940 to 1973. Establishment of additional chemical pulping capacity was proposed in 1958 and in the mid-1960s chlorine bleaching was introduced. Discharge of highly coloured chemical wastewaters changed the colour of the lake (Lake Bonney Management Committee, 1996, p.10). The main concern with Lake Bonney following its use for log storage has been that remaining logs create boating hazards (Lake Bonney Management Committee, 1996, p.21).

13.4.3 Regulatory issues

Use of Lake Bonney after the Ash Wednesday fires was under the regulatory framework of that time and the lake had existing environmental issues as noted. Investigation of current regulatory requirements and appetite

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[12] Sourced from https://www.epa.sa.gov.au/environmental_info/water_quality/programs/lake_bonney on the 11/03/2020.

for such a storage option has not been undertaken in Australia. After the 2002 Canberra fires lake storage was considered, tested with local authorities, and dismissed as an option. Preparation for future events to include storage of logs in water (even private dams) would require significant due diligence in addition to the identification of candidate water bodies.

13.4.4 Social licence issues

While a range of unknown hurdles exist, in theory it may be possible to store fire-impacted logs in a water body. A critical point is gaining a social licence to do so. In Sweden, plans for widespread lake storage of salvage logs encountered local stakeholder resistance and was implemented only in one lake (Sodra, 2006 cited by Whitehead, et al, 2008, p.12). An assessment of impacts on voluntary third party certification (Forest Management and Chain of Custody) status would be required as part of due diligence of water body storage of logs.

13.4.5 Cost effectiveness

Development of a cost profile for log storage and management in water bodies would be required for this option to be considered. Indicative information from South Australia fire salvage suggests a significant difference in costs (in 1985 dollars) between stockpiles and sprinklers (costing $1/m$^{3)}$, compared to Lake Bonney storage ($2.60/m^3).

13.5 Best practice

Best practice 90: Review and comply with the environmental and regulatory requirements to undertake in water storage of logs in a water body.

Best practice 91: Review the environmental impacts of water-based log storage under Australian conditions.

14 Storage strategies – as woodchips

14.1 Summary

Stockpiles of woodchips create ecosystems with their own biological processes. A woodchip pile develops three layers: an outer weather layer, an aerobic layer and an inner core with anaerobic conditions. Woodchip degrade is minimal in the weather and aerobic layers and pile management aims to reduce deterioration by minimising development of an anaerobic layer. It is critical to maintain air passageways from the centre of a woodchip pile to allow heat and moisture to escape. A woodchip pile should be triangular and no more than 10-15 m high, receive uniform woodchips with minimal fines and not be managed with heavy plant (which can crush woodchips, resulting in fines). Drier woodchips from fire-impacted trees that have dried out are more susceptible to fine development. A woodchip pile will occupy a significant area (e.g. a 10 m high pile 10 m long would hold 316 to 522 m^3 roundwood equivalent of woodchips), generate a range of leachates and require protection to reduce risk of contamination (e.g. with plastics). A woodchip pile base can be solid or have a sacrifice layer. A broad range of regulatory requirements must be addressed.

14.2 Introduction

Woodchip handling facilities vary in configuration matched to the intended use for either on-site supply at a domestic processor or for export. Stockpiles are usually adjacent to recovery systems to facilitate loading and can be limited in area. In some examples, logs are processed in-field and woodchips are delivered by truck, processed at satellite static chipmills and delivered to a facility by road freight (e.g. Midway's Myamyn facility) or by rail. Surge capacity will require off-site storage in appropriately developed sites. For example, WAPRES has a primary site at the Port of Bunbury with chipping and stockpile capacity at the Diamond Mill (WAPRES, 2017); the company makes use of surge (satellite) stockpiles, stockpiles for biomass and softwoods. This section addresses woodchips management from fire-impacted plantations.

14.3 At roadside *in situ* storage

Hardwood woodchip production can include in-field chipping (IFC) of trees. Trees are fallen and bunched for extraction to roadsides. At the roadside trees, are de-barked and IFC direct into a waiting van trailer. Under such operations c.0.5% of annual production is held in transit. An option to manage a surge in production due to fire is to in-field chip smaller logs in each plantation and retain woodchip stockpiles *in situ* until required by the market. A point of caution is that woodchips recovered from dead standing trees will break down faster than green-processed woodchips, limiting successful storage duration. Other issues to consider are presented in Box 31.

Box 31: Key issues to address in selecing a woodchip stockpile site.

- Control: A temporary storage site within a plantation is likely to be difficult to control.
- Carbon: There is a risk of carbon contamination from the surrounding environment if a storage stockpile is within fire impacted plantations.
- Contamination: Woodchip specifications are stringent on contamination by a range of items.
- Security: A woodchip stockpile could be exposed to a range of mischief and vandalism.
- Services: A temporary storage site will lack service (e.g. electricity and water).

With a CTL system, harvested trees are delivered within three days, suggesting 1.5% of annual production in transit at any time. In some cases, there is a preference to hold log stocks at roadsides to allow a degree of drying to reduce weight before delivery to an export woodchip facility. It is unlikely that an increase in production due to fire salvage can be held in the forest as logs due to degrade (e.g. bluestain with softwoods), so delivery will be required.

A relatively new market is to export biomass for energy production. Under such systems trees are harvested and bunched as whole-trees that remain on-site for 4-6 weeks prior to extraction, IFC and transport. Under such systems c.15% of stocks are in transit at any one time. This method could increase on-site storage to address a fire salvage surge in resources.

14.4 Woodchip degrade and losses

Engineering requirements of a permanent woodchip storage facility are well documented (e.g. Smook, 2002) and understood, with high levels of sophistication and control. Development of temporary woodchip storage capacity will require a balance between ‘fit for purpose’ outputs and costs. The overall objective is to:

- ensure a relatively uniform mix of fire origin woodchips on the chip pile
- provide a uniform infeed to pulping sites (woodchip moisture content is a key issue).

During storage, biological materials decompose as a result of chemical (Wästerlund et al, 2017, p.182) and biological (wood components metabolised by fungi: Heinek et al, 2015, Abstract; Wästerlund et al, 2017, p.182) processes resulting in dry matter loss. Biological and chemical actions can also result in woodchip discolouration during storage. Significant discoloration is caused by bluestain fungi, brown-rotting fungi and by some thermophilic (tolerate high temperatures) ascomycetes (FAO (1976, p.106). Discoloration is often extensive in hotter zones of a woodchip pile with low pH (FAO, 1976, p.106). The degree and rate of decomposition primarily depend on woodchip moisture content, temperature and time. With increasing storage time and change in temperature, a woodchip pile undergoes a succession of microflora (Smith, 1972 cited by FAO, 1976, p.106). Under North American conditions, it is assumed that woodchips in stockpiles reduce in wood substances by 1%$_{\text{WEIGHT}}$/month of storage due to a combination of respiration, chemical reactions and microbial activity (Smook, 2002, p.33). In another example, storage of woodchips for heat and energy production recorded weight losses of up to 5% /month (Heinek et al, 2105, Abstract). A trial of biomass for energy storage recorded pile volume reductions of 3-% after 5.5 months: an uncovered compacted pile shrunk c.6% in volume over the same period (Wästerlund et al, 2017, p.182). A fundamental difference between a green and fire-impacted woodchips is that a green woodchip delivered to a stockpile is still respiring.

An option is to recover fire-impacted logs, process into woodchips and store in woodchip piles. A trade-off with temporary storage under less than perfect conditions is that some loss of woodchips (e.g. due to pressure and decay at the base of a stockpile) will be expected but with a gain by saving of otherwise ‘lost resources’. This reduces a requirement to transport resources from other regions to fill local supply gaps. A key concern is how long woodchips in such stockpiles will be ‘fit for purpose’.

Development of temporary woodchip stockpiles will require either delivery of woodchips or development of on-site processing capacity. A key point will be the quality of logs and woodchips delivered, and the quality of woodchips placed in stockpiles. A need for quality woodchips is heightened with prospective increased time in storage. Issues such as bluestain and fines need to be addressed to avoid contamination of sound woodchips with decayed wood. Screening fines and oversized woodchips will be required before placement in stockpiles (Smook, 2002, p.33). Bluestain log tolerances will need to be set and enforced.

14.5 Storage sites

14.5.1 Storage site requirements

Development of temporary woodchip storage capacity needs to secure an appropriate site. Scale of proposed stockpiles will drive the area required. Appropriate sites need to address the points in Box 32.

Box 32: Key issues to address in selection of site for a woodchip stockpile.

- Regulatory: Any local and state government requirements, including change in operating hours, noise and increased on-site capacity.
- Community: There are likely to be community issues due to changes in truck movements, noise and other environmental changes.
- Hygiene: Management of site hygiene will be critical. Adequate space will be required to separate de-barkingof fire-impacted logs with a risk of carbon dust or particles, entering stockpiles. Other pollution risk factors include potential contamination with wind-blown plastics and other refuse.
- Access: Road access is needed for increased truck movements and for marshalling of trucks within a site.

Development of storage bunkers with overhead protection is not required (Heinek et al 2013, Conclusions). For kraft pulping, outside woodchip storage, while resulting in a reduction of pulp yield and quality, is balanced against advantages in handling and transport (FAO, 1976, p.115). Routine woodchip stockpile management seeks to recovers and use 100% of woodchips, hence a well-managed stockpile does not have a sacrifice layer base. A base is required on which to build a woodchip stockpile (Smook, 2002, p.33). If a woodchip stockpile is created directly onto earth, mixing with soil is possible as the base layer is compressed into the ground. Crushed rock is an option as a base, but greater care is required during woodchip recovery to manage contamination risks. An alternative is use of geotextiles to prevent layer mixing or to assume a sacrifice layer. More permanent solutions include engineering a solid foundation (e.g. a concrete base or use of cement stabilisation).

14.5.2 Site OHS and environmental issues and regulatory requirements

A range of OHS and environmental issues require addressing. While in some cases no evidence of significant health risk arising from exposure to wood dust or fungal spores during routine operations was found, a point of caution based on experience in Sweden is to minimise exposure to woodchips that have been stored (Garstang et al, 2002, p.iii&88).

Environmental issues will require addressing for temporary site development for longer-term storage of woodchips. Woodchips can generate leachate that can contaminate streams (Rex et al, 2016, p.1). A Canadian study found that all '*woodchip types produced a toxic leachate despite differences in their chemistry. The consistent toxicity response highlights the need for runoff management that will disconnect processing sites from aquatic environments*' (Rex et al, 2016, p.1). Storage allows leaching of wood extractives (Smook, 2002, p.33) and large woodchip piles have the capacity to release leachate quickly and for an extended period. These findings indicate that woodchip stockpile runoff should be maintained on-site (Rex et al, 2016, p.12). With longer-term storage, this issue will require specific solutions, particularly with storage over winter months. This points to a need for careful site selection and design of site infrastructure, and a checklist of issues to address during regulatory approvals processes. There is also a need to understand and work with government to seek a rigorous but expedited process; government cooperation is critical.

14.6 A woodchip stockpile

14.6.1 Woodchip stockpile structure

A woodchip stockpile is composed of three zones, each with different growth conditions for micro-organisms (Heinek et al, 2105, p.42).

- Weather layer: A layer in direct contact with ambient conditions between 0.2-1.0 m deep depending on woodchip quality and stockpile shape (Heinek et al, 2105, p.42). Moisture content is generally highest in this layer (Garstang et al, 2002, p.ii) with most moisture from condensation of water vapour from lower parts of the stockpile and from rainfall (FAO, 1976, p.104).
- Aerobic layer: The aerobic layer is the biggest zone of a woodchip stockpile, with optimal growth conditions for fungi. Temperatures range from 20°C to 45°C but can reaches 60°C if air permeability is inhibited by compaction or a high fines content in the woodchips. Due to vaporisation and condensation of water, wet and dry parts alternate in this zone (Heinek et al, 2105, p.42).
- Anaerobic layer: With increased woodchip stockpile height (beyond c.15 m), an anaerobic zone (core) can develop. Compaction, fine content and moisture content trigger an anaerobic zone (Heinek et al, 2105, p.42).

Compaction contributes to woodchip deterioration by restricting air movement into a stockpile and creation of anaerobic conditions (Fuller, 1985, p.51; Heinek et al, 2105, p.42).Woodchips should be piled loose, rather than compacted, in '*order to maximise convective heat loss and related moisture loss, and reduce risk of spontaneous combustion*' (Garstang et al 2002, p.88). Permanent woodchip stockpiles have infrastructure to deliver woodchips directly to a pile (FAO, 1979; Snook, 2002, pp.33-34; Fuller, 2005, p.48). A challenge with woodchips stockpiles developed in response to fire salvage will be delivery of woodchips to a stockpile without creating adverse compaction.

14.6.2 Woodchip stockpile dimensions

A high triangular section woodchip pile, with flanks formed by the natural angle of repose of woodchips (rather than flat topped) will reduce deterioration by shedding rainfall (Smook, 2002, p.33; Heinek et al 2013, Conclusions) and reducing the surface area exposed to sunlight (Smook, 2002, p.33). Woodchip stockpiles can be conical or linear (Fuller, 2005, Chip storage and handling). Storage capacity is determined by height and width (fixed by the angle of repose) and length for linear stockpiles. The literature suggests 10 m (Garstang et al, 2002, p.88; Heinek et al, 2013, Conclusions) to 15 m (Fuller, 1985, p. 51) as maximum woodchip stockpile heights. The driver of stockpile height limits is to allow adequate ventilation (to reduce stockpile heat build-up) (Fuller, 1985, p. 51; Garstang et al, 2002, p.88; Heinek et al, 2013, Conclusions). The angle of repose of a woodchip pile is 42° to 55°. Examples of linear woodchip pile storage capacity are calculated and presented in Table 28: as angle of repose increases, stockpile footprint and volume decreases for the same height. A stockpile of 100,000 m^3 solid wood equivalent of woodchips with a 42° angle of repose stacked 10 m or 15 m high would be 3.9 km or 2.0 km long respectively. A perfectly conical 10 m high woodchip pile with an angle of repose of 55° would have a capacity of 1122 m^3 of woodchips with a circular footprint of 962 m^2 and a square footprint of 1225 m^2.

Table 28: Example of calculated woodchip storage capacity for 10 to 15 m height stockpiles.

	Maximum height (m)	Angle of repose (o)	Calculated maximum width (m)	Calculated footprint (m^2/10m)	Volume (m^3/10 m length)	Fluffing factor (m^3/m^3)	Woodchip volume (m^3/10 m length)
Lower range	10.0	42°	29.9	299	1494	2.86	522
	15.0	42°	44.8	448	3361	2.86	1175
Upper range	10.0	55°	24.4	244	1220	2.86	316
	15.0	55°	36.6	366	2746	2.86	565

14.7 Woodchip attributes

14.7.1 Woodchip moisture content

Woodchip moisture content, particularly its uniformity, affects kraft pulping (van der Merwe et al, 2016, Abstract). Woodchips recovered from green wood have a moisture content of c.67–150%$_{\text{DRY BASIS}}$ (FAO, 1976, p.104). In many cases, moisture content of fire-impacted woodchips is very low c. 15–25% $_{\text{DRY BASIS}}$ (Pickrell 1998 cited by Watson & Potter, 2004, p.475). A driver of reduced moisture content can be the scale of a fire salvage harvest and duration of storage on the stump, delays in log recovery, storage on in-field stockpiles and delivery. For example in South Africa, moisture content of woodchips produced from logs dried for two weeks was 5.5% to 13.2% lower than woodchips produced from logs dried for one week (van der Merwe et al, 2016, Abstract).

If planned salvage stockpiles are intended for static long-term storage, uneven moisture content will increase. Natural air drying can reduce woodchip moisture without unacceptable degradation in the core of a stockpile where woodchips are insulated from ambient conditions by a surface 'weather layer' (Garstang et al 2002, p.88). Storage during summer can result in woodchips lower in a stockpile and in the sides becoming drier, a decrease of c.10% after three months' storage. With storage over winter, woodchips in the centre zone are driest relative to other zones (FAO, 1976, p.104). Uneven woodchip moisture content will require management (at utilisation) and mixing of dry with green woodchips to increase dry woodchip moisture content is minimally effective (Pickrell, 1998 cited by Watson & Potter, 2004). While log storage under sprinklers is an accepted method, sprinkling of woodchip stockpiles is much less favourable. Historic data suggests that in the southern United States, water spraying over woodchips was found to offer no advantages over dry woodchip storage in preserving wood and pulp quality (Bois et al, 1962; Djerf & Volkman, 1969 cited by FAO, 1976, p.110). It was proposed that '*the reason why water spraying is less effective for chips than roundwood is probably the difference in microflora. The soft rot fungi which are common in chip piles can tolerate a considerably higher moisture level than the fungi which are common in logs*' (Bergman, 1972 cited in FAO, 1976, p.111).

14.7.2 Woodchip dimensions uniformity, fines and management

In routine pulpmill operations, woodchips are conveyed to stockpiles and in some cases they simply fall from the end of a conveyor or a jet-slinger is used (which may fragment woodchips and increase fines). Increased fines with a jet-slinger can be more an issue with finely tuned operations that aim to maintain woodchip dimensions specific to different processing: woodchip sizes can vary between different pulping systems (e.g. NSSC, continuous kraft and batch kraft mills) and with tree species. Given that woodchip stockpile airflows are critical to maintenance of quality, the aim is to store as uniform as possible woodchips to create air pathways.

A comparison of woodchip and biomass storage concluded that standard woodchips had lower losses and microbiological growth (Heinek et al, 2013, Conclusions) compared to biomass which was more susceptible to fungal growth with higher biomass loss (Heinek et al, 2013, Abstract).

14.8 Woodchip stockpile management

14.8.1 Initial processing

A first step is to ensure that chipping generates as uniform a woodchip size as possible with minimum fines to provide a low resistance to air-flow within a stockpile (Garstang et al, 2002, p.88). A reduction in fines on average and per batch of woodchips added is important; concentrations of fines in a woodchip stockpile will inhibit dissipation of heat generated within (Smook, 2002, p.33). In one example, it was stated that fine content should be kept low and that woodchips should not be stored longer than one month (Heinek et al, 2013, Conclusions). Woodchip uniformity can be impacted by chipping dry and smaller logs. South African experience found that with one and two weeks drying, over-thick woodchip production increased with decreasing log size, reducing accepts produced. Logs dried for two weeks produced woodchips with significantly less under-sized woodchips than logs dried for 1 week (van der Merwe et al, 2016, Abstract). This experience is consistent with reported increases in fines and oversized woodchips recovered from processing fire salvage logs down to an SED of 7 cm.

14.8.2 Woodchip handling methods

Each woodchip handling event can increase fines and/or fibre loss reducing pulp yield. With routine operations, woodchips are more friable after storage (due to drying) than when placed into storage (FAO, 1976, p.109). This suggests that increased fine production from handling initially drier fire-impacted log sourced woodchips is possible with handling onto woodchip stockpiles. Bulldozing will increase fines content by physically breaking woodchips into smaller pieces (FAO, 1976, p.109). Caution is required during delivery of woodchips to a stockpile with 'pneumatic conveyors' as fines slow down more rapidly than woodchips (particularly against the wind), which may result concentrations of fines within a stockpile (FAO, 1976, p.109).

14.8.3 Woodchip stockpile management objectives

Table 29 gives a summary of management to reduce potential degrade of woodchips stored in stockpiles (based on Fuller, 1985, p.51). A primary objective is to maintain air passages throughout a stockpile. Duration of storage is a key variable as woodchip deterioration is largely a function of time in storage (Smook, 2002, p.33). While routine operations address this issue by woodchip stockpile management on a first-in first-out basis (Smook, 2002, p.33), this may not be possible with long-term storage of fire-impacted trees processed into woodchips. For example, routine pulpmill management seeks to turn over softwood woodchip stockpiles on a 9.5 day cycle based on the time for woodchips to dry (to a target level) and phenols to evaporate (phenols can cause un-desirable foaming during pulping). A typical operation takes woodchips to paper in 10 days, hence stockpile size is based on this parameter. Industry information suggests that a well-managed softwood stockpile could last 3-6 months with dry woodchips. Long-term storage of fire salvage origin woodchips in stockpiles will require monitoring to identify conditions favourable to degrade. Research has indicated that NIRS analyses provided a good correlation between wet chemistry and dry matter, lignin and cellulose content. This technology has potential application to predict woodchip degradation in stockpiles (Garstang et al, 2002, p.iii).

Table 29: A summary table of key management issues for woodchip stockpile.

Recommendation	Deterioration mechanism involved	Adverse impact	Benefit
Maintain stockpile height below 15 m.	Avoids compaction	Reduction in air passages	Allows faster escape of heat generated by woodchip respiration, microbial growth and chemical reactions.
Restrict tractor spreading of just-delivered woodchip to a minimum.	Avoids excessive compaction.	Reduction in air passages	Allows faster escape of heat, particularly in reclaim pit or conveyor areas.
	Fines created by tractor movement.	Reduction in air passages	Allows faster escape of heat generated by woodchip respiration, microbial growth and chemical reactions.
Avoid including fine particles (e.g. sawdust, shavings & woodchip fines)	Increased fines delivered to a stockpile	Reduction in air passages	Avoid creating compactions zone which prevents heat escape.
Avoids creating compacted zones in woodchip stockpiles, particularly where layering can occur.	Mixing fine particles (e.g. sawdust, shavings, woodchip fines pulp mill knotter rejects) creates excessive compaction.	Reduction in air passages	Avoid creating a compaction zone that prevents heat escape.
Avoid mixing species with different deterioration rates.	Pockets of woodchips fast-deteriorating species.	Heat generation resulting in a larger zone of high-temperature woodchips.	Avoids high temperature deterioration.
Store full-tree chips (containing bark, foliage and living parenchyma (ray cells), in piles less than 8 m high for less than 2-4 weeks	Bacteria, mould and fungi can thrive on fresh wood, bark and foliage.	A very rapid build-up of heat.	Avoids some of high temperature deterioration.
Monitor stockpile temperature routinely.	Excessive heat build-up.	Biological & chemical impacts on woodchip quantity & quality.	Determines the heating pattern of a particular storage system. Allows early detection of heating problems.

14.9 Recommended best practices

14.9.1 Pre-event planning

Best practice 92: Develop a checklist of issues to address and approvals processes with Government. There is a need to understand and work with Government to seek a rigorous but expedited process. Government cooperation is required to make things fall into place.

14.9.2 Storage

Best practice 93: Design woodchip stockpiles that are no more than 10 to 15 m high, and triangular or conical in shape; a woodchip pile should not have a flat top.

Best practice 94: Aim for woodchips that are uniform in size and have minimal fines. This will maximise effective ventilation of moisture and heat. To reduce the risk of woodchip breakdown and creation of fines, do not use heavy plant to handle woodchips. Screening of woodchips may be required prior to storage.

Best practice 95: Deliver woodchips to a stockpile without creating adverse compaction.

Best practice 96: Development and manage the stockpile to keep woodchips in a ‘fit for purpose’ state.

Best practice 97: Address design and composition of the base beneath the pile. A base can be a sacrificial layer of woodchips or engineered (e.g. rock, cement or bitumen) with implications for cost and recovery of woodchips.

Best practice 98: Manage water runoff, which will have a range of chemical compositions.

Best practice 99: Maintain woodchip hygiene as this is critical to subsequent use and acceptance by markets.

Best practice 100: Select an appropriate site for woodchip storage. A woodchip stockpile can have a significant footprint. An ideal woodchip stockpile is triangular is shape and well aeriated to reduce woodchip deterioration particularly with longer duration storage.

Best practice 101: It not a requirement to apply water to a woodchip stockpile to maintain woodchip quality. A woodchip stockpile will reduce and stabilise in moisture content with time due to air movements.

Best practice 102: Blend fire-impacted logs in to dilute potential impacts of drier logs at the point when de-barked logs are chipped. If the scale is beyond acceptable limits, logs can be batch chipped.

Best practice 103: Woodchips delivered to a stockpile may require screening, depending on the fines levels. Determine how well fire-impacted logs, which may be drier, are chipping (e.g. the level of fines produced).

Best practice 104: Document and consider potential environmental impacts of woodchip stockpiles under local conditions and for the species of woodchips stored.

Best practice 105: Document and consider regulatory approvals required to develop a woodchip stockpile either standalone or as part of an existing facility..

14.10 Observations

Observation 56: Research options for the base of a woodchip stockpile. In a simple case, this can be crushed rock; with crushed rock greater care is required during woodchip recovery to manage contamination risks. An alternative is use of geotextiles to prevent layer mixing or to assume a sacrifice layer. More permanent solutions include engineering a solid foundation (e.g. a concrete base – there is potential for use of cement stabilisation systems

Observation 57: Research has indicated that near infra-red reflectance spectroscopy (NIRS) analyses provided a good correlation between wet chemistry and dry matter, lignin and cellulose content. There is a need to understand this option and other technology to assist with the management of woodchip stockpiles.

15 Fire and wood properties

15.1 Summary

Impact of fire on log utility has been the subject of many studies. Carbon on a tree stem and logs is an obvious impact but the wood within a burnt tree maintains its attributes immediately after a fire. It is possible under extreme fire storm conditions that mechanical damage (compression fractures) can result due to wind forces. The other exception is where a crown fire removes foliage, causing a drop in transpiration and water within a tree stem, which creates pressure on cell pits resulting in pit aspiration (closure). This is the first of a number of changes to wood involving water conductance with time since a fire event and storage methods. If wood is subject to direct heat (>100°C) for more than c.1 hour, there are impacts under laboratory conditions. The heat of a fire is unlikely to penetrate greatly into a tree's stem and therefore there is limited direct impact. With time and storage on the stump, drying from the top down will increase brittleness during harvesting and affect pits. Bluestain may penetrate a stem and create localised uneven sections with changed permeability. Where logs are stored in wet conditions, bacterial action will increase wood porosity within logs by damage to pits and consume cell contents, all contributing to increased permeability. These effects reduce log homogeneity and require judicious batching of logs for processing and drying. Logs should be batched based on green (unburnt), fire impacted (segregated into fire storm or not) and, after storage on the stump, by position within tree stems as a proxy for degree of drying. Regardless of other segregation, logs that have been wet stored should not be processed with other logs (due to increased porosity and permeability). Due to differences in initial moisture content and permeability, published information recommends that fire impacted logs, particularly after wet storage, should be kiln dried with a gentler drying gradient and be reconditioned (equalised) pre-grading. An important point is that machine grading is unlikely to identify compression fractures that may cause failures once in service.

15.2 Introduction

Timber 'fit for purpose' is defined against an intended use (e.g. structural timber for house construction). Mechanical properties of timber include density (green, air dry and kiln dried – see Appendix 2: Wood attributes), modulus of elasticity (MoE), modulus of rupture (MoR), and hardness. All mechanical attributes combine to define the utility of a single stick of timber. This is simplified by development of timber grading systems where a single grade supported by design specifications allows safe use of timber. This section provides the culmination of fire impacts and storage on wood properties.

15.3 Historic studies

Studies of the impact of fire, log utilisation and storage on the stump on wood properties have been undertaken for natural forest resources (e.g. 1939 fire killed *E. regnans*, Turnbull et al, 1950a) and for plantation grown softwoods (e.g. *P. radiata* plantations in South Australia – see Box 33). A trial researched natural forest *E. regnans* trees killed by the 1939 fires that were either harvested and storaged under sprinklers for nine years (Turnbull et al, 1950b) or harvested after 10 years storage on the stump (Turnbull et al, 1950b). Tree stems were segregated into butt, centre and top logs and the outcomes are presented in Figure 29. The study compared the two treatments but did not present a control dataset of green direct-to-mill outcomes. Boards produced were graded and initial recovery is presented. The boards were then re-graded to remove defects to maximise grade recovery. Figure 30 presents the re-grading percentage increase in grade.

The study concluded '*that the salvage method of dumping and spraying fire-killed E. regnans logs ensured satisfactorily utilization at least for a period of 9 years after fire damage*' (Turnbull et al 1950a, p.1). Of note is that difference in butt log grade recovery was less than that for centre and top logs between storage on the stump and under sprinklers. This may reflect maintenance of log moisture content in butt section of standing trees but this was not reported. Re-graded board recovery of select grade indicated that storage under sprinklers better 'preserved' wood quality compared to storage on the stump.

Figure 29: Recovery of select grade or better from 1939 fire killed *E. regnans* after storage on the stump or as logs under sprinklers (based on Turnbull et al, 1950a&b).

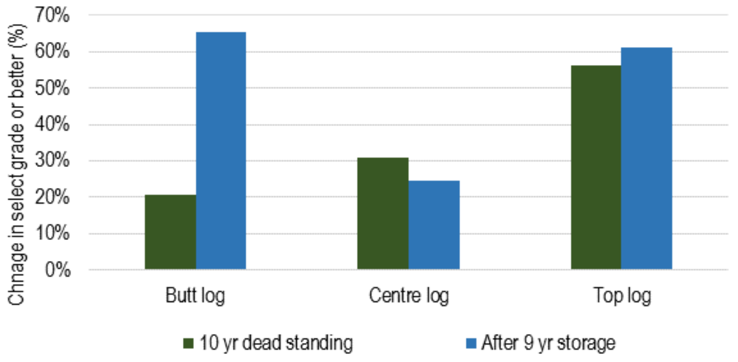

Figure 30: Change in percentage select grade or better with re-grade (based on Turnbull et al, 1950a&b).

Box 33: Timber properties, variation within trees and impacts of fire (bluestain) have been a subject of past research.

1930/31 Woods and Forests Annual Report:

'The milling of burnt Pinus radiata at Caroline was completed in February, and a total volume of 1,800,000 super feet [4248 m^3] *was salvaged from the area. The milling of this burnt stand was not completed until over two years after the fire, and the quality of the sawn product was maintained throughout, thus discounting general opinion that the timber of this species is useless a short time after a burn.'*

(Note: at that stage nil air drying, grading standards & probably not for structural applications.)

1940/41 Woods and Forests Department, South Australia Annual report:

'*Attention was direct also to various matters connected with timber as opposed to the growing trees, and the work done embraced , inter alia; investigation of moisture content of the wood throughout the year and its variation with age and other factors; the density of wood produced under varying conditions and at different points in the stem; the influence of defects, such as knots, cone holes, and pith on the grade of timber produced; the rate of drying of stringybark fuel and pulp wood when stacked in cords, and the occurrence of bluestain in fire killed trees.'*

1941/42 Woods and Forests Department, South Australia Annual report:

'Investigation of the moisture content of logs, the density of wood, and the various causes of defects in sawn timber had to be discontinued. Studies of the rate of drying of radiate cord wood and stringybark fuel were completed, as was that dealing with moisture content and deterioration of the timber of fire killed trees.'

15.4 The impact of heat on wood

15.4.1 The impact of heat in the absence of fire

Research of impacts of heat on wood properties has tested temperature by time interactions (see Box 34 for definitions of exothermic and endothermic). For example, Phuong et al (2007, pp.185 & 186) tested brittleness of *Styrax tonkinensis* after 160˚C, 180˚C and 200°C temperature over 2, 4, 8 and12 hour periods in a nitrogen gas atmosphere; this eliminates combustion and therefore observations are due to heat. Their research found that '*heat treatment made wood more brittle when wood was heated at a higher temperature or for a longer time*' (Phuong et al 2007, p.181). Changes in wood crystallinity (exothermic transformation) may contribute to its brittleness. For example, '*brittleness increased to four times that of the control when wood was heated at 200°C for 12 h'* (Phuong et al, 2007, p.181). After two hours heating at 160, 180 and 200°C, there was little change in wood brittleness (Phuong et al, 2007, p.183, Figure 3). Over the same treatments, there was weight loss of c.1%, 2% to 4% respectively (Phuong et al, 2007, p.183, Figure 4). Samples heated at 160°C for up to 12 h changed less than 2% in weight, with a 37% and 34% increase in brittleness after 8 and 12 h respectively (Phuong et al, 2007, p.183, Figure 3). A clarification is that heat was applied without an ability to combust. It was concluded that '*lignin relocation was suggested as the cause of brittleness at relatively low temperature around 160˚C, in addition to the thermal degradation of amorphous parts*' (Phuong et al, 2007, p.185). Treatment at 160°C, increased brittleness without any change in weight is thought to be caused by relocation of lignin molecules. At higher temperatures, loss of amorphous polysaccharides due to degradation is thought to become the main factor affecting brittleness. The crystallites newly formed after 2 h of treatment showed brittleness that was different from that of the inherent crystallites remaining after 12 h of heat treatment. This inherent crystalline cellulose possibly plays a role in brittleness (Phuong et al, 2007, p.181).

Box 34: Definitions of chemical reaction processes and transformation.*

Exothermic:

- *Exothermic process*: A system releases heat into the surroundings
- *Exothermic transformation*: From amorphous to crystallisation

Endothermic:

- *Endothermic process*: A system gains heat from the surroundings and so the temperature of the surroundings decreases.
- *Endothermic transformation*: From the amorphous to an undercooled liquid state.

*(based on https://chem.libretexts.org/Bookshelves/Introductory_Chemistry/Book%3A_Introductory_Chemistry_(CK-12)/17%3A_Thermochemistry/17.03%3A_Exothermic_and_Endothermic_Processes downloaded on 01/05/2020 & Clavaguera, et al, 1998, p.745)

Change in brittleness is a function of temperature and time. Therefore, it is possible that heat of a fire may impact lignin within a stem's wood but only to the depth where temperature rises above critical thresholds and remains for critical times. Lignin decomposes slower over 200-500°C than cellulose and hemicellulose components of biomass. An endothermic (amorphous to an undercooled liquid state) peak at 100-180°C (at the elimination of humidity) was followed by exothermal (amorphous to crystallisation) peaks from 280 to 390°C and a peak around 420°C with a long tail beyond 500°C (Brebu, & Vasile, 2010, p.353). Thermal degradation of lignin is generally influenced by heat and mass transfer processes (Brebu, & Vasile, 2010, p.354). The impact of temperature and time was considered (Brebu, & Vasile, 2010, p.353):

- Below 700°C: Heated by 10°C/min, lignin decomposes very slowly (<0.15%$_{\text{WEIGHT}}$ /°C), losing only 40%$_{\text{WEIGHT}}$ of its initial mass below 700°C.
- Above 750°C: The degradation rate increases to 0.3%$_{\text{WEIGHT}}$ /°C above 750°C, the mass loss at 850°C being c.67%$_{\text{WEIGHT}}$.

Table 30 presents a summary of published information on heat impacts on wood. Chemical decomposition of wood commences when wood is exposed to temperatures exceeding approximately 100°C (Bowyer et al., 2003 cited in Malan, 2011, p.4). Structural properties of wood are reported to change as a result of heat treatment (Kubojima, 1998; Andersson et al, 2005; cited in Phuong et al, 2007, p.181). A key point is that in a wildfire heat is due to combustion of biomass on-site and standing trees compared to artificial heat applied in a laboratory. Further, heat differentials from outer bark surface to the wood below will change with time but initially there will be differences.

15.4.2 Heat modification due to fire

When trees are killed by fire, there is generally little loss of wood (Wright & Grose, 1970, p.149) unless fire damage burns into stem wood. For example, in *E. delegatensis* (alpine ash) there was no immediate destruction or damage of sound wood, regardless of fire intensity (Wright & Grose, 1970, p.154). Greaves et al (1965, p.161) found that damage to *E. dalrympleana* (mountain grey gum) and *E. delegatensis* attributable directly to fire was less than 5% of defects in merchantable wood. Fire killed *P. radiata* pine (aged c.35 years) had little loss of wood as a result of fire (Wright & Grose 1970, p.149). South African studies of softwood trees killed by fire indicated that, in the majority of cases, fire damage was limited to 2-3 mm of the outer bark layer and nil logs had visible damage to the wood (Malan, 1999; Malan, 2000). Fire-burnt stems can have a layer of charcoal where wood has combusted, but burnt '*stems exhibit a demarcation layer between the char and undamaged wood which is only a few cells thick*' (Watson & Potter, 2004, p.473). While a tree's wood may appear to be intact, it is possible that heat will penetrate through bark and, once at 60°C for one second, kill the cambium and continue to heat the wood beneath. As noted in Table 30, there are a range of heat thresholds (temperature by time) beyond which wood's chemistry is affected.

As a consequence of low thermal conductivity and moderate values for both density and specific heat, wood has a low thermal diffusivity (rate of heating: Panshin & de Zeeuw, 1980 cited by Watson & Potter 2004, p.473). This implies that fire damage will be confined to the outer part of a tree that is in contact with a heat/fire source (Watson & Potter 2004, p.473). Therefore, other than burnt or charred wood, '*the direct effects of fire are fairly minimal due to the high moisture content of live stems and the insulating properties of bark. Thus within days or weeks after the fire, strength properties of wood are scarcely affected, but after longer periods of time the effects increase*' (Neilson, 1998 cited by Watson & Potter, 2004, p.474). South African experience noted that: '*The black-stick appearance of fire-killed trees is thus very deceiving, as beneath the bark and the cambium, the wood is almost always intact. That is why fire-killed trees can usually be logged and milled without any difficulty. Removal of the bark layer usually removes all evidence of the fire'* (Malan, 2011, p.4). Such observations are at odds with a body of research that found '*different cell structure and chemical composition due to thermal degradation could be observed as well as different drying performance and variation in mechanical properties*' (Meincken et al, 2010, p.455). A key point is that there is an issue where a tree's wood does not burn but is scorched and the temperature rises.

Table 30: A summary of the impact of heat on wood components.

Temperature	Impact	Reference
>100°C	Chemical decomposition of wood (pyrolysis) commences.	Bowyer et al., (2003) cited in Malan, (2011, p.4).
100-180°C	An endothermic peak for lignin (at the elimination of humidity) – increased crystallinity.	Brebu, & Vasile (2010, p.353).
100-200°C	Water vapour, carbon dioxide and carbon monoxide are driven off, while chemical decomposition (pyrolysis) commences relatively slowly in the beginning.	Bowyer et al (2003) cited in Malan, (2011, p.4).
100-160°C	Extended exposure results in a migration of fats and waxes along axial parenchyma cells to the wood surface.	Nuopponen, et al (2003) cited in Meincken et al. (2010, p.256).
	At higher temperatures fats and waxes are no longer detectable.	Meincken et al (2010, p.256).
>150°C	When wood is heated, hemicelluloses, degrades breaking down into various volatile components.	Hill (2006) cited in Meincken et al (2010, p.256)
	Hemicelluloses degradation increases with temperature and time of exposure.	Bourgois et al (1989) cited in Meincken et al (2010, p.256).
	Loss of hemicelluloses leads to increased crystallinity of wood and a rearrangement of amorphous cellulose.	Meincken et al (2010, p.256)
160°C	Lignin relocation as the cause of brittleness, combined with thermal degradation of solids.	Phuong et al (2007, p.185).
	Lignin can migrate to the wood surface and result in an observable colour change towards yellow/brown.	Meincken et al, (2010, p.256).
200-500°C	Lignin decomposes slower than cellulose and hemicellulose.	Brebu & Vasile (2010, p.353)
	Lignin (the most thermally stable wood component) thermal degradation commences at relatively low temperatures, producing various phenolic products.	Sandermann & Augustin (1964) cited in Meincken et al. (2010, p.256).
>200°C	Pyrolysis starts to accelerate.	Bowyer et al (2003) cited in Malan (2011, p.4).
At 230°C for 24 hours	Loss of volatile extractives indicated by volatile organic compound (VOC) emission profiles.	Manninen, et al (2002) cited in Meincken et al (2010, p.256).
	Migration of extractives to the surface of wood can result in formation of resin patches and general yellowing.	Hill, (2006) cited in Meincken et al (2010, p.256).
280 to 390°C	A first exothermic peaks for lignin	Brebu, & Vasile, 2010: p.353
260 to 350°C	Flammable gases start to form which with oxygen, may self-ignite if the temperature becomes high enough, or by an ignition source.	Bowyer et al (2003) cited in Malan (2011, p.4).
>270°C,	A fire will support itself; the rate of heat produced is greater than the heat required to generate wood gas.	Bowyer et al (2003) cited in Malan (2011, p.4).
> 300–340°C	Crystalline cellulose degrades.	Kim et al. (2001) cited in Meincken et al (2010, p.256)
	Extended exposure, results in scission of cellulose molecules, decreasing the degree of polymerization and crystallinity.	Hill (2006) cited in Meincken et al (2010, p.256).
c.420°C	A second exothermic peak for lignin.	Brebu, & Vasile (2010, p.353)
>500°C	A long exothermal tail for lignin	

15.4.3 Heat modification due to kiln drying

Kiln drying aims to reduce wood moisture content in a controlled manner. Box 35 presents high-order details of kiln-drying schedules for *P. radiata* boards. The maximum temperature is 120°C (ambient air temperature basis) under a high-temperature schedule. Based on data in Table 30, at 120°C the change in wood properties commences with water vapour, carbon dioxide and carbon monoxide being driven off, while chemical decomposition (pyrolysis) commences. In summary, controlled kiln drying is unlikely to reach temperatures impacting broader wood properties.

Box 35: An example of a kiln drying schedule for P. radiata sawn timber (Ananias et al., 2012, p.2).

After warm-up, the schedule moves into the drying stage by gradually increasing the difference between dry-bulb and wet-bulb temperatures with time.

In average numbers, dry-bulb/wet-bulb temperatures for drying 40 mm radiata pine could reach approximately:

- 70/50°C for a 72 h conservative schedule.
- 90/60°C for a 36 h accelerated schedule.
- 120/70°C for a 12 h high temperature schedule.

The dried lumber is then allowed to cool down for about 1 h, assessed with a handheld meter for average moisture content, and finally exposed to a conditioning stage in which air humidity is maintained as close as possible to saturation for another 4 h.

15.5 Other mechanical damage to wood as a result of a fire

Localised defects in wood can result from severe stress in a tree due to high winds and cause serious reductions of tensile strength and impact resistance leading to a brittle fracture. Such impacts are difficult to detect visually and machine grading is ineffective due to the very localised nature of the defect (Bootle, 1996, pp.31&32). Differences in attributes of fire events are noted in Box 6. In extreme fires, a fire storm may generate high winds (Box 7). This can be addressed in the fire mapping protocols to potentially predict areas where a higher incident of compression fractures is possible.

15.6 Surviving trees and impact on wood properties: resin content

The extent to which fire damage affects wood production depends on whether the trees are killed by the fire (Wright & Grose, 1970, p.150&151). Softwoods can survive a fire and grow on, with impacts on growth rates, wood properties and resin content. Nicholls and Cheney (1972) investigated sawn timber losses due to degrade for 28-year-old *P. radiata* trees after a series of experimental fires with a range of intensities. They found that, in some cases, average wood density was slightly decreased in the first year (Nicholls & Cheney 1972, p.177). Fires with higher maximum intensities caused physical damage to some trees, with a slight loss of sawn timber volume (Nicholls & Cheney, 1972, p.176). In South Africa, after a fire in a softwood plantation, newly formed growth rings were narrower. It was speculated that this was probably accompanied by slight changes in some wood properties, particularly density (Malan, 2011, p.6&7). The effect on wood quality of cambial injury to *P. caribaea* and *P. elliottii* was not localised to the immediate area of injury, potentially extending up and down a stem (Harding, 1989, p.5). Fire-caused wood quality defects to *P. caribaea* and *P. elliottii* (apart from those associated with injury overgrowth) did not extend to wood laid down post-fire (Harding, 1989, p.4).

Abnormal quantities of resin are considered a defect because it makes boards more difficult to machine and coat with paint. Based on Queensland experience with southern pines, wood quality defects result from fires only where there is cambial injury/death (Harding, 1989, p.4). Resin pockets formed in *P. radiata* where fires were severe enough to cause mechanical or physiological damage were described as '*copious resinous accumulations occurred; but there was not an overall increase in resin content within the stem*' (Nicholls & Cheney, 1972, p.177). Van Loon (1967, p.28) described resin pocket formation in *P. taeda and P. elliottii* following fire. Resin was secreted covering exposed wood and impregnating stem wood radially inwards from the injured surface. The wood covering the injury grew from uninjured cambium surrounding the dead tissue and was not connected to the inner wood; due to the irregular nature of its growth, irregularities in grain direction were expected. In Queensland after fire, resin impregnation by *P. caribaea* is not typically as heavy as for *P. elliottii* (Harding, 1989, p.4), and cambial injury to *P. caribaea* may initiate more widespread wood discolouration around the complete stem than *P. elliottii* (Harding, 1989, p.4). With *P. elliottii*, typical fire damage involves localised resin impregnation behind the arc of cambium death (Harding, 1989, p.4). Resin bleeding in *P. caribaea* and *P. elliottii* is not an indicator of internal resin impregnation unless associated with an apparent open wound (e.g. snigging damage or localised bark burn through) (Harding, 1989, p.4).

15.7 Post-fire impacts on pit function and wood permeability

15.7.1 Fire impacts (crown and moisture loss) and pit aspiration impacts wood drying and permeability

Because of its impact in reducing permeability (with nil change in porosity), pit aspiration has long been of interest (Hart & Thomas, 1967, Abstract). As wood dries, pit torus are displaced, contacting pit borders and this is referred to as pit aspiration (Comstock, & Côté, 1968, p.280). Aspirated pits are effectively closed to passage of moisture. Zhang and Cai (2008) found that pit aspiration can play a major role in the effectiveness of moisture removal from wood during drying. Studies have demonstrated that pit aspiration decreases permeability in all softwoods (Koch, 1972, p.309). The forces that cause it are presented in Hart and Thomas (1967; cited by Comstock, & Côté, 1968, p.280). Aspirated pits result when a tree's crown stops functioning after a fire. It is speculated that the sudden drop in transpiration on the closed water system can cause pit aspiration; a pressure differential forces pit membranes towards their borders and the tori, to seal the pit aperture, isolating vapour-filled columns from the sap-conducting columns (Walker, 2006 cited in Malan, 2011, p.17). In the process, moisture is trapped in pockets inside the stem, which is more difficult to remove during drying compared to other parts in the stem. Pit aspiration is possible with storage on the stump as stems lose moisture and dry. Where sawn timbers are to be treated (e.g. with LOS), wood permeability is a key attribute. Industry experience suggests that a higher frequency of aspirated pits after drying results in significantly lower permeability of wood, increasing the difficulty achieving required penetration of preservative chemical solution for H2 and H3 products. Treatment schedules require modification to increase pressures and time under pressure to get more chemical solution into the wood.

15.7.2 Water storage, bacteria increased porosity and impacts wood drying and permeability

Log storage under sprinklers is a long-term strategy. Greaves (1971, p.8) noted that most reports describing bacterial decay of wood in natural environments illustrate a long-term hazard. Laboratory-induced decay with bacteria generally requires incubation periods of 1½-2 years. UK experience found that three years water storage increased the porosity of *P. nigra* (Corsican pine) and *Picea sitchensis* (Sitka spruce) by 50% (Maun & Webber, 1996, p.40). Increase in porosity was often apparent after six months (Maun & Webber, 1996, p.35) and more than 50% of the increase in porosity occurred during the first 12 months (Maun & Webber, 1996, p.40). Based on this experience, it was suggested that softwoods should not be stored for more than 6-12 months when very porous timber is unacceptable to end markets (Maun & Webber, 1996, p.40).

15.7.3 Effect on wood utility of increased board permeability

Increased timber permeability has been documented after log storage under sprinklers (Webber & Gibbs, 1996, p.x; Malan 2011, p.2). Bacteria-induced porosity results in excessive absorption of moisture, adhesive, paint, or preservative during treatment or use. This impact has been an issue for sapwood processed after log storage immersed in water (Highley, 1999, pp.14-19). While not making reference to sawn timbers, Highley (1999, p.14-19) noted that there '*is evidence that bacteria developing in pine veneer bolts held under water or sprayed with water may cause noticeable changes in the physical character of the veneer, including some strength loss*'.

- <u>Porosity</u>: Increased porosity '*could either be a friend or a foe*' (Malan, 2004, p.77). It increases permeability and will allow chemicals and moisture to diffuse quicker through the wood (Malan, 2004, p.77).
- <u>Wood quality</u>: Increased permeability negatively influences check-formation properties of sawn products (Malan, 2004: p.77).
- <u>Preservative treatments</u>: Penetration of preservatives can be improved with increased porosity (Dunleavy & Fogarty, 1971 cited by Liese, 1984, p.127) and bleeding of creosote-treated pine poles may be prevented (Liese, 1984, p.127). Increased uptake of preservative treatments, potentially in excess of what is required for effective protection, thereby adding to the cost of treating against stain and decay (Maun & Webber, 1996, p.40).
- <u>Drying rates</u>: Differences in drying rates due to increased porosity, result in different moisture contents between and within boards at the end of drying cycles (Malan, 2004, p.77).
- <u>Surface finishing</u>: Uneven absorbance of surface finishing layers in pine furniture manufacture and other surface finishing (Maun & Webber, 1996, p.40; Malan, 2004, p.77).
- <u>Fungal attack</u>: Bacteria or a succession of bacteria increased permeability of wood structure predisposes wood to fungal attack (Clausen, 1996, p.105). A caveat is that UK experience found that boards sawn from pine logs '*wet stored for 6 months quickly suffered surface defacement from moulds and sapstainers* [bluestain]' but little defacement occurred in boards cut from logs stored for two to three years. It was suggested that nutrient leaching associated with long-term water storage and the inhibitory action of bacteria in wet stored wood reduced fungal action (Webber et al, 1996a, pp.ix&x).
- <u>Surface coatings</u>: Increased permeability results in increased absorbance affecting surface finishing (e.g. varnishing, painting and other sealants) (Malan, 2011, p.2).
- <u>Gluing properties</u>: Increased permeability results in increased absorbance affecting gluing characteristics (Malan, 2011, p.2).

15.8 Wood mechanical properties and grades

15.8.1 Timber 'fit for purpose' attributes

Timber's 'fit for purpose' status is informed by the mechanical properties of that timber relative to the intended use. Modulus of elasticity (MoE) and modulus of rupture (MoR) (Box 36) are two mechanical attributes that can be measured. 'Fit for purpose' is defined by attributes beyond just MoE and MoR, and combines a range of attributes. The F-grade system (see Box 37) assigns a single code that includes a range of attributes. As an advancement over the F-grade system, the machine-graded pine system (MGP) was developed (see Box 38). The MGP system combines a range of mechanical properties into a simple four grade system (including non-MGP standard pine) (see Table 31 for the design characteristics for mechanical grading of sawn pine timber Boughton & Juniper, 2010, p.6; Table 2). As wood moisture content falls, MoE and MoR increase (Wilson, 1932, p.8; Figure 4). A literature review of variation in MoE and MoR with change in wood moisture content noted that for every 1% increase in moisture content, MoR decreased by 4% (moisture content change range c.0% to FSP) and MoE increased by 1 to 2% (moisture content change range c.0% to FSP) (Báder & Németh, 2019, p.1011, Table 1).

Box 36: Definitions of MoE and MoR.[13]	
MoE	Modulus of elasticity (MoE) measures a wood's stiffness, and is a good overall indicator of its strength. A measurement of the ratio of stress placed upon the wood compared to the strain (deformation) that the wood exhibits along its length. MoE is expressed in gigapaschals (GPa).
MoR	Modulus of Rupture, (MoR) (is a measure of a specimen's strength before rupture. It can be used to determine a wood species' overall strength. MoR is expressed in megapaschals (MPa).

Box 37: An explanation of the F-grade system.[14]

'An F-grade is a name for the grouping of the timber. The F-grade system gives a key to characteristic design strengths for graded structural timber without having to determine different properties for each of the thousands of timbers milled for structural purposes worldwide. The F-grades are a series of categories into which different grades of different species can be placed. Once a species has been commercialised, its basic engineering properties can be determined on the basis of a few tests on small clear specimens of that species. The results will determine which series of F-grades will suit that species.'

Box 38: A narrative describing the machine graded pine (MGP) system.

'MGP grades were first incorporated in AS 1720.11 in the 1997 edition, though they had been in production for two years prior. AS 1720.1 defined MGP graded timber as seasoned softwood that complied with the mechanically stress-graded timber product standard AS/NZS 17482 and was subject to a continuous monitoring program to ensure that the structural properties were maintained. AS 1720.1 also required, via AS/NZS 44903, that the grade properties be initially verified by in-grade evaluation and the graded timber be subjected to periodic monitoring – an annual test of bending properties for one size and grade combination' (Boughton. & Juniper, 2010, p.1).

'MGP was introduced into the market place in 1996 by Pine Australia (now Plantation Timber Association Australia), following an extensive, nation-wide in-grade testing program of Australian Pine (radiata pine, pinaster pine, slash pine and Caribbean pine), undertaken by CSIRO and State Forests of NSW. The MGP grades are the result of a substantial research and development program by the pine industry to ensure that accurate and reliable design properties are available for structural pine timber in Australia. As a result of this testing program, some MGP structural properties reflect the performance of pine better than the properties derived using the traditional F-grade system. These properties are appropriate for higher levels of confidence in engineering design.'[15]

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[13] Downloaded from https://www.wood-database.com/wood-articles/modulus-of-elasticity/ & https://www.wood-database.com/wood-articles/modulus-of-rupture/.

[14] Downloaded from https://www.woodsolutions.com.au/articles/structural-grading on 16/09/2019.

[15] Downloaded from https://www.woodsolutions.com.au/articles/structural-grading on 13/04/2020.

Table 31: Design characteristics of MGP grades (Boughton. & Juniper, 2010, p.6; Table 2).

	MGP10	MGP12	MGP15
MoE (GPa)	10.0	12.7	15.2
Bending strength	17	28	41
Tension strength	7.7	12	18
Compression strength	18	29	35
Shear strength	2.6	3.5	4.7

15.8.2 Published information on change in modulus of elasticity and modulus of rupture

Success is defined by maintenance of ‘fit for purpose’ of the logs under storage. UK experience found that the timber strength of a range of hardwood and softwood species altered during water storage; strength of softwood timbers reduced slightly without a reduction yield of construction grade timber (Webber & Gibbs, 1996, p.x). South African experience concluded that the slow rate of wood degradation in storage was largely attributable to the systems being maintained rigorously to ensure that all logs were constantly covered in a layer of moisture (Malan, 2011, p.2). Experience in Germany found that there were reductions of up to 10-35% in impact strength, bending strength and compression strength after three years wet storage with nil further changes after five years (Liese, 1984, p.129). In a UK study, increased porosity of softwoods was strongly associated with reduced strength recorded during stress grading of kiln-dried sample boards. These decreases in strength were not sufficient to reduce the proportion of battens normally expected to conform to commercial structural classifications (Maun & Webber, 1996, pp.34, 40&41). A point of caution was that long-term water storage (e.g. up to seven years) should be viewed with caution if critical strength reductions are to be avoided (Maun & Webber, 1996, pp.40&41). A review of wet storage of logs in South Africa found that in general ‘*wet-storage has little effect on wood quality apart from some degradation of the thin outer layer of the log, as well as an increase in moisture content. Strength loss seems to be rare and when it occurs it develops slowly*’ (Malan, 2004, p.77). The review found that water storage for prolonged periods of *P. taeda* saw logs containing large amounts of compression wood yielded boards that were considerably less prone to distortion during processing. Water storage of eucalypt logs was found to be ‘*a useful method of reducing growth stress related defects such as log splitting and board distortion*’ (Malan, 2004, p.77).

Other research has noted that MoR decreased with increasing fire exposure, and this was attributed to the degradation of lignin, which commences at relatively low temperatures (Meincken et al, 2010, p.460). Experience in South Africa with fire-killed Pinus species and stored under sprinklers for c.3 years found no significant difference in MoE between control and boards recovered from wet-stored logs. Electron microscopic examination found no sign of cell wall degradation, apart from some disintegration of the pit membranes (Malan, 2011, p.35). Overall, storage under sprinklers appeared to have little effect on wood utility after drying (Malan, 2011, p.2).

15.8.3 Wood brittleness

Brittleness is characterised by sudden breaking at relatively small deflection across the grain (Koehler, 1933, p.1; Phuong et al 2007, p.181). It is caused by localised crease reducing wood’s tensile strength and impact resistance leading to a brittle fracture (Bootle, 1996, pp.31&32). There are four fire related impacts that increase wood brittleness: 1) fire storm winds; 2) heat impacts on lignin; 3) stemwood drying; 4) mechanical damage during harvesting. Inherent brittleness may result from winds associated with a fire event. Bootle (1996, pp.31&32) noted that severe stress in the tree due to high winds can result in brittleness. With time and storage on the stump, a stem's moisture content will reduce (see Box 7) and a lack of canopy sail area will increase the velocity of fall and impact on the ground during harvesting; this can result in brittle fractures (Bootle, 1996, pp.31&32). Post-harvest moisture loss can continue. Brittleness and wood moisture content was reported in 1933: *'Dry wood usually breaks more suddenly and to a greater degree than moist wood, a fact that gives it some of the characteristics of brash wood, but the type of failure normally is splintering. Even when wood that has been dried is resoaked it has more brittleness in fracture than similar wood broken when green'* (Koehler, 1933, p.9). Brittleness (abrupt fractures) is not produced by heat unless a temperature high enough to darken wood throughout is applied (Koehler, 1933, p.37). The use of colour to predict brittleness of heat-treated wood was also suggested by Phuong et al (2007, p.181). Prolonged high temperature may make wood brittle*, 'but temperatures such as those ordinarily maintained in commercial dry kilns do not cause abrupt fractures in wood, although the strength of the wood may be reduced thereby'* (Koehler, 1933, p.38). Decay in wood is a-well-known cause of brittleness. 'Shock resistance' is the first mechanical property affected by wood decay by fungi. Wood may show a reduction in this property even before decay has advanced far enough to be observed or before this type of fracture (Koehler, 1933, p.37). Observed discolouration (e.g. brown rotted wood) is usually brittle (Eriksson et al, 1990 cited in Phuong et al, 2007, p.181) suggesting that lignin plays some role in its brittleness (Phuong et al, 2007, p.181). Koehler (1933, p.37) makes a blanket recommendation that '*no wood, therefore, that shows the slightest signs of infection by decay should be used where a high degree of toughness is required*'. Poor storage can have disastrous consequences; some logs from the Beerburrum stockpile where so badly degraded they snapped when picked-up during recovery from stockpiles after storage (Johnson, 1996, p.5). This was attributed to changes in the watering regime, but it may also be due to mechanical damage to logs prior to delivery to storage.

15.8.4 Impact of wet storage on wood colour

Observed discoloured wood (e.g. brown rotted wood) is usually brittle (Eriksson et al, 1990 cited in Phuong et al, 2007, p.181). A South African review noted that softwood sawn timber colour might change (Malan, 2004, p.77) and specifically that sawn timber recovered from wet-stored logs was more subject to staining and turning a deep yellow or light brown colour when dried (Malan, 2011, p.26). The severity of staining increased with increasing drying temperature but was generally of little concern, as the stained surfaces could be easily removed by planing (Malan, 2011, p.2). This suggests that discolouration is only on the surface rather than within boards. It was proposed that the reason sawn timber recovered from water-stored logs is more prone to brown staining, probably stems from increased porosity due to bacterial action during wet-storage, increasing the rate at which moisture is removed during drying, carrying extractives to the surface (Malan, 2011, p.29).

15.9 Comparative assessment of salvage strategies: Ash Wednesday (1983) experience

15.9.1 Experimental base

A comprehensive trial was established in South Australia to determine the effectiveness of log storage under sprinklers and immersed in a lake following the February 1983 Ash Wednesday fires. Sample logs were periodically recovered from storage, processed (including kiln drying) and board mechanical properties tested, from 1983 to 1991 (lake storage) and 1993 (storage under sprinklers) (Atkins, 1983a; Atkins, 1983b; Atkins, 1992; Atkins, 1993). A control set of data was captured for fire-killed trees stored on the stump and delivered direct to sawmills four months after being killed (Atkins, 1983b). Samples of boards from logs stored on the stump and delivered direct to sawmills were collected in October 1983 (Atkins, 1983b), one and two years after the fire (Atyeo, 1985).

15.9.2 Aggregated population mechanical properties

Data from all reports was collated by time since the Ash Wednesday by wood type (sapwood and heartwood) and management (storage on the stump, harvest and storage under sprinklers and, harvest and storage immersed in a lake). Data for MoE and MoR was presented as a single population average and are presented in Figure 31 to Figure 34. Direct harvest presents data for logs stored on the stump, harvested and supplied direct to processors for processing. Heath refers to a specific storage site where logs were harvest and delivered for storage under sprinklers (see Table 21; Thomas, 1985). Lake Bonney refers to the lake in which logs were stored fully immerses in water (see Table 21; Thomas, 1985). The data indicate that:

- Combined:
    - There are differences between sapwood and heartwood for MoE and MoR regardless of log supply system.
    - Trees harvested within 0.3 years (in May after the February fire) and processed, produced sawn timber with higher MoE and MoR than for logs stored by either method. This difference was apparent by c.2 years since the fire.
    - Trees harvested after 2 years (in February 1985) and processed, produced sawn timber with broadly equivalent MoE and MoR to logs wet stored by both methods.
- Storage on the stump:
    - Storage on the stump trees harvested and delivered direct to processors show a decline in MoE and MoR with time since the fire, with the exception of the MoR of heartwood.
    - Considering MoE and the MGP system (see Table 31) and treating the data as a population, for storage on the stump, sapwood grade reduced from MGP 12 to MGP 10 after two years.
- Storage systems:
    - While there is variation, a general trend is that storage under sprinklers and storage immersed in a lake had similar outcomes after 9 to 10 years in regard to sawn timber MoE and MoR.
    - Considering MoE and the MGP system (see Table 31) and treating the data as a population, for storage under sprinklers and immersed, sapwood and heartwood maintain MGP 12 grade and below MGP grade respectively.

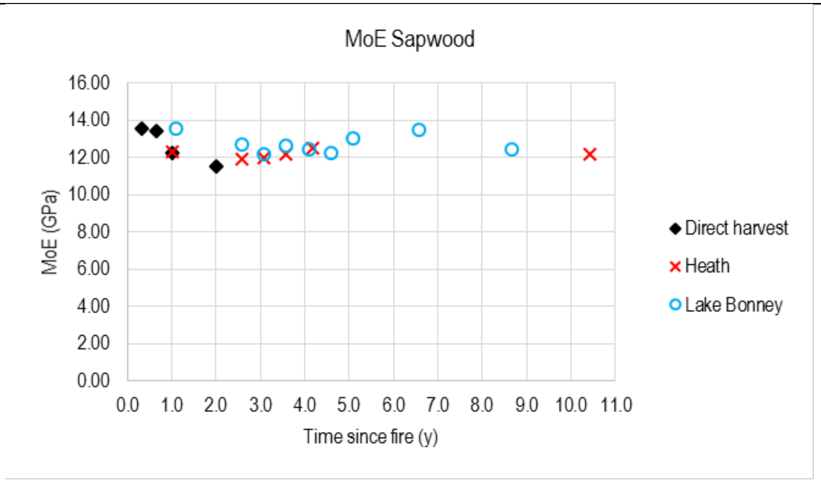

Figure 31: Sapwood MoE of *P. radiata* boards recovered from logs under direct harvest (nil storage), storage in water (Lake Bonney) and storage under sprinklers (Heaths).

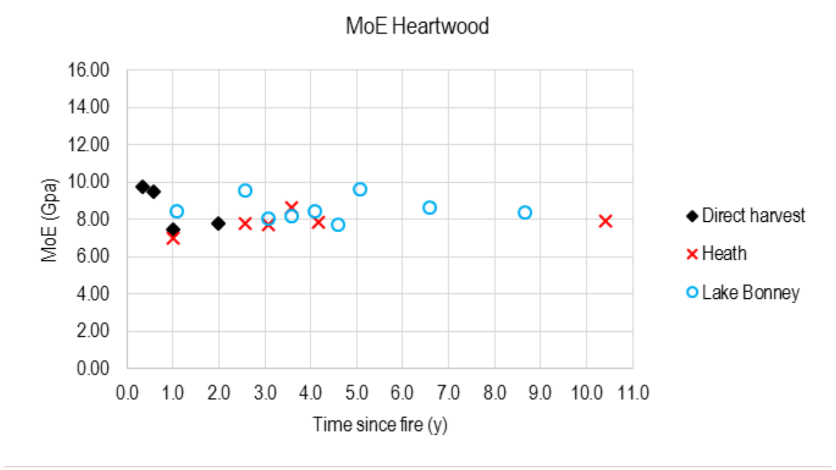

Figure 32: Heartwood MoE of *P. radiata* boards recovered from logs under direct harvest (nil storage), storage in water (Lake Bonney) and storage under sprinklers (Heaths).

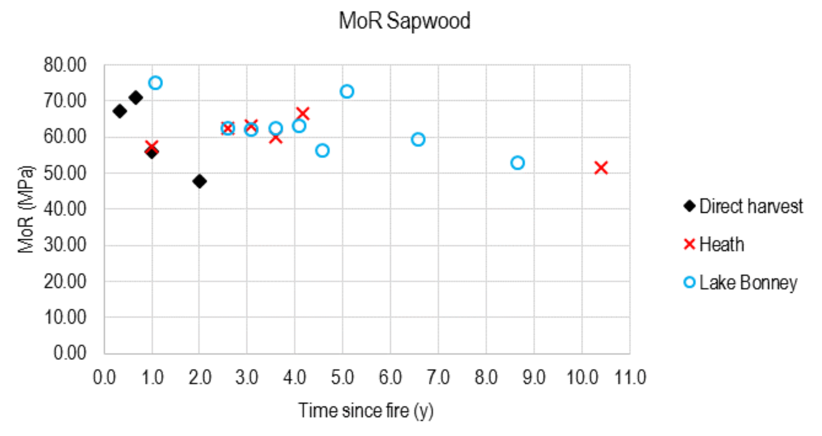

Figure 33: Sapwood MoR of *P. radiata* boards recovered from logs under direct harvest (nil storage), storage in water (Lake Bonney) and storage under sprinklers (Heaths).

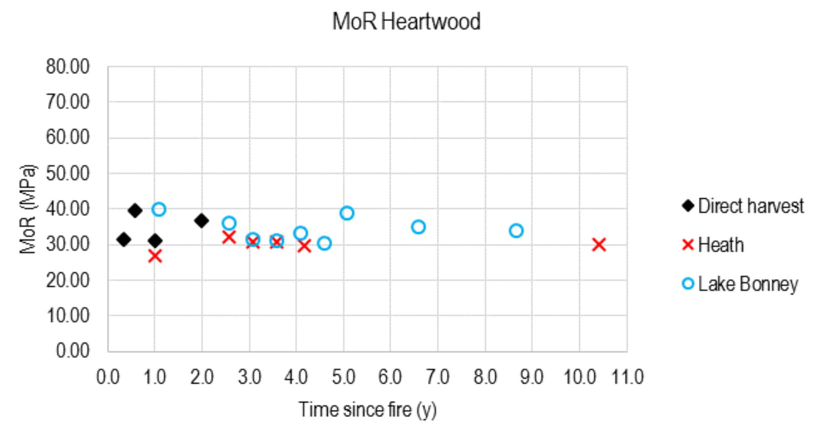

Figure 34: Heartwood MoR of *P. radiata* boards recovered from logs under direct harvest (nil storage), storage in water (Lake Bonney) and storage under sprinklers (Heaths).

15.9.3 F-grade system

Data for each population over time was presented based on F-grade breaking each pool of mechanical tests into one of five classes: F11 as the strongest timber to be ‘rejected’ by failing to meet F-grade requirements. The data presents a more detailed exploration of changes over time since the fire event. The data presents sapwood and heartwood results. Data for direct delivery logs is presented in Figure 35 and Figure 36 for sapwood and heartwood respectively, for storage under sprinklers in Figure 37 and Figure 38 for sapwood and heartwood respectively and for storage immersed in a lake in Figure 39 and Figure 40 for sapwood and heartwood respectively. Each chart includes a control case (wood attributes of trees harvested in May 1983, three months after the fire and delivered direct to processors) as a benchmark to gauge change over time.

- The data indicates that there are differences in outcomes between sapwood and heartwood commencing with the control population and over time.
- For all populations there is a reduction in the percentage of F11 grade boards for sapwood and heartwood.
- For direct delivery boards, by two years after the fire, F11 graded sapwood boards had reduced from 75% to 50% with most boards downgrading to F8.
- Logs stored under sprinklers and immersed both show a pattern of minimal F11 grade (12% for sprinklers and 13% for immersion) for 3.1 years since the fire, and then increasing with time.
- Log in storage decreased the percentage of F11 grade boards recovered; sapwood from 75% to 51% (under sprinklers by 10.4 years) and 75% to 60% (water immersion by 8.7 years).
- For sapwood under all strategies, boards oscillated between F11 and F8 with minimal increases in less than F8 grades.
- For heartwood under all strategies, boards downgraded with a decrease in F11 and increase in F8 and F5 graded boards.

While logs may be successfully processed, this data suggests a change in ‘fit for purpose’ due to time stored on the stump, storage under sprinklers and storage immersed in a water body. Longitudinal variation in wood properties within a log and resulting boards result from:

- Change in moisture content of stems in trees stored on the stump.
- Discrete infestations with bluestain.
- Incomplete penetration of and activity by bacteria impacting wood porosity and permeability.

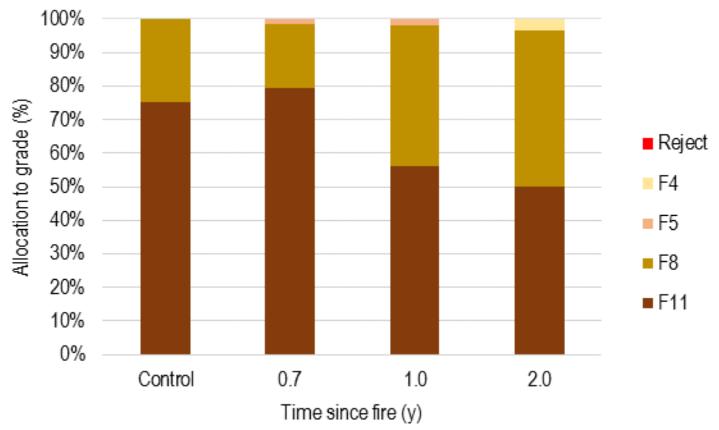

Figure 35: Sawn *P. radiata* sapwood timber strength grade for standing trees delivered direct to sawmills with time since Ash Wednesday fires.

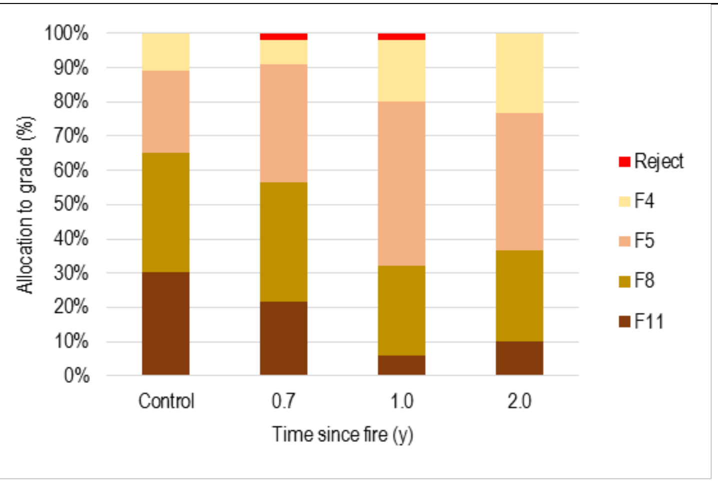

Figure 36: Sawn P. radiata heartwood timber strength grade for standing trees delivered direct to sawmills with time since Ash Wednesday fires

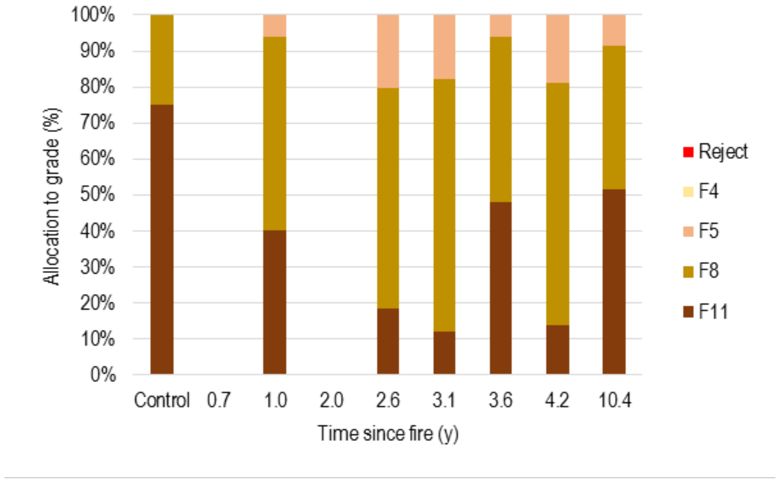

Figure 37: Sawn *P. radiata* sapwood timber strength grade for logs stored under sprinklers prior to processing with time since Ash Wednesday fires.

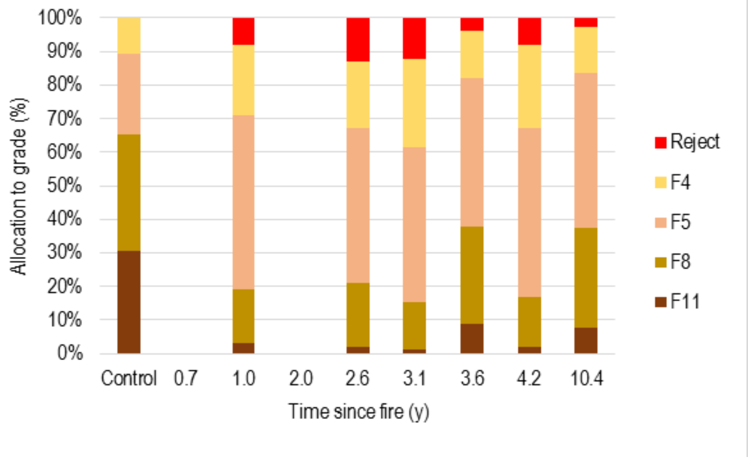

Figure 38: Sawn *P. radiata* heartwood timber strength grade for logs stored under sprinklers prior to processing with time since Ash Wednesday fires.

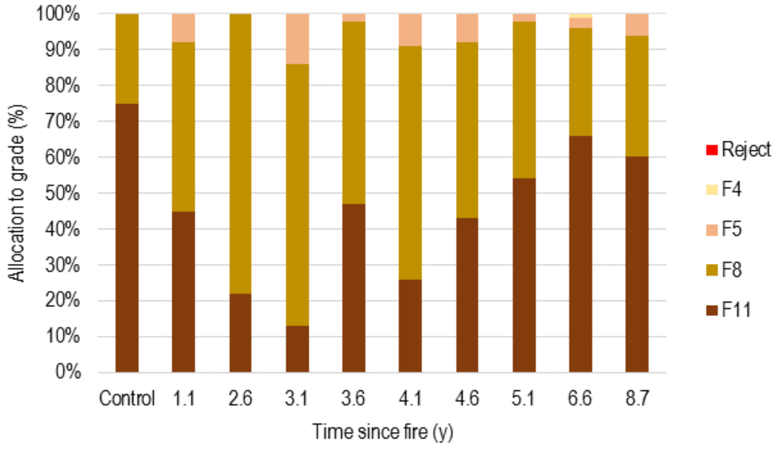

Figure 39: Sawn *P. radiata* sapwood timber strength grade for logs stored in water prior to processing with time since Ash Wednesday fires.

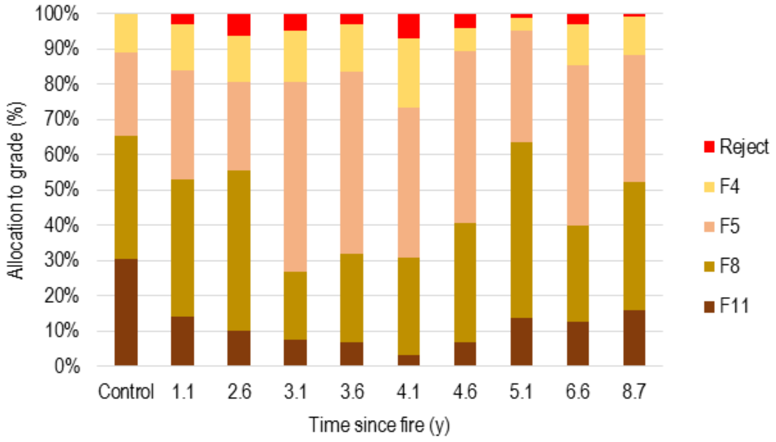

Figure 40: Sawn *P. radiata* heartwood timber strength grade for logs stored in water prior to processing with time since Ash Wednesday fires.

15.10 Processing strategies to address fire-impacted logs

15.10.1 Segregation of logs and batch processing in the greenmill

In a North America example, water-stored logs (in log ponds) are often mixed with green logs on a log deck and are processed and dried together (Shmulsky & Taylor, 1999, p.75) but it was concluded that when possible, sawn timber from water stored logs should be dried in separate kiln charges (Shmulsky & Taylor, 1999, p.77). A comparative study of green processed and water stored logs for veneer production concluded that batching throughout processing was preferred because it allows adjustments to be made to processing parameters (e.g. lathe settings and adhesive properties) to improve recovery (Shmulsky, 2002, p.84). Past studies have compared wet-stored and green log processing, whereas this study includes fire impact prior to storage. Wood recovered from fire-impacted trees performs differently to green wood when dried together regarding other physical and mechanical properties (Meincken et al, 2010, p.455). Batching of logs for processing is a common theme throughout this analysis with an intent to maximise input homogeneity.

There are three broad cohorts of logs that should be batched and processed separately: 1) green logs (not impacted by fire); 2) logs from trees stored on the stump; and 3) logs after a period of wet storage (see Table 32). Green logs will have ‘business as usual’ wood and processing properties. Logs recovered from trees stored on the stump are likely to have moisture content reduction and variation, with increased pit aspiration (reduced permeability) and with lower moisture content and potential for bluestain. Bluestain will increase wood permeability, expediting drying in the affected section and creating uneven board attributes. Logs processed after a period of wet storage will have bacterial impacts, specifically increased porosity and therefore permeability. The degree of penetration of bacteria from log ends will determine any variation in this impact with individual boards. The three point segregation noted is a blunt approach. Ideally for logs recovered after storage on the stump, segregation can be informed by monitoring the degree of wood deterioration in dead standing trees. A technique has been assessed. Longitudinal compression strength (LCS) of plugs removed from four *P. ponderosa* (ponderosa pine) stems was assessed after varying degrees of fire damage from a prescribed burn four years prior (Kangas et al, 2009, p.33). Plugs (25.4 mm long and 9.5 mm diameter by grain direction) were recovered from 100 mm thick disks recovered from the base, 3 m and 6 m above ground level. The disks were conditioned to constant weight at 23°C and a relative humidity of 65%, and then plugs were extracted from the outer sapwood (0–37.5 mm inwards) and inner sapwood (37.5–75 mm inwards) at three equidistant locations around each disk (Kangas et al, 2009, p.34). The degree of stem char on fire-killed trees had a significant effect on LCS values. LCS could be a useful tool for forest managers assessing MoE and MoR properties of standing fire-impacted trees (Kangas et al, 2009, p.33).

Table 32: A summary of potential log segregation by wood properties to be addressed.

Basis		**Impact**				
	Secondary element	**Carbon**	**Heat impacts**	**Mechanical damage**	**Moisture content**	**Permeability**
Green logs	Routine logs	Nil	Nil	Nil	Routine	Routine
Logs from trees stored on the stump	Nil scorched bark	Nil	Nil	Nil	Drying from top down.	Reduced in dry sections due to pit aspiration.
	Scorched bark	Carbon on bark and potentially from burnt branch stubs.	Bark may be fused on. This may result in surface lignin crystallisation.	Potential for combustion of wood under bark.	Drying from top down.	Reduced in dry sections due to pit aspiration.
	Intact but dead crown (radiant heat)	Carbon on bark and potentially from burnt branch stubs.	Bark maybe fused on. This may result in surface lignin crystallisation.	Sail area in place to reduce the impact of felling.	Drying from top down.	Reduced in dry sections due to pit aspiration.
	Crowns significantly reduced or absent	Carbon on bark and potentially from burnt branch stubs.	Bark maybe fused on. This may result in surface lignin crystallisation.	Reduced sail area and higher impact felling with potential for compression fractures.	Drying from top down.	Reduced porosity due to pit aspiration due to crown loss shock.
	From areas subject to a fire storm	Carbon on bark and potentially from burnt branch stubs.	Bark maybe fused on. This may result in surface lignin crystallisation.	A potential for compression fractures due to fire storm and reduced sail area and higher-impact fealling.	Drying from top down.	Reduced porosity due to pit aspiration due to crown loss shock.
	From different heights in the stem	Carbon on bark and potentially from burnt branch stubs.	Bark maybe fused on. This may result in surface lignin crystallisation.	A potential for compression fractures due to fire storm and reduced sail area and higher-impact felling.	Drying from top down.	Reduced in dry sections due to pit aspiration.
	Logs with bluestain	Carbon on bark and potentially from burnt branch stubs.	Bark maybe fused on. This may result in surface lignin crystallisation.	Reduced sail area and higher-impact felling with potential for compression fractures.	Drying from top down.	Increased porosity due to fungal actions
Logs after a period of wet storage		As per entry into log storage	As per entry into log storage	As per entry into log storage	Close to routine or higher	Increased porosity due to bacterial actions

15.10.2 Kiln drying

Effective drying of boards recovered from fire-impacted logs is complicated by a juxtaposition of impacts on permeability: crown fire-impacted trees and trees drying during storage on the stump may have aspirated pits, trees standing on the stump may have bluestain resulting in increased permeability and logs wet stored may have increased porosity due to bacteria resulting in increased permeability. In all cases, it is possible that significant variation in permeability will occur within a stem, logs and boards. There is a possibility that drying difficulties with fire-impacted boards may result from aspirated pits (Walker, 2006 cited in Malan, 2011, p.17).

South African experience notes that there are potential processing and behavioural differences between boards processed from water-stored logs (with higher wood porosity) and green logs direct from plantations (Malan, 2004, p.81). Large differences in moisture content between and within individual boards recovered for water-stored logs after kiln drying was noted. Moisture contents of adjacent boards in a stack varied from c.12% to beyond the limit of an electric moisture meter. Within-board variation occurred (sometimes within 10 cm between measuring points) (Malan, 2011, p.27). Kiln operators processing such wood claimed a range of implications: increased drying rates, longer drying time with increased moisture content and increased shrinkage (Shmulsky & Taylor, 1999, p.75). This reinforces a need for batch processing to allow tailoring of drying schedules to sawn timber recovered from wet-stored logs (Malan, 2011, p.2).

A North American study (Shmulsky & Taylor, 1999) compared sawn timber processed from routine-harvested and sprinkler-stored southern yellow pine logs (a species group including: *P. taeda*; *P. palustris* – long leaf pine; *P. echinata* – shortleaf pine; *P. elliottii*). Logs were stored for 4-21 months before processing. Results indicated that differences in drying times were of little practical significance and that shrinkage values were also not significantly different (Shmulsky & Taylor, 1999, p.75). While the paper abstract suggested that '*it is not necessary to segregate sawn timber from water-stored material for kiln drying*', the authors concluded that when possible, sawn timber from water-stored logs should be dried in separate charges (Shmulsky & Taylor, 1999, p.77). In an absence of an ability to batch process, Shmulsky and Taylor (1999, p.77) provide the following guidance when green and wet-stored origin sawn timber are dried together. Increased kiln monitoring and control is required. Although sawn timber from sprinkler-stored logs dries more rapidly, increased initial moisture may require that kiln schedules are lengthened. This would be more so if increased drying rates of more permeable water-stored wood creates difficulties in maintaining target kiln temperatures. It was proposed that commercial kilns may not be able to duplicate the results obtained in the experimental kiln, as heating systems may not be able to maintain the kiln at target temperature set points when highly permeable, high moisture content sawn timber is dried. An equalising treatment to reduce final moisture content variation is recommended with mixed charges. A similar guidance is provided for unbatched veneer production to reduce dryer temperatures and slow feed speeds in order to maximise value for both freshly cut and water-stored material (Shmulsky, 2002, p.84). Kilns equipped with effective moisture and humidity control systems should have fewer problems in delivering quality dried sawn timber (Malan, 2011, p.18).

15.10.3 Drymill

Batching of kiln charges can reduce adverse impacts of kiln drying (e.g. due to initial uneven board moisture content and permeability). Low board moisture content can impact dry mill operations due to an increased frequency of board jams at the planer infeed and through grading equipment. Shrinkage of sawn timber from sprinkler stored and fresh logs was similar in a North American study with nil adjustments to processing equipment or rough sawn timber sizes was necessary when processing sprinkler-stored logs (Shmulsky & Taylor, 1999, p.77). Increased variation in moisture content flows through reducing recovery of MGP products with an increased occurrence of end splits and reduced grade yield due to more distorted (bow, spring, twist) boards. Residual output boards are graded for mechanical properties as a ‘catch-all’ at the end of processing. There are issues (impacts) on grading created by reduced population homogeneity (as expressed by an increase in standard deviation) as noted in Box 39.

Box 39: Points to consider with machine grading of fire-salvage softwood sawn timber.

- Population variability: Increased moisture content standard deviation leads to lower grade yields as more pieces downgrade to utility compared to boards at the upper end of the moisture distribution.
- Distorted relationships: A possible change in stiffness to strength relationship with structurally graded products.
- Combined impacts: Drier wood may result in a slight increase in stiffness properties with grading but strength may be significantly reduced with brittle failures in bending and shear.
- Re-calibration: Potential increases to grading set points to maintain structural grading compliance.
- Compression fractures: Machine grading in ineffective in detecting compression fractures because of the localised nature of the defect (Bootle, 1996, pp.31&32).

15.11 Recommended best practices

15.11.1 Processing – wood yard management / de-barking, sawing, drying

Best practice 106: Fire-affected trees may be more likely to fracture during harvesting. This can increase with stem drying during storage on the stump for extended periods.

Best practice 107: Logs should be batched for processing based on green (unburnt), whether impacted by fire storm conditions (with potential for compression fractures), stored on the stump (potentially segregated by position within the stem as a proxy for log moisture content) or stored under wet conditions (with increased porosity and permeability due to bacteria) and level of bluestain.

Best practice 108: As logs dry cracks or checks may result. Saw blades may follow such defects causing damage to blades. Dry logs will also generate greater friction and heat during sawing which may impact saw blades. This can be addressed by reducing mill throughput speeds.

Best practice 109: Batches of boards with increased porosity and permeability and/or un-even moisture content after green mill processing should be dried in a more-gentle kiln regime over longer periods. Once dried, boards should be reconditioned to equalise board moisture contents.

15.12 Observations

Observation 58: A crown fire and sudden loss of foliage will result in water within a tree’s conductive tissue changing from a conductive pull to being under the influence of gravity causing pressure of cell pits resulting in pit aspiration. This will impact water movement within wood and this may remain in logs and sawn timber once processed.

Observation 59: Logs recovered after a period of storage on the stump are likely to have dried out from the top of the stem downwards and radially within a tree stem. Timber recovered from such logs will have different and variable moisture content which can be addressed by sacrificing upper stem logs to a different grade and/or by batch processing of logs in green mills through to batching for kiln drying based on green density.

Observation 60: Log recovered after a period of wet storage will have different porosity and permeability due to bacterial activity excavating out conductive and storage tissue, and consuming pit membranes. These changes will impact drying rates and may be non-uniform creating differential drying behaviour within a single board.

Observation 61: Logs recovered from trees affected by a fire storm may have compression fractures creating issues with timber grading.

Observation 62: Fire heat and heating during kiln drying is unlikely to cause changes in mechanical properties of sawn timber, with any change more likely to be due to changes in and lack of homogeneity of porosity and permeability creating differential drying.

Observation 63: Sawn timber should be batched for kiln drying based on at least whether logs were direct supplied from unburnt plantations, after a period of storage on the stump or after storage of logs under sprinklers.

Observation 64: Sawn timber recovered from logs after either storage on the stump or wet storage can have different wood properties (reduced F-grade) if kiln dried via routine schedules. Published information strongly suggests that such sawn timber should be batch processed and kiln dried via an altered drying schedule.

Observation 65: Although sawn timber from sprinkler-stored logs dries more rapidly, increased initial moisture may require that kiln schedules are lengthened. This would be more so if increased drying rates of more permeable water stored wood creates difficulties in maintaining target kiln temperatures. An equalising treatment to reduce final moisture content variation is recommended with mixed charges.

Observation 66: Output sawn timber is graded for mechanical properties as a ‘catch-all’ at the end of processing. There are issues (impacts) on grading created by reduced population homogeneity (as expressed by an increase in standard deviation).

Observation 67: Assess the radial penetration of heat from the bark to log core into a tree stem to determine the impact on wood properties in particular lignin crystallisation. .

Observation 68: Determine the impact of any change in lignin attributes to pulp and paper utilisation of fire-affected logs.

Observation 69: Assess the economic impact of compression fractures on board brittleness.

Observation 70: Whether a ‘more gentle’ sawn timber kiln drying regime will address inherent variation in board permeability and initial moisture content; moisture content variation between boards and within boards.

Observation 71: Whether board reconditioning will address issues associated with variation in board permeability and initial moisture content; moisture content variation between boards and within boards.

Observation 72: Longitudinal variation in board attributes due to discrete pockets of bluestain and differential penetration of bacteria into logs under wet storage. A method is required to identify such variation within logs and how to address such variations during processing of logs and drying of boards

Observation 73: A method to test for pit aspiration in logs (prior to processing) and in resulting boards.

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Appendix 1: Project process and methods

Project parties

Project management included a Project Team (PT) and Technical Expert Working Group (TEWG) (see Table 33). The PT was responsible for collation of the body of information and management of the project. The TEWG is an authorship list of the guidelines and includes members with specific technical expertise and experience to oversee the project out-put and content. Extensive industry consultation was undertaken with the parties consulted and/or providing information listed in Table 33. The project recognised and focused on the needs of key stakeholders.

- Information users: The objective of this project was to provide information for current and potential future parties with plantation resources impacted by fire.
- Information sources: The project broadly consulted with a range of parties:
    - *GRAC*: FWPA's Grower Research Advisory Committee (GRAC) members.
    - *SWPTC*: Australian Forest Products Association's Solid Wood Processing Technical Committee (SWPTC) members.
    - *Individuals*: Current and past industry professionals with specific experience and insights.

Methods

The following were the project methods:

- Stage 1: Project meetings
    - TEWG meetings via video conference were held as required.
    - PT meetings were on a weekly basis via video conference.
- Stage 2: A summary of plantation fire experiences.
    - Published, unpublished and submitted information (by consultation and written submissions) was captured and collated.
    - The collated information was distilled and analysed to identify key issues and insights.
- Stage 3: Confirmation of priority issues.
    - Working paper: A working paper (a draft of the final supporting document) was prepared based on the distilled insights. This included development of a working draft technical guidelines titled: *Guidelines for salvage harvest, storage and processing of fire impacted plantation grown logs*.
    - Review A: Each member of the TEWG had the opportunity to review the working paper and provide comments.
    - Review B: TEWG comments were included into the draft working document.
- Stage 4: Development of guidelines matched to priority issues: two documents have been produced.
    - Guidelines for salvage harvest, storage and processing of fire impacted plantation grown logs.
    - A supporting technical report and summary of identified and collated existing information.
- Stage 5: Standalone guidelines have been developed.

Table 33: A list of parties participating in or contacted during the project.

Last	First	Company	Project Committee	TEWG	Consulted	Provided information
Andrews	Graham	Laminex Pty Ltd			X	
Annetts	Peter	AKD Limited		X		
Barr	Brad	Wespine Industries Pty Ltd			X	
Bartlett	Tony	Consultant		X		X
Berry	Chris	Plantation Pine Products			X	
Boughton	Geoff	TimberED Services Pty Ltd				
Bruce	David	University of South Australia				X
Carnegie	Angus	Forestry Corporation of NSW		X	X	X
Dorward	Craig	Big River			X	
Downes	Geoff	Forest Quality Pty Ltd		X		X
Dumbrell	Ian	Industry Plantation Management Group			X	X
Elms	Stephen	HVP Plantations				X
Epp	Kenneth	Visy Pulp and Paper		X	X	
Evans	Aaron	DR Henderson			X	
Geddes	David	Geddes Management Pty Ltd		X	X	
Green	Rab	AKD Limited		X		
Harding	Kevin	Harding Forestry Services			X	
Harris	Kim	AKD Limited		X	X	
Houghton	Jim	Forest and Wood Products Australia Ltd				X
Hurley	Vince	Australian Sustainable Hardwoods			X	
Iskra	Boris	Forest and Wood Products Australia Ltd				X
Jenkin	Braden	Sylva Systems Pty Ltd	X	X		
Lafferty	Chris	Forest and Wood Products Australia Ltd	X	X		
Last	Ian	HQPlantations Pty Ltd		X		
Lengenberg	Belinda	Hyne & Son Pty Ltd		X		
Matthew	Gavin	Australian Forest Products Association	X	X		X
McNaught	Andy	Engineered Wood Products Association of Australasia				X
Meder	Roger	Forest Industries Research Centre, USC		X		
Morrell	Jeff	National Centre for Timber Durability & Design Life, USC		X	X	
Myers	Baden	University of South Australia			X	
O'Hehir	Jim	University of South Australia	X	X		
O'Reilly	Damien	Mayday Hill Consulting		X	X	
Parsons	Lew	Wokurna Forestry		X		X
Peters	Stefan	University of South Australia				X
Piercy	Kevin	Australian Paper			X	
Price	Tony	Midway Limited			X	
Ramsden	Michael	HQPlantations Pty Ltd		X		X
Rivers	Glen	OneFortyOne				X
Robertson	Islay	HQPlantations Pty Ltd				X

Table 33: A list of parties participating in or contacted during the project.

Sawyer	Troy	Forest Products Commission			X	
Schaffner	Richard	Wespine Industries Pty Ltd			X	
Springer	Gerrit	International Timber Solutions Pty Ltd				X
Sulkin	Owen	Natural Systems Analytics				X
Sutton	Mike	Forestry Corporation of NSW	X	X	X	X
Telfer	Ian	WAPRES (WA Plantation Resources)			X	
Tombleson	Jeff	Jeff Tombleson & Associates Ltd (NZ)				X
Watt	Duncan	Forestry Corporation of NSW			X	
Weir	Gary	Country Fire Authority				X
Wells	Evan	Evan Wells Panel Consulting			X	
Zed	Peter	Omega Consulting		X		

Appendix 2: Wood attributes

Basic density

Basic density is the bone-dry mass of solid wood per green wood volume (Equation 1[16]). The determination of basic density is set by AS/NZS 1080.3:2000[17]. Bone dry weight is determined by weighing the green wood, placing it into an oven and drying it until the weight remains constant.

Equation 1 Wood basic density calculation.

$$BD = \frac{(M_{oven\,dry\,wood})}{(V_{green\,wood})}$$

Where:

BD = Basic density in kilograms per green cubic metre.
$M_{oven\,dry\,wood}$ = Mass oven dry wood in kilograms.
$V_{green\,wood}$ = Volume green wood in m³.

Moisture content

Wood moisture content can be defined as the weight of water as a percentage of the green weight of wood (Equation 2) or the weight of water as a percentage of the dry weight of wood (Equation 3) and care is required when stating moisture contents. The determination of wood moisture content is set by ISO 3130:1975[18]. Wood moisture content will vary with time, handling and conditions and is not a constant.

Equation 2 Wood moisture content on a green basis.

$$MC_{GREEN\,BASIS\,i}\,\% = \frac{(M_{water})}{(M_{oven\,dry\,wood} + M_{water})}\,X\,100$$

Where:

$MC_{GREEN\,BASIS\,i}\,\%$ = Moisture content on a green basis at value chain point "i"
M_{water} = Mass water
$M_{oven\,dry\,wood}$ = Mass oven dry wood

Equation 3 Wood moisture content on a dry basis

$$MC_{DRY\,BASIS\,i}\,\% = \frac{(M_{water})}{(M_{oven\,dry\,wood})}\,X\,100$$

Where:

$MC_{DRY\,BASIS\,i}\,\%$ = Moisture content on a dry basis at value chain point "i"
M_{water} = Mass water
$M_{oven\,dry\,wood}$ = Mass oven dry wood

Conversion factors: volume to green weight

Basic density remains as constant, while moisture content will vary as indicated and to convert volume to weight (in green metric tonnes), we need to estimate the weight of water and bone dry wood in the wood based on Equation 4, Equation 5 and Equation 6, with the bone dry weight of wood as a link. The weight of water can be estimated based on wood basic density and moisture content.

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[16] Bootle (1996: p.415).
[17] Timber – Methods of test: Method 3: density.
[18] Wood – Determination of moisture content for physical and mechanical tests.

Equation 4 Estimated wood water content.

$$Wt_i = \frac{MC_i \times BD}{1 - MC_i}$$

Where:

W_{ti} = Water (t / m^3).
BD = Basic density expressed in t / m^3 (i.e. 530 kg / m^3 = 0.53 t / m^3).
$MC_{GREEN\ BASIS\ i}$ = Moisture content as a ratio (i.e. 52.6% = 0.526).

Equation 5 Conversion factor for GMT per m^3 of wood.

$$CFV_i = BD + \frac{MC_{GREEN\ BASIS\ i} \times BD}{1 - MC_i}$$

Where:

CFV_i = Conversion factor, weight per round wood volume (GMT / m^3) at value chain point "i".
BD = Basic density expressed in t / m^3 (i.e. 530 kg / m^3 = 0.53 t / m^3).
$MC_{GREEN\ BASIS\ i}$ = Moisture content as a ratio (i.e. 52.6% = 0.526).

The conversion factor becomes:

Equation 6 A simplified Conversion factor for GMT per m^3 of wood

$$CFV_i = \frac{BD}{1 - MC_{GREEN\ BASIS\ i}}$$

Where:

CFV_i = Conversion factor, weight per round wood volume (GMT / m^3) at value chain point "i".
BD = Basic density expressed in t / m^3 (i.e. 530 kg / m^3 = 0.53 t / m^3).
$MC_{GREEN\ BASIS\ i}$ = Moisture content as a ratio (i.e. 52.6% = 0.526).

Appendix 3: Key species profiles

Eucalyptus globulus

Tolerance of fire

Eucalyptus globulus Labill. (Tasmanian bluegum) is highly flammable, but is seldom killed by fire. The bark catches fire readily, and deciduous bark streamers and lichen epiphytes tend to carry fire into the canopy and to disseminate fire ahead of the main front (Ashton, 1981; Skolmen & Ledig, 1990; Colwell 1973; Gill, 1977: cited in Esser, 1993).

Bark attributes

Because the stringy outer bark is highly flammable and bark thickness is readily reduced by fire, past fire frequency largely determines the relative protection bark offers. Repeated fire damage to bark before bark thickness has been restored may result in top-kill, or at times, tree mortality. If bark is sufficiently thick, Tasmanian bluegum branches survive crown fire and send out epicormic sprouts (Gill, 1977 cited by Esser, 1993). Epicormic sprouting is common in trees only scorched by fire. It is also common in trees where crown fire occurred but bark was thick enough to protect dormant branch buds. Heat-damaged bark is shed, and sprouting proceeds rapidly (Gill, 1977 cited by Esser, 1993). No studies quantifying bark thickness with tree survival were found (Esser, 1993).

Crown and foliage

Tasmanian bluegums can promote fire spread due to heavy litter fall, flammable oils in the foliage, and open crowns bearing pendulous branches, which encourages maximum updraft (Ashton, 1981; Crosby, 1992: cited in Esser, 1993). Despite the presence of volatile oils that produce a hot fire, leaves of Tasmanian bluegum are classed as intermediate in their resistance to combustion, and juvenile leaves are highly resistant to flaming (Dickinson & Kirkpatrick, 1985 cited by Esser, 1993).

Recovery strategies

Tasmanian bluegum recovers well from fire (Ashton, 1981 cited by Esser, 1993). Adaptations to fire include seed-banking, sprouting, and heat-resistant seed capsules (Ashton, 1981; Skolmen & Ledigl, 1990 cited in Esser, 1993) Top-killed trees sprout from the lignotuber with vigorous sprouting supported by food reserves stored in the root system and lignotuber (Ashton, 1981 cited by Esser, 1993).

P. caribaea

Fire tolerance

Fire rarely kills mature *P. caribaea*, (Caribbean pine) but seedlings and pole-stage pines can suffer high fire mortality (Munro 1966 cited in Paysen et al, 2006, p.423; Cabi, 2020, p.32). Mature trees have morphological adaptations for fire tolerance: self-pruning limbs, thick bark, and the ability to re-flush scorched crowns (Obrien et al, 2008, p.542). Needles are dropped after scorch and green regrowth is typically seen within three weeks of drop (O'Brien, *pers. comm.* 2012 cited by Mark, 2012, p.20). Natural stand saplings will usually survive a fire when isolated and more than 1-2 m tall, but crown fires in groups of natural regeneration can kill 75% of trees up to 5 m tall and all fires cause a severe check in growth (Lamb, 1973: p.141). *P. caribaea* saplings become resistant after 3-6 years, depending on the quality of the site (Lamb, 1973: p.140) and it is suggested that from 5 years of age trees are rarely killed by fire (Taylor, 1959 cited Paysen et al, 2006: p.423).

Resistance to fire depends on site factors, growth rate and general ground cover (Lamb, 1973, p.190). When planted as an exotic, tall grasses (normally absent in Central American pine forests) (e.g. Imperata grass) will produce hotter fires when burnt (Lamb, 1973, p.140). Controlled burning and grazing trialled in Fiji can reduce the incidence of needle blight in humid climates (Lamb 1973, p.141). Potential damage to a stand after a fire should be weighed against the benefits to be gained from fire; benefits gained from treatment with fire may outweigh the setbacks that might occur as a result of fire damage (Paysen et al, 2006, p.423). Results suggest a relationship between tree vigour and fire history; there was a loss of vigour after fire for trees (Paysen et al, 2006, p.423). In Australia, *P. caribaea* on the coastal plain is more fire resistant than *P. elliottii* but such sites are too low and tropical for slash pine (Lamb, 1973, p.141).

Bark attributes

Provenance variation in bark thickness has been noted (Birks & Barnes, 1990, p.32). *P. caribaea* bark type in pole sized trees varied from long flaky slab bark to short blocky bark (Lamb, 1973, p.39). *P. caribaea* plantation trees in Papua New Guinea have bark 1.5 to 2.0 cm thick (Conn & Damas, 2009) and in Queensland, 1.8–2.1 cm (Dieters & Brawner, 2007, p.694).

P. elliottii

Fire tolerances

Young *P. elliottii* are susceptible to fire, but mature trees are fire resistant (Brown & Davis, 1973 cited in Carey, 1992). Well conducted prescribed burning can be undertaken with minimum crown scorch (Forestry Department Queensland, 1981, p.1). The first experimental burning in *P. elliottii* plantations was carried out at Toolara in 1967 (Forestry Department Queensland, 1981, p.1). Success led to introduction of burning on a buffer-strip basis in the early 1970s and evolved to virtually all exotic pine plantations being burnt at least once during a rotation (Hunt & Crock 1987, p.179). Fire frequency is a consideration. In Louisiana, annual and biennial prescribed burning of a 4-year-old stand (mean height 2.4 m) reduced growth, but triennial fires did not, and fire season had no effect on growth (Grelen, 1983,: cited in Carey, 1992).

Bark attributes

P. elliottii bark thickness and structure provide protection from fire. Outer-bark layers overlap and protect grooves where the bark is thinner (de Rhonde, 1982: cited in Carey, 1992) and during fire, the platy bark flakes-off to dissipate heat (Landers, 1991: cited in Carey, 1992). *P. elliottii* bark thickness varies: one study indicated that bark was 0.5 cm think at breast height (Eberhardt, et al 2017, Table 4) and a study in Australian indicated bark thickness of 11.5 to 16.7 cm (Dieters & Brawner, 2007, p.694). For bark thicker than 1.5 cm, mortality due to cambium damage is unlikely from low-severity fires; in one study, 0.2 cm thick bark protected the cambium from externally applied heat of 300 °C for 1 minute. Bark 1.2 cm thick protected the cambium from 600 °C for 2 minutes (de Ronde, 1982 cited in Carey, 1992).

Crown structure and damage

High, open crowns allow individual *P. elliottii* to survive fire (Carey, 1992). One and two year old trees are killed by low-severity fire. After 3 to 4 years, seedlings survive low-severity fire but not moderate-severity fire. 3.0–4.6 m saplings will survive moderate-severity fires. Once *P. elliottii* is 10–12 years old, it will survive a fire that does not crown (Garren, 1943; Lohrey et al, 1990; Wade, 1983; Wright & Bailey, 1982, cited in Carey, 1992). *P. elliottii* needles were killed instantly when immersed in water at 64°C but survived 9.5 minutes at 52°C (Byram & Nelson, 1952, cited in Carey, 1992). *P. elliottii* is tolerant of crown scorch with scorched foliage replaced by new shoots. Trees as young as 5 years old may recover from 100% crown scorch (de Ronde, 1982;

Wade, 1983, cited in Carey, 1992). The extent of foliage removal will dictate tree survival. *P. elliottii* taller than 1.5 m seldom die at less than 70% crown scorched (McCulley, 1950, cited in Carey, 1992). In NSW, an autumn wildfire burned a *P. elliottii* plantation (mean height of 6.1 m) (Van Loon, 1967). The fire crowned in most areas and recovery was documented.

- Most foliage removed: Trees with no green needles, few or no brown needles, and a drooping apical branch had 31% survival.
- Brown needles: Trees with mostly brown needles and few or no green needles present had 93.8% survival.
- Green needles: Trees with clearly visible green needles at the top had 96.9% survival.

P. elliottii growth response to fire is variable: fire may result in a short-term reduction in growth, although fires that result in light or no scorch may actually enhance growth (Wade, 1983, cited in Carey, 1992). For example, in the Georgia Coastal Plain, a 9-year-old stand (mean height 7.5 m and mean DBHOB 8.9 cm) was prescribed burned and in the first post-fire growing season, trees with 0–15% crown scorch outgrew control trees, trees with 15–40% crown scorch were not significantly different in growth to control trees, and trees with more than 40% scorch showed reduced growth. Growth returned to normal in the second post-fire growing season (Johansen, 1975, cited in Carey, 1992). Height increment is slightly more sensitive to needle scorch than DBHOB increment. Height growth loss occurred in trees with no crown scorch if they were smaller than 18 cm DBHOB, but diameter growth loss occurred in trees with greater than 30% crown scorch (McCulley, 1950, cited in Carey, 1992). Severely scorched, 25-year-old *P. elliottii* in Georgia (mean DBHOB of 20 cm) lost almost a full year's growth for two growing seasons. Growth of trees with less than 10% crown scorch was 85% of unburned trees after 2 years (Johansen & Wade, 1987: cited in Carey, 1992). Experience with prescribed burning in Queensland suggest that growth loss in exotic pine plantations due to scorching is directly related to the proportion of the crown impacted (Forestry Department Queensland, 1981: p.1).

P. pinaster

Fire tolerances

P. pinaster plantations are inherently susceptible to fire (Fernandes & Rigolot, 2007: p.9) but the species has physical characteristics that allow survival after low-intensity fire, e.g. thick-bark and reproduction processes that facilitate recovery from seeds stored in serotinous cones (Fernandes & Rigolot, 2007: p.1). *P. pinaster* was considered a species highly resistant to heat (Duhoux, 1994; Ryan et al. 1994; cited in Botelho et al, 1998b, p.475) and further results indicate that this species can withstand relatively high levels of fire with mortality restricted to small and supressed trees (Botelho et al 1998b, p.475). Fuel management decreases tree injury and mortality, and enhances effectiveness of fire suppression operations and salvage value of timber (Fernandes & Rigolot, 2007, p.9).

In natural stands of *P. pinaster*, larger, dominant trees are killed by surface fires with moderate intensity fires (1000–4000 kW/m) (Fernandes, 2002 cited in Fernandes & Rigolot 2007, p.3). A low to moderate intensity fire (up to 1000 kW/m) is unlikely to kill *P. pinaster* and increasingly unlikely for trees with DBHOB greater than 5 cm (Vega, 1978; Botelho, 1996; Botelho et al., 1998c; Rigolot, 2000; Fernandes et al., 2005 cited in Fernandes & Rigolot, 2007, p.3). Green-crown height reduction by fire in *P. pinaster* is followed by several years' reduction in diameter increment, but where branch death is limited to the lower crown, the impact appears to be negligible (McCormick, 1976, p.3). Fire impact and outcomes combine a number of factors. *P. pinaster* growth is not impaired at less than 25–50% crown scorched. Examples of high levels of mortality from north-west Spain have been related directly to excessive duff combustion (Vega, 1988 cited by Fernandes et al, 2008, p.249). Delayed mortality due to fungus (*Leptographium* spp.) has resulted after harvest residue pile burning in the same region (Fernandez de Ana, 1982 cited Fernandes et al, 2008, p.249). Bark beetles can be a factor in delayed mortality of *P. pinaster* trees surviving wildfire (Fernandez & Salgado, 1999 cited Fernandes et al, 2008, p.249).

Bark attributes

The main fire resistance trait of *P. pinaster* is thick bark which develops quite early (Ryan et al., 1994 cited in Fernandes & Rigolot, 2007, p.2). When bark thickness exceeds 10 mm, injury to the stem is an irrelevant contributor to *P. pinaster* mortality under prescribed burning conditions, as long as smouldering combustion is avoided or minimized (Ryan et al., 1994 cited in Fernandes & Rigolot 2007, p.3). Overall, bark thickness of *P. pinaster* is somewhat variable: 16.1 to 27.8 mm (Tapias et al., 2004, p.62, Table 6). Interspecific bark thickness at breast height in 26-year-old *P. pinaster* from 28 provenances varied with mean genetic group values of: Atlantic (2.4 cm), Mediterranean European (2.2 cm) and Maghrebian (North-African – 1.8 cm) (Tapias et al. 2004, based on p.58; Table 2 & p.62, Table 6). Bark thickness decreases with stem height, especially in young individuals (de Ronde, 1982 cited in Fernandes & Rigolot, 2007, p.2): basal bark thickness at age 10 years almost doubles the value at breast height (1.3 m).

The maximum cambium temperature in *P. pinaster* trees during experimental fires did not reach 60 °C (the lethal level) with fire intensity from 92 to 5443 kW/m for trees with diameter and bark thickness at 1 m height from 9 – 40 cm and 0.7–3.3 cm, respectively (Vega et al. 1998 cited in Fernandes & Rigolot, 2007, p.3). Regardless of fire intensity, mortality caused by bole injury is unlikely unless trees have DBHOB of less than 20 cm or heat from extended smouldering girdles the stem base. The threshold DBHOB for tree mortality in experiments emulating prescribed burns is usually 5–10 cm (Fernandes et al, 2008, p.249).

The bark of *P. pinaster* is laminated and outer layers are exfoliated during combustion, which contributes to expelling heat from the stem (Fernandes & Rigolot, 2007: p.3). This has been documented in Western Australian (Burrows et al, 2000,: p.258) where a wildfire (head-fire from c.1500 kW/m to c.18,000 kW/m – Burrows et al, 2000, p.254) reduced bark thickness by c.30% on all burned trees measured at 1.5 m: 29.7 mm to 19.5 mm. The moisture content of the outer 5 mm of bark measured one day after the wildfire was c.10%. During the same event, low intensity back-burning (about 350 kW/m) in deep / heavy needle bed fuels killed c. 50% of large trees (age 43 years), even though the scorch and stem char heights were relatively low. The stands had not been burnt prior to the wildfire, hence the needle bed fuel burnt completely under the very dry conditions. Inspection of trees, whose crowns were mostly undamaged, or slightly damaged, indicated that the trees had been killed by stem girdling. The bark was burned down to the cambium, from ground level to the height of the needle bed (40-80 mm) (Burrows et al 2000, p.257&258). This provides a caveat to the protective nature of bark; fuel loads are a significant issue and deep forest floor fuel consumption by fire can result in tree death by basal stem girdling independently of surface fire intensity (Burrows et al., 2000).

Crown structure and damage

Tall crowns of large trees reduce their exposure to heat increasing the odds of surviving a fire (Ryan, 1998 cited in Fernandes & Rigolot, 2007, p.3). *P. pinaster* has resistance to crown kill due to bud tolerance to heating (inferred from bud width), bud shielding from heat provided by needles, and time-temperature thresholds for needle and bud necrosis (Fernandes et al, 2008, p.251). The lethal temperature threshold is higher for *P. pinaster* buds than for needles (Duhoux, 1994, cited in Fernandes & Rigolot, 2007, p.3) suggested to be due to the large size of buds with a cross-sectional bud to needle ratios of 5.5, (as inferred from Daligault, 1991, cited in Fernandes & Rigolot, 2007, p.3; Tapias et al., 2004) providing higher heat capacity. *P. pinaster* buds are shielded by scales and by long needles (Fernandes et al, 2008, p.249) increasing resistance to convective heat transfer (Michaletz & Johnson, 2006b, cited in Fernandes & Rigolot, 2007, p.3). Therefore, needle kill is not always synonymous with crown kill, allowing tree survival after total defoliation (de Ronde et al. 1990; Botelho et al. 1998a, cited in Fernandes & Rigolot, 2007, p.3). This species crown are well branched especially at younger ages and natural pruning is weak (Pinto, 2004, p.21). Weak natural pruning and the depth of crown (often with big branches) is noted to cause reduced log quality in the upper stem (Tavares, 1999 cited by Pinto, 2004, p.33).

P radiata

Fire tolerance

P. radiata has been described as '*very fire sensitive*' (Dawson, 1982: p.1) and that it is more vulnerable to fire than *P. elliotti*, *P. caribaea* and *P. pinaster* (Luke & McArthur, 1978: p.146). The species is killed by severe surface or crown fire (Cope, 1993). Although not routine, control burning of *P. radiata* stands has been tested and guidelines developed. While crown scorch reduces growth rates and can kill trees, it is possible to carry out fuel-reduction burns under older stands with low intensity fires (200–300 kW/m), provided that duff does not ignite (Mead, 2013, p.22). For example, low-intensity (<200 kW/m) fuel reduction burns can be used to kill wildling regeneration (up to 15-m tall) under mature stands; wildings with scorch to more than 80% of crown height had an 88% chance of mortality (Burrows et al., 1989, p.45). In Victoria, results indicate that low intensity fire (a qualitative rather than quantitative description) can be used to reduce fuel quantities from first thinning operations (Billing, 1979: Summary). A key point is that a low intensity will achieve satisfactory burning of almost all fine fuels in first thinning slash on the ground but above the duff layer (Billing, 1979, p.7).

Impact of fire on *P. radiata* is increased by fuel loads (e.g. associated with thinning). A flame height of height <1.5 m (Billing, 1979, Summary & p.6) or fire line intensity <200 kW/m (Burrows et al., 1988, p.3) did not result in noticeable injury to tree boles. With increased fuels after heavy first thinning, c.10% of trees exhibited cracks in the bark and resin exudation due to irregular fuel distribution and extended flame residence time (up to 4 min) (Norman, 1985, p.3).

Bark attributes

Trees are damaged by direct heat with exposure to a temperature of 200 °C for more than half a minute resulting in cambium death wherever heat was applied (de Ronde, C. 1982; Vogl, et al., 1977, cited in Cope, 1993). Natural population variation in *P. radiata* basal bark thickness has been linked to anthropogenic fires; differences in bark thickness on mainland populations (0.7-6.6 cm) with anthropogenic fires compared with island provenances (0.3–4.0 cm) with limited anthropogenic fires (Stephens & Libby, 2006, p.648, p.650 Table 1). Young, thin-barked *P. radiata* are often killed by fire, particularly when stands are dense and crown fires occur (Vogl, et al., 1977, cited in Cope, 1993).

A literature review of fire and *P. radiata* indicated that stem damage is restricted to small sections of trees with DBHOB <21 cm or bark thickness <2.5 mm but it does not impact merchantable wood volume (Woodman & Rawson, 1982, p.16). Under a low intensity prescribed burns (<300 kW/m), 0.6% of sampled trees in stands 11–26 years had bole damage 3 months after fire (Thomson, 1978, p.1,7&9). In mature trees, Burrows et al. (1989, p.50) considered stem damage unacceptable when cambium kill occurred above 0.5 m height, which can result from woody fuels accumulation, in all cases without consequences to diameter growth. Further damage can result where resin on the outer bark of living trees ignites and causes some bole damage (Burrows et al., 1988, p.3). A low intensity fire (flame height <1 m but with a high-residence time) caused fire scars up to a height of 7 m and stem girdling between of 22% and 46% of the stem circumference at stump height (Woodman & Rawson, 1982, p.16). Localized burning or scorching of bark of mature trees causes scarring (where not 100% of a tree circumference) but may not result in tree death (Vogl, et al., 1977, cited in Cope, 1993).

Crown structure and damage

Crown scorch reduces growth rates (Mead, 2013, p.22) and can kill trees (Mead, 2013, p.22; Cope, 1993). Trees with greater than 50% crown scorch had DBHOB increment reduced by 59% (dominant trees) and 38% (co-dominant trees) in comparison with un-scorched individuals (Woodman & Rawson, 1982, p.15). Low intensity fire (<200 kW/m) has been used to control pine wildlings (up to 5 m tall) under mature stands. Death results from fire defoliated or completely scorched crowns: c.90% of trees exceeding 1 m in height died when crown scorch exceeded 80% and 88% of the same size trees with less than 60% scorched crown survived (Burrows et al 1989, pp.45&47). In South Africa, tree death following prescribed burning is expected when crown scorch reaches 90% (de Ronde, 1982 cited in Fernandes et al, 2008, p.248; de Ronde, 1990 cited in Cope, 1993). *P. radiata* can be killed by severe surface fires, and it has been demonstrated in South Africa that survival of a surface wildfire only occurred where crown scorch was less than 90% (de Ronde, 1982; de Ronde, 1990, cited in Cope, 1993).

Appendix 4: Identified best practice elements

Introduction

A body of knowledge has been collated in regard to fire impacts, fire salvage and implications for wood products recovered from such logs. By necessity, the body of knowledge is detailed and has documented under-pinning evidence based facts on each element considered. A result has been to distil out best practice options and considerations around each element (e.g. check lists for use in planning). Best practice is defined based on current available information and where there was a gap or lack of specificity, this has been documented in Appendix 5: Observations. The following appendix presents the best practice elements as noted in each section, and distillation into single statements. This distilled version is presented in Part A of this document.

Pre-fire season planning

An operating framework

Best practice 1: Maintain a fire database to help document fire impacts and history (see https://www.fwpa.com.au/resources/reports/market-access/1966-database-capture-of-individual-significant-scale-australian-forestry-plantation-fire-losses.html).

Best practice 2: Publish details of fire events, preferably in a format that facilitates contribution by operational as well as by research staff.

Best practice 3: Address the four underlying considerations in a fire response strategy: expected woodflows; the ability to store on the stump; current processing and market capacity; and whether dedicated storage is required.

Best practice 4: Establish a pre-fire season planning roundtable to pre-plan a range of fire salvage related considerations.

Best practice 5: Define all parties (stakeholders) within a supply area who have an interest and can influence a fire salvage event.

Best practice 6: Develop protocols for cooperation between parties.

Best practice 51: Establish a memorandum of cooperation between parties defining processes / protocols to plan fire event responses.

Best practice 53: Develop a portfolio of pre-planned administrative systems to support a fire salvage operation.

Best practice 66: Develop and include fire response clauses in all contracts associated with harvesting and supply of logs to processors to expedite the response processes to fire. Develop standard clauses in harvest contracts to take account of increased wear and tear.

Best practice 90: Review and comply with the environmental and regulatory requirements to undertake in water storage of logs in a water body.

Best practice 91: Review the environmental impacts of water-based log storage under Australian conditions.

Best practice 92: Develop a checklist of issues to address and approvals processes with Government. There is a need to understand and work with Government to seek a rigorous but expedited process. Government cooperation is required to make things fall into place.

Specific plans

Best practice 50: Prepare a contractor capacity plan and strategy that can be shared between industry parties as part of pre-summer fire pre-preparation planning.

Best practice 52: Develop specific plans, e.g. Workforce capacity and training; Health, safety and environmental concerns (e.g. erosion risk and management); Community support.

Development of a fire salvage strategy and response

Planning and decision framework

Best practice 3: Address the four underlying considerations in a fire response strategy: expected woodflows; the ability to store on the stump; current processing and market capacity; and whether dedicated storage is required.

Best practice 37: Understand fall-down market options for materials where adequate/effective bark management is not possible.

Best practice 10: Determine harvesting sequences and whether any resource is unsuitable for salvage (whole stands) or any sections of individual trees remain un-recovered by a triage system.

Best practice 29: Reduce log moisture content variation by sacrificing upper crown logs once management is confident of adverse log moisture content issues.

Fire Impacts

Best practice 7: Document potential fire impacts, likely outcomes and options to inform pre-planning.

A fire event

Fire type and impact classification, mapping and monitoring

Best practice 24: Develop a two-way matrix fire damage classification system matrix with crown damage based on remote sensing data and stem damage initially based on ground based assessment. The aim is of this system is to define tree damage that can be related to subsequent impacts (e.g. tree mortality, lost volume and changes in tree moisture content).

Best practice 25: Ensure resource modelling systems incorporate a modified fire impact classification system.

Best practice 34: Develop operational plans informed by changes in standing trees post-fire, beginning with application of a robust fire impact classification system. Harvesting schedules require a degree of plasticity to take account of identified Ips issues and change harvest operations. There is likely to be a degree of 'stopping the Titanic' in ability and agility to swap harvesting around limited by markets, contractor capacity and pre-harvest road construction and maintenance.

Best practice 23: Combine remote sensing and on-ground information in a fire classification system as a basis of mapping fire impacts. This should include crown damage, stem damage and fire intensity.

Best practice 35: Determine timelines for operations after a fire, based on the fire's timing and expected subsequent weather. This will drive options and triage decisions and ultimately the rate of salvage and a need for dedicated storage.

Best practice 54: Develop standard monitoring protocols for plantations post-fire to feed information into ongoing management of fire salvage operations. Monitoring of insect and fungal attack, and moisture content can support the scheduling process in order to prioritise susceptible stands. Care is needed to achieve an 'agile' and responsive process, and avoid a chaotic and reactionary one. Given the biology of bluestain and Ips as a vector, monitoring of Ips levels can be used to determine when to harvest.

Expected woodflows

Woodflow plans

Best practice 8: Ensure industry yield regulation systems have capacity to take account of expected fire salvage outcomes in the short, medium and longer terms and the management of the non-burnt forest.

Best practice 25: Ensure resource modelling systems incorporate a modified fire impact classification system.

Best practice 55: Ensure that resource modelling systems used to develop fire response plans have the capacity to address expected losses due to fire impacts such as compression fractures, brittleness and butt log direct fire impacts.

Best practice 56: Address resource losses due to harvesting damage caused by brittle wood. This should include consideration of compression fractures created by fire storm winds and stem drying.

Best practice 63: Develop and include fire-impacted log specifications in all log specifications agree between parties to a wood supply agreement.

Triage and log specifications

Best practice 11: Set harvest priorities as part of the triage.

Best practice 12: Change harvest priorities by a switch of harvest from green plantations to fire-impacted plantation.

Best practice 13: Reduce risks of adverse logs (e.g. limit passenger and carbon within the wood of logs or logs which are brittle) and/or match expected resource flows over a period of storage on the stump to processor capacity by accepting losses of upper stem logs that will dry out first.

Best practice 14: Include in the triage an option to not harvest a stand (e.g. trees are non-merchantable size), change log specifications (changes in stem form, defects and small end diameter) or exclude specific sections of tree stems (e.g. butt log sections by long-butting or upper crown logs which have dried out with time).

Best practice 15: Agree on a definition of acceptable and rejected logs, and log specifications, to increase reduce the risk of log breakage, improve de-barking efficacy and reduce risk of carbon contamination.

Best practice 16: Develop and include fire-impacted log specifications in all log specifications agreed between parties to a wood supply agreement. Industry yield regulation systems should have capacity to take account of expected fire salvage outcomes in the short, medium and longer terms. With time trees will dry-out and this increases the risk of insect attack and bluestain.

Harvesting and logistics

Best practice 64: Develop a harvesting manual as an agreed set of best practice processes and protocols to undertake fire salvage harvesting works.

Best practice 65: Develop a protocol to address road construction and maintenance requirements as part of a fire response plan. This should include linkages to regulatory authorities and their processes and protocols.

Best practice 57: Change scheduled/planned harvests are part of a salvage response plan. This will necessitate a review of road construction and maintenance, harvesting and haulage requirements.

Best practice 58: Assess may require regulatory approvals, access to materials and contractor capacity as part of the road construction and maintenance requirements. The protocols and requirements should be in place as part of pre-fire season planning and development of a response manual.

Best practice 59: Match the triaged change to harvesting schedules with upgrade and construction of roads, which will dictate the sequence of harvest and planning of operations.

Best practice 60: Re-allocate harvesting and haulage capacity from current green harvest operations, which will require a degree of negotiation. The next step is to increase harvesting hours of operation and/or bring in contractors from other locations. A high degree of coordination and cooperation will be required.

Markets

Best practice 21: Document the specific needs (log type and specifications) of all processors in a supply area who may be impacted by a fire salvage operation.

Best practice 22: Assess the ability to export logs surplus to local needs and undertake a benefit cost analysis of the impacts of log exports on local industry. This will inform decisions of whether to stockpile logs that are surplus to current processor capacity.

Best practice 17: Store trees on the stump to supply logs direct from plantations to processors, as the cheapest and simplest solution to a fire salvage. Success with this strategy requires the maximum duration of such an approach to be defined by the rate of stem drying combined with insect attack and any resulting fungal infestation (e.g. bluestain). Such changes will be influenced by the nature of fire impacts, fire timing and subsequent weather (e.g. insect impacts may be reduced over cold winters).

Best practice 18: Supply fire-impacted logs to current markets either as supplementary resource or as a replacement of green logs. This will require cooperation and coordination between all parties.

Best practice 19: Access log export markets as a buffer to take a surge in supply. This may take time to develop and requires access to specific infrastructure, or be a relatively simple option.

Best practice 20: Supply fire salvage logs into alternative domestic markets where possible. New markets could be within the same or alternative wood supply zones. The latter requires greater investment in haulage.

Storage on the stump

Best practice 61: Storage on the stump and direct delivery to market is the cheapest option.

Best practice 62: Monitor standing trees to assist with harvest planning to minimise deterioration below intended log grades.

Storage of logs in a wet log storage facility

An on-site or dedicated log wet storage facility

Best practice 67: Determine, on best available information, whether a log wet storage facility can be developed on-site at a processors. This must be informed by water input requirements and an ability to recycle water. This would be the next cheapest option to storage on the stump.

Best practice 68: Develop a dedicated facility, if development of on-site log wet storage facility is not an option.

Development of a wet log storage facility

Best practice 82: Seek specific expert advice on design and development of a wet log storage facility.

Best practice 83: Select a suitable site that allows development and operation of a log wet storage facility.

Best practice 72: Consider adverse impacts of prevailing winds on the spatial arrangement of the individual log stockpiles within a log wet storage facility. Logs stockpile should minimise wind impacts that would affect water application and drying rates.

Best practice 78: Plan removal of logs from a stockpile to minimise interruption to the watering regime.

Best practice 73: Design log stockpiles to maximise watering efficiency and effectiveness. Store logs directly on the ground rather than on bearer logs. Consider use of membrane or other material to assist with water management. Stack logs as uniformly as possible to create a flush-sided stockpile to prevent rain shadows.

Best practice 69: Review efficacy of the watering system and impact of settling of log stockpiles on overall storage.

Best practice 77: Ensure watering infrastructure can maintain an appropriate watering regime. Water quality can be a management issue for blockages to equipment. Failures of watering application (e.g. due to mechanical faults), even for a short time, can be catastrophic. Water management should include retention within the site with recycling and cleaning.

Best practice 79: A wet storage area must have 'fit for purpose' irrigation infrastructure (e.g. pumps with adequate capacity and redundancies), back-up systems (e.g. electricity) and robust irrigation pipes and sprinklers. It is suggested that circular sprinklers should overlap by 25%. The irrigation system should be designed in modules to allow isolation of trunk-lines to move logs in and out and to effect repairs and maintenance of hardware.

Best practice 80: Consider that ability for water capture and recycling to prevent run-off, maintenance of water quality by appropriate filtration systems, and adequate equipment redundancies to ensure nil gaps in watering.

Best practice 84: Establish a development (capital) and operational budget. Unless developed as a service provider, a log wet storage facility is an expense against future revenues.

Best practice 85: Analysis the financial implications of all possible scenarios (e.g. is it a better proposition to sacrifice upper stem logs due to drying, to maintain logs on the stump or harvest and store in a wet storage facility). Analysis must consider risk and uncertainty.

Log stockpile management: log condition and segregation

Best practice 74: Segregate log stockpiles to contain one type of log. Segregation should be based on dimensions (length and/or diameter), processor-specific log grade, fire impact and bluestain status. Understand which attributes are of the greatest importance to inform log segregation.

Best practice 76: Monitor quality of logs entering a stockpile. This will determine the maximum log quality after storage. To prevent development of bluestain, maintain sapwood moisture content above 110%DRY BASIS. To prevent ambrosia beetle (pin-hole borer) and fungus attack, maintain a film of water on log surfaces. Attention should also be paid to anaerobic decay fungi which can operate under watered conditions.

Log stockpile management: water management

Best practice 70: Ensure log storage facility is ready to receive and water logs before beginning deliveries to prevent log degrade once on-site.

Best practice 76: Monitor quality of logs entering a stockpile. This will determine the maximum log quality after storage. To prevent development of bluestain, maintain sapwood moisture content above 110%DRY$_{\text{BASIS}}$. To prevent ambrosia beetle (pin-hole borer) and fungus attack, maintain a film of water on log surfaces. Attention should also be paid to anaerobic decay fungi which can operate under watered conditions.

Best practice 75: Begin water application as soon as logs are delivered to a storage area. Water applied at a rate of 100 mm/day (temperate conditions) and 150 mm/day (tropical conditions) with continuous application will maintain log quality. This was for log stockpiles 6 m and 4 m high under temperate and tropical conditions respectively.

Log stockpile management: duration of storage

Best practice 86: Define the point in time where log condition is expected to begin deteriorating.

Best practice 69: Review efficacy of the watering system and impact of settling of log stockpiles on overall storage.

Best practice 87: Operational experience in New Zealand and South East South Australia had success in storage of P. radiata logs for 24 and 29 months respectively.

Best practice 88: Softwood log storage was recommended to be no longer than 6 months and required a continuously operating watering system.

Log stockpile management: monitoring regime

Best practice 81: Include development and implementation of a monitoring program to ensure effective management and maintenance of log quality.

Storage of woodchips

Site selection and planning

Best practice 99: Maintain woodchip hygiene as this is critical to subsequent use and acceptance by markets.

Best practice 100: Select an appropriate site for woodchip storage. A woodchip stockpile can have a significant footprint. An ideal woodchip stockpile is triangular is shape and well aeriated to reduce woodchip deterioration particularly with longer duration storage.

Woodchip stockpile attributes and management

Best practice 93: Design woodchip stockpiles that are no more than 10 to 15 m high, and triangular or conical in shape; a woodchip pile should not have a flat top.

Best practice 100: Select an appropriate site for woodchip storage. A woodchip stockpile can have a significant footprint. An ideal woodchip stockpile is triangular is shape and well aeriated to reduce woodchip deterioration particularly with longer duration storage.

Best practice 97: Address design and composition of the base beneath the pile. A base can be a sacrificial layer of woodchips or engineered (e.g. rock, cement or bitumen) with implications for cost and recovery of woodchips.

Best practice 98: Manage water runoff, which will have a range of chemical compositions.

Best practice 94: Aim for woodchips that are uniform in size and have minimal fines. This will maximise effective ventilation of moisture and heat. To reduce the risk of woodchip breakdown and creation of fines, do not use heavy plant to handle woodchips. Screening of woodchips may be required prior to storage.

Best practice 95: Deliver woodchips to a stockpile without creating adverse compaction.

Best practice 96: Development and manage the stockpile to keep woodchips in a ‘fit for purpose’ state.

Best practice 101: It not a requirement to apply water to a woodchip stockpile to maintain woodchip quality. A woodchip stockpile will reduce and stabilise in moisture content with time due to air movements.

Operations: preparing woodchips

Best practice 41: Apply a light watering system to supress dust and particulate carbon from migrating from wood yards to other sections of a processing site. This should include management of site water run-off.

Best practice 42: Process fire-impacted logs differently to routine green logs due to heat baked on bark, carbon and reduced stem moisture content.

Best practice 43: Subject fire-salvage logs to an enhanced log specification to minimise risk of carbon contamination and to maximise de-barking efficacy. This should be included in routine log specifications to be triggered by a fire event, as agreed between parties.

Best practice 44: Segregate fire-impacted logs from fresh green logs to allow management of carbon risk, de-barking and blending onto stockpiles via chipping. This may include segregation based on diameter class to facilitate de-barking. If the scale of fire-impacted logs is beyond what is possible to blend in such resources, batching will be required and this is an individual site decision.

Best practice 45: Reduce the risk of carbon entering a woodchip pile by more aggressive management of de-barking equipment. This is facilitated by changes in log specifications and batching of logs into de-barkers.

Best practice 102: Blend fire-impacted logs in to dilute potential impacts of drier logs at the point when de-barked logs are chipped. If the scale is beyond acceptable limits, logs can be batch chipped.

Best practice 103: Woodchips delivered to a stockpile may require screening, depending on the fines levels. Determine how well fire-impacted logs, which may be drier, are chipping (e.g. the level of fines produced).

Processing in sawmills

Recognising that fire-impacted logs are different

Best practice 106: Fire-affected trees may be more likely to fracture during harvesting. This can increase with stem drying during storage on the stump for extended periods.

Processing strategy sawmills

Best practice 26: Establish a strategy to address carbon risk by either prohibiting fire-impacted logs from a site or applying management strategies to address carbon. Management strategies need to address passenger and inherent carbon on logs.

Best practice 27: Use site management strategies, including segregation and batching of fire impacted and green logs.

Best practice 33: Up to site- and process-specific percentages, address moisture content variation by dilution with green logs, after which batching is required.

Best practice 36: Define trigger thresholds for transition from dilution to batch strategies for log-yard and de-barking strategies.

Best practice 71: Implement the different requirements for wet storage of hardwood and softwood logs. Softwood logs require a free water film to be maintained across log surfaces to prevent insect attack and decay fungi infestation.

Wood yard management, log segregation

Best practice 30: Consider benefits from batching logs of similar moisture content for processing.

Best practice 38: Understand the potential for effective surge storage capacity on routine processing sites.

Best practice 107: Logs should be batched for processing based on green (unburnt), whether impacted by fire storm conditions (with potential for compression fractures), stored on the stump (potentially segregated by position within the stem as a proxy for log moisture content) or stored under wet conditions (with increased porosity and permeability due to bacteria) and level of bluestain.

Log specifications

Best practice 63: Develop and include fire-impacted log specifications in all log specifications agree between parties to a wood supply agreement.

Best practice 47: Sacrifice some logs to increase log homogeneity for processing to address a range of fire impacts to trees and therefore logs.

Best practice 43: Subject fire-salvage logs to an enhanced log specification to minimise risk of carbon contamination and to maximise de-barking efficacy. This should be included in routine log specifications to be triggered by a fire event, as agreed between parties.

De-barking sawlogs and carbon

Best practice 28: Have an overall strategy to address logs with carbon impacts with a range of possible alternatives.

Best practice 39: Understand the best financial outcomes in a trade-off between more aggressive de-barking and fibre loss.

Log batching strategy

Best practice 44: Segregate fire-impacted logs from fresh green logs to allow management of carbon risk, de-barking and blending onto stockpiles via chipping. This may include segregation based on diameter class to facilitate de-barking. If the scale of fire-impacted logs is beyond what is possible to blend in such resources, batching will be required and this is an individual site decision.

Best practice 46: Determine the level (percentage) of fire-impacted logs processed and when a dilution strategy should be replaced with a batching strategy.

Best practice 48: Segregate logs and batch process as a fundamental strategy to address issues associated with sawing of fire-impacted logs.

Best practice 49: Assess log moisture content and, if possible, determine whether logs contain compression fracture or fractures caused during harvesting. Include this information as an element of a log batching strategy.

Hygiene

Best practice 40: Manage hygiene strategies in processing centres, including consideration/identification of all positions where bark may obscure sensors.

Best practice 41: Apply a light watering system to supress dust and particulate carbon from migrating from wood yards to other sections of a processing site. This should include management of site water run-off.

Sawing

Best practice 108: As logs dry cracks or checks may result. Saw blades may follow such defects causing damage to blades. Dry logs will also generate greater friction and heat during sawing which may impact saw blades. This can be addressed by reducing mill throughput speeds.

Best practice 109: Batches of boards with increased porosity and permeability and/or un-even moisture content after green mill processing should be dried in a more-gentle kiln regime over longer periods. Once dried, boards should be reconditioned to equalise board moisture contents.

Drying

Best practice 31: Address variation in board moisture content during kiln drying by adopting a less aggressive schedule and including an equalisation process post kiln drying and prior to pre-reconditioning.

Best practice 32: Address issues with kiln drying of boards sourced from fire-impacted logs by use of batch rather than continuous kilns.

Best practice 109: Batches of boards with increased porosity and permeability and/or un-even moisture content after green mill processing should be dried in a more-gentle kiln regime over longer periods. Once dried, boards should be reconditioned to equalise board moisture contents.

Appendix 5: Observations

Administration and planning

Regulatory issues

A range of regulatory issues require documentation:

- Water storage: The requirements to undertake water storage of logs immersed in a water body.
- Woodchip stockpiles: All approvals required to develop a woodchip stockpile either standalone or as part of an existing facility.

Resource pre-planning

Observation 3: Develop and implement mechanisms to gather / collate / capture Australian data on fire outcomes (i.e. burnt crown, scorched crown, char score/severity, etc) and consequent impact for the main hardwood and softwood species.

Observation 47: Regional fire response plans should consider socio economic impacts in addition to salvage harvest planning.

Mechanisms are required to capture fire data to contribute to a broader understanding of fire related issues and to inform development of fire scenarios.

- Data capture: There is a need to develop and implement mechanisms to gather / collate / capture Australian data on fire outcomes (i.e. burnt crown, scorched crown, char score/severity etc.) and impacts for the main hardwood and softwood species.
- Planning scenarios: Develop woodshed specific fire scenarios as a basis for pre-planning fire responses. The scenarios should be assessed by a benefit cost analysis (BCA) to understand the financial implications and best options. This analysis should then progress to an economic analysis considering broader implications e.g. addition of multiplier effects and externalities. Socioeconomic issues need to be considered such as the impact of processor closure due to resource issues.

Environmental impacts

Observation 54: Document potential environmental impacts of wet storage facilities for logs under local site conditions and for the species of woodchips stored.

Storage strategies will require various environmental permits and this will require enabling information.

- Wet stockpiles: There is a need to document potential environmental impacts of wet storage facilities for logs under Australian conditions.
- Water storage: There is a need to review the environmental impacts of an in water log storage option under Australian conditions.
- Woodchip stockpiles: There is a need to document potential environmental impacts of woodchip stockpiles under Australian conditions and for the species of woodchips stored.

Markets

Woodshed attributes and processor needs

Pre-planning of a fire response requires details of markets.

- Local markets: Document the specific needs of all processors in a woodshed who may be impacted for a fire salvage operation (e.g. log type and specifications).
- Export markets: The ability to export logs surplus to local needs must be addressed and a BCA undertaken of impacts to local industry to inform decisions of whether to stockpile logs surplus to current processor capacity.

Tolerance to fire impact: carbon

Observation 12: Establish acceptable limits of carbon and impurities in products and processing systems.

Observation 15: Investigateall options and strategies to address carbon and impurities in the supply chain this could include in situ de-barking for reduction/removal.

Observation 16: Investigate in situ de-barking in the forests to reduce risk of carbon and impurities embedded in bark which impact processing operations and costs.

Variable tolerances to carbon between products and processors has been identified.

- Acceptable limits: There is a need to define acceptable limits of carbon in products and processing systems.
- Addressing carbon:
    - *Options to remove*: There is a need to undertake a BCA of all options and strategies to address carbon and grit in a supply chain.
    - *De-barking*: A BCA is required of de-barking in the forests to reduce risk of carbon and grit embedded in bark which impact processing operations and costs.

Tolerance of post fire agents: bluestain

Observation 25: Define the thresholds of bluestain in logs at which processing by various operations experience issues to determine decision points for a change from dilution to batching or rejection of bluestained logs.

Variable tolerance to bluestain between products and processors has been identified.

- Thresholds: There is a need to define the threshold of bluestain in logs at which processing by various operations experience issues. This is the trigger points of a change from dilution to batching strategy or rejection of bluestained logs.
- Impacts: Determine the impact of bluestain – will it affect products or not?

Tolerance of post fire changes in log moisture content

Observation 18: An understanding of the cross sectional moisture content and impacts on log peeling and plywood manufacture is required.

Variable tolerance to moisture content variation between products and processors has been identified.

- Radial variation: Understand cross sectional moisture content variation and impacts on log peeling and plywood manufacture
- Sacrifice logs: Determine the decision making process to sacrifice upper stem sections as trees which have dried from the top down post fire.
- Thresholds: There is a need to determine at what 'point' is it too late to harvest based on market requirements

Predictive models

Fire impact to trees: fire type and intensity

Observation 5: Review current tree improvement programs to consider potential for improving fire tolerance by enhancing bark thickness.

Observation 69: Assess the economic impact of compression fractures on board brittleness.

Observation 6: Understand the attributes of fire in plantation forests, the impact of fuel levels and the ability to change management practices (e.g. harvesting residues) to mitigate potential fire temperatures.

Observation 58: A crown fire and sudden loss of foliage will result in water within a tree's conductive tissue changing from a conductive pull to being under the influence of gravity causing pressure of cell pits resulting in pit aspiration. This will impact water movement within wood and this may remain in logs and sawn timber once processed.

Observation 59: Logs recovered after a period of storage on the stump are likely to have dried out from the top of the stem downwards and radially within a tree stem. Timber recovered from such logs will have different and variable moisture content which can be addressed by sacrificing upper stem logs to a different grade and/or by batch processing of logs in green mills through to batching for kiln drying based on green density.

Observation 60: Log recovered after a period of wet storage will have different porosity and permeability due to bacterial activity excavating out conductive and storage tissue, and consuming pit membranes. These changes will impact drying rates and may be non-uniform creating differential drying behaviour within a single board.

Observation 61: Logs recovered from trees affected by a fire storm may have compression fractures creating issues with timber grading.

Observation 62: Fire heat and heating during kiln drying is unlikely to cause changes in mechanical properties of sawn timber, with any change more likely to be due to changes in and lack of homogeneity of porosity and permeability creating differential drying.

Observation 63: Sawn timber should be batched for kiln drying based on at least whether logs were direct supplied from unburnt plantations, after a period of storage on the stump or after storage of logs under sprinklers.

Observation 64: Sawn timber recovered from logs after either storage on the stump or wet storage can have different wood properties (reduced F-grade) if kiln dried via routine schedules. Published information strongly suggests that such sawn timber should be batch processed and kiln dried via an altered drying schedule.

Observation 65: Although sawn timber from sprinkler-stored logs dries more rapidly, increased initial moisture may require that kiln schedules are lengthened. This would be more so if increased drying rates of more permeable water stored wood creates difficulties in maintaining target kiln temperatures. An equalising treatment to reduce final moisture content variation is recommended with mixed charges.

Observation 66: Output sawn timber is graded for mechanical properties as a 'catch-all' at the end of processing. There are issues (impacts) on grading created by reduced population homogeneity (as expressed by an increase in standard deviation).

Observation 67: Assess the radial penetration of heat from the bark to log core into a tree stem to determine the impact on wood properties in particular lignin crystallisation. .

Observation 68: Determine the impact of any change in lignin attributes to pulp and paper utilisation of fire-affected logs.

Fire will impact trees via a range of mechanisms.

- Fire temperature: A key issue with a fire is the heat generated and duration of that heat. Maximum temperature is at the flame base and this will impact the lower stem of trees.
    - *Heat*: Understand the attributes of fire in plantation forests, the impact of fuel levels and the ability to change management practices (e.g. harvesting residues) to mitigate potential fire temperatures.
    - *Impact on trees*: Understand basal bark thickness as an indicator of fire survival. This will be species and management specific as they influence ground and surface fires. Given the importance of bark thickness, and increasing fire frequency, there is a need to revisit current tree improvement programs to consider potential for enhancing fire tolerance by bark thickness.
    - *Penetration*: Determine penetration of heat into a tree stem during fire events and therefore any effect on wood, in particular lignin crystallisation. This will require assessment radially from the bark to log core.
    - *Impact on wood*: Impacts on wood properties by different levels of fire intensity and fires as classified (e.g. any change in lignin attributes affecting pulp and paper utilisation of fire-impacted logs).
- Compression fractures: Techniques to identify compression fractures leading to board brittleness as early as possible in the sawmilling process to minimise risk of not 'fit for purpose' boards reaching the market and sunk costs in producing such boards. This may commence with segregation of logs from fire storm impacted stands (compression fractures) and stands harvested after a period of storage on the stump (harvesting fractures within dry upper-stem logs).
- Fire storm mapping: An area of forest subject to a fire storm will have experienced high winds. This can be addressed in fire mapping protocols to potentially predict a higher incident of compression fractures.

Fire impact to trees: fire impact classification, mapping and outcomes

Observation 8: Understand immediate and later impacts of fire as they relate to a damage class assessment protocol to assist in stand impact mapping and triage.

Observation 21: Based on a fire impact classification, there is a need to document patterns of stem drying in standing trees over time from a fire event.

Observation 2: Calibrate fire intensity classification to impacts on plantation species; current bark mortality models are based on temperature by time and not fire intensity.

Observation 4: Map areas of plantations burnt by a fire storm with associated high winds as opposed to a lesser crown fire.

Observation 11: Address anomalies in remote sensing assessment of fire intensity such as RAFIT (e.g. recently thinned stands where ground reflectance overwhelms crown reflectance), and quantify the accuracy in terms of fire intensity/damage severity. Determine the relationship between fire intensity mapping and survival and salvage across different age-classes and thinning regimes. Test approaches over a range of plantation types (e.g. climate, species and management).

Fire salvage planning commences with an assessment and classification of the impact of a fire event.

- Fire intensity classification: Calibration of fire intensity classification and impacts on plantation species; current bark mortality models are based on temperature by time and not fire intensity.
- Fire impact classification: Based on a fire impact classification, document patterns of stem drying in standing trees over time from a fire event. This will relate fire impact classification to tree condition outcomes over time as a basis of salvage planning and triage.
- Impact over time: Understanding immediate and temporal impacts of fire as they relate to a refined damage class assessment protocol to assist in stand impact mapping and triage.
- Fire storm mapping: Mapping areas burnt by a fire storm with associated high winds as opposed to a lesser crown fire.
- Remote sensing tools: While remote sensing is accurate based on relatively limited field observations, there are some anomalies (e.g. recently thinned stands where ground reflectance overwhelms crown reflectance), and that more work is required to quantify its accuracy in terms of fire intensity/damage severity and its implications for survival and salvage (across different age-classes and thinning). This requires testing for a range of plantation types (e.g. climate, species and management).

Fire impact predictive models

Observation 1: Predicting tree mortality following a fire as a critical step to planning and effective and efficient fire salvage operation. There is a need to develop a predictive tool that combines remote sensing data (e.g. NBRs), pre-fire conditions (e.g. stand conditions and fuel loads) and fire intensity. This should be species specific. This can result in enhanced mapping of stands and will allow linkages between fire outcomes (e.g. mortality, damage and resource properties) and post-fire stand classifications.

Observation 7: Review and understand trade-offs between harvesting methods, plantation fuel loads and nutrient removals. Consider strategies for in situ fuel modification to maintain *site* nutrient levels.

Effective triage of fire impacts must be based on an understanding of expected outcomes (e.g. tree damage and expected survival).

- Tree mortality: Prediction of tree mortality following a fire is a critical step to planning an effective and efficient fire salvage operation. A predictive tool is required which combines remote sensing data (e.g. NBRs), pre-fire conditions (e.g. stand conditions and fuel loads) and fire intensity to predict tree mortality. This should be species specific. This can result in enhanced mapping of stands and allow linkages of fire outcomes (e.g. mortality, damage and resource properties) to stand post-fire classifications.

- Storage on the stump: There is a need to determine the outcomes of storage on the stump after different fire types and resulting damage to trees. This would include consideration of variation of pest attacks that may impact log quality (e.g. boring insects). Do severely burnt trees last longer compared to mildly burnt trees?
- Fuel loads: Review and understand trade-offs between impact of whole tree harvesting to reduce plantation fuel loads and nutrient removals. This should consider strategies for *in situ* fuel modification to maintain site nutrient levels.

Changes within a tree stem

Patterns of change in standing tree moisture content

Observation 29: Define determinates of timelines and drying profile of fire-impacted trees (radially as well as vertically).

Observation 30: Revisit data collected after fire events. For example, where data presented was based on aggregated data for discs taken from within sample trees at known heights within stems. Therefore, while bluestain may have been ‘present’ it would be important to revisit the individual tree data sets to determine the timeline of tree drying, actual moisture content of sample discs and the corresponding level of bluestain.

Changes in standing tree moisture content contribute to defining when trees are past harvest (e.g. too dry and/or bluestained) or when it would be prudent to sacrifice upper stem logs.

- Timelines: Define determinates of timelines and drying profile of fire-impacted trees (radially as well as vertically).
- Past data: There is potential to revisit past data collected after fire events. For example, where data presented was aggregated for discs taken from within sample trees at known heights within stems. Therefore, while bluestain may have been ‘present’ it would be important to revisit the individual tree data sets to determine the timeline of tree drying, actual moisture content of sample discs and the corresponding level of bluestain.

Insects, Ips and bluestain

Observation 9: Capture and collate data on insect attack and linkages to season, weather and stand condition. Include consideration of spatial arrangement of harvest residues and other potential sources of infestation.

Observation 31: There is a need to better understand the mechanisms and nuances of Ips and bluestain. This should address actual moisture content and/or timelines for Ips and bluestain and the conditions which determine timelines and moisture contents.

Observation 32: Understand Ips population dynamics in relation to harvest residues associated with a plantation and in surroundings areas. This would then link to population build up in fire killed trees that remain standing, and impact on surrounding trees.

Observation 28: Predict (by indicators) the onset of impending Ips infestations. This could include field sampling for pheromones.

Observation 26: Model to predict the onset of bluestain based on stem damage, crown damage, season of fire and expected subsequent weather conditions.

Observation 33: Understand the potential for pheromone and ethanol as attractants of insects to logs in wet storage and whether both compounds could be used in tools to control potential insect pests.

Observation 53: Determine the rate of bluestain development once logs are removed from wet storage to inform log management and processing and its impact on wood properties.

The two causes of bluestain to address; Ips and Ophiostoma and Diplodia via wounds and stress. Ips and bluestain impact trees and logs, and Diplodia forms in standing trees and there is a need to develop capacity to better predict bluestain development.

- <u>Predictive model</u>: There is a need for a model to predict the onset of bluestain based on stem damage, crown damage, season of fire and expected subsequent weather conditions.
- Ips:
  - <u>Season and insect attack</u>: Collate and capture data on insect attack and linkages to season, weather and stand condition. This should include consideration of spatial arrangement of harvest residues and other potential sources of infestation cohorts.
  - <u>Ips populations</u>: Understand Ips population dynamics in relation to harvest residues associated with a plantation and in surroundings areas. This would then link to population build up in fire killed trees that remain standing, to surrounding areas.
  - <u>Indicators</u>: To be able to predict (by indicators) the onset of impending Ips infestations (e.g. field sampling using pheromones).
  - <u>Attractants</u>: Understand the potential of pheromone and ethanol as attractants of insects to logs in wet storage and whether both compounds could be used in tools to control potential insect pests.
- Bluestain:
  - <u>Ips and bluestain</u>: Understand the mechanisms and nuances of Ips and bluestain (e.g. address actual moisture content and/or timelines for Ips and bluestain and the conditions which determine timelines and moisture contents).
  - <u>Bluestain and logs</u>: The rate of bluestain development once logs are removed from wet storage to inform log management and processing.

Bacteria

Observation 34: Understand rate of penetration of bacteria into logs during wet storage and the impact of a failure for bacterial to completely colonise a log. There is potential that incomplete or uneven changes in log porosity could impact drying outcomes for sawn timber.

Bacteria attack logs in wet storage increasing log porosity and permeability with implications for sawn timber drying. Bacteria enter logs ends.

- <u>Rate of spread</u>: The rate of penetration of bacteria into logs during wet storage and the impact of a failure for bacterial to completely colonise a log. There is potential that incomplete or uneven changes in log porosity could impact drying outcomes for sawn timber.

Monitoring protocols and tools

Monitoring protocols and tools

Observation 10: There is a need to develop an agreed and standard protocol to establish and monitor plots within and around fire impacted stands for stand condition changes linked to fire impact classifications.

Maintenance of log quality requires support from an appropriate monitoring regime.

- Standard protocols: Develop an agreed and standard protocol to establish and monitor plots within and around fire impacted stands for stand condition changes linked to fire impact classifications.

Determining moisture content of trees, logs and boards

Observation 20: A non-destructive method to determine absolute tree and log moisture content radially and longitudinally is required. Ideally the technique would provide immediate data and be independent of laboratory analysis.

Observation 19: A number of techniques and tools exist that could be used to measure tree and log condition and these may require further testing and calibration.

Observation 57: Research has indicated that near infra-red reflectance spectroscopy (NIRS) analyses provided a good correlation between wet chemistry and dry matter, lignin and cellulose content. There is a need to understand this option and other technology to assist with the management of woodchip stockpiles.

Observation 22: Technology is required to address board moisture content variation as part of effective board batching based on green density.

Tree, log and sawn timber board moisture content change will define subsequent processing options and a sampling strategy is required.

- Non-destructive sampling of trees: A non-destructive method to determine absolute tree moisture content radially and with height is required. Ideally the technique would provide immediate data and be independent of laboratory analysis.
- Non-destructive options log options: A non-destructive method to determine absolute log moisture content radially and with length is required. Ideally the technique would provide immediate data and be independent of laboratory analysis. There are newer techniques and tools that could be used and these require testing and calibration. Research has indicated that near infra-red reflectance spectroscopy (NIRS) analyses provided a good correlation between wet chemistry and dry matter, lignin and cellulose content. There is a need to understand this option and other technology to assist with the management of woodchip stockpiles.
- Non-contact options for sawn timber: Technology to address board moisture content variation as part of board batching based on green density.

Monitoring tools; pit attributes and status

Observation 73: A method to test for pit aspiration in logs (prior to processing) and in resulting boards.

Pits and pit status play a significant role in timber moisture content mechanisms. A method to test for pit aspiration in logs (prior to processing) and resulting sawn timber is required.

Monitoring tools; biological agents

Observation 27: A simple non-destructive test is required to identify presence of bluestain development within stems. Currently Ips infestation is a proxy. Possible strategies include: colour, acoustic technology, odour as well as visual.

Bluestain is a driver of market acceptance of logs and outputs.

- Bluestain identification: A simple non-destructive test is required to identify presence of bluestain development within stems. Currently Ips infestation is a proxy for associated bluestain development, but not for Diplodia based bluestain. Possible strategies include: colour, acoustic technology, odour as well as visual.

Monitoring tools; carbon detection

Observation 13: Explore options to detect carbon and impurities in primary products and processing residues prior to entering a manufacturing system.

Observation 14: The option to combine scanning technology systems within supply chains needs to be considered along with the various options in a supply chain where it is possible or best advantage to detect carbon and impurities. The option to combine this with log identification and tracking should be addressed.

Carbon impurities will determine market options for processing residues and detection tools and techniques.

- Scanning technology: With advances in scanning technology and image analysis, there is a need to explore options to detect carbon impurities in primary products and processing residues prior to entering a manufacturing system. The option to combine scanning technology systems within supply chains need to be considered along with various options in a supply chain where it is possible or a best advantage to detect carbon. The ability to combine this with log identification and tracking should be considered.

Log storage options

Log specifications

Observation 45: Log specifications to address passenger bark risk and to maximise de-barking efficacy. These should be agreed in advance of fire seasons.

Observation 35: Determine whether softwood logs entering wet storage should be de-barked or not based on storage outcomes and any effect on biological degrade.

Observation 49: Determine what factors are important for log segregation during storage and recovery of logs.

Log specification are required for logs into wet storage.

- Log specifications: Log specifications to address passenger bark risk and to maximise de-barking efficacy.
- Log conditions: Determine whether softwood logs entering wet storage should be de-barked or not based on storage outcomes and any effect on biological degrade.
- Log segregation: Determine which factors (see Box 40) are important for log segregation during storage and recovery.

Box 40: Log attributes as a potential basis of log segregation in a wet storage facility.

- Green logs: Not fire-impacted.
- No impact: No signs of bark scorch nor bluestain, but from fire-impacted trees.
- Bluestain: No signs of bark scorch but with bluestain.
- Both: Bark scorch and bluestain.
- Length classes: Segregated by log length to maximise stockpile efficacy.
- Products: Products in a log classification system.
- Position within a stem: Segregate logs by location within tree.

Log stockpile attributes and management

Observation 50: Consider management options including site engineering, base materials, log stack design, watering, log delivery and removal when selecting log storage sites.

Observation 48: Investigate the relationship between log stockpile height, water application rates and maintaining supply of 'fit for purpose' log. Stockpile height will determine site capacity and water application rate will determine the amount of water used.

Observation 52: Determine the most effective watering regime for logs in wet storage. This should include consideration of advances in watering technology and monitoring and control systems.

Observation 54: Document potential environmental impacts of wet storage facilities for logs under local site conditions and for the species of woodchips stored.Observation 55: Investigate the impact of species, operating environment and equipment on the management of wet storage facilities.

Observation 55: Investigate the impact of species, operating environment and equipment on the management of wet storage facilities.

Management of wet storage facilities is based on limited experience in Australian and there is a need to better understand options.

- BCA analysis: Undertake BCA of log wet storage site and management options including site engineering, log stack design, watering rates, log delivery and removal.
- Stockpile height: Investigate the relationship between log stockpile heights, water application rates and maintaining log quality. Stockpile height will determine site capacity and water application rate will determine water use.
- Watering regime: Determine the most effective watering regime for logs in wet storage. This should include consideration of advances in watering technology, monitoring and control systems.
- Species variation: Investigate the impact of species, operating environment and equipment on management of wet storage facilities.

Woodchip stockpile attributes and management

Observation 51: Explore options for base materials (e.g. bitumen, crushed rock, pasture) in a log storage area and the role of geotextiles. Issues to consider include soil properties, mechanical strength, machine-access and water management.

Observation 56: Research options for the base of a woodchip stockpile. In a simple case, this can be crushed rock; with crushed rock greater care is required during woodchip recovery to manage contamination risks. An alternative is use of geotextiles to prevent layer mixing or to assume a sacrifice layer. More permanent solutions include engineering a solid foundation (e.g. a concrete base – there is potential for use of cement stabilisation systems

Development of a woodchip stockpile must consider options for the base of the stockpile.

- Woodchip stockpile base: Research options for the base of a woodchip stockpile. In a simple case, this can be crushed rock; with crushed rock greater care is required during woodchip recovery to manage contamination risks. An alternative is use of geotextiles to prevent layer mixing or to assume a sacrifice layer. More permanent solutions include engineering a solid foundation (e.g. a concrete base – there is potential for use of cement stabilisation systems).

Processing requirements

Processing strategies – log batching

Observation 24: Define trigger points between dilution and batch strategies to address variation in moisture content of fire-impacted logs.

Observation 39: Debarking is a critical factor when processing fire affected logs.

Minimising variation in log attributes can be facilitated by log batching supported by addressing the following knowledge gaps.

- Trigger points: Define trigger points between dilution and batch strategies to address variation in moisture content of fire-impacted logs.

De-barking of logs

Observation 36: Logs with lower moisture content may cause increased friction during drying and heat up saws. Such logs may have cracks and checking which can divert saws causing damage to saw blades.

Observation 37: Success in de-barking and removal of potential carbon contamination will impact market options where carbon sensitivity is a barrier to supply.

Observation 38: Determine and understand the impact of micro-organisms on bark adhesion.

Observation 40: Develop a better understanding of MC and de-barking effort.

Observation 41: To assist planning for fire events develop a difficulty of de-barking index for standing trees and stored by species: fire impact X stand pre condition X time since fire X de-barking methods.

Observation 42: Bark adhesion variation with the different levels of fire impact to tree stems as defined by the fire impact classification system. This would then allow planning for salvage logging.

Observation 43: Impact of log wet-storage on bark adhesion and log de-barking strategies.

Observation 44: Trade-off between bark removal and fibre loss with more aggressive de-barking. This would include quantification of losses.

De-barking is the primary method of addressing carbon impacts on logs. To support more effective de-barking, the following knowledge gaps should be addressed.

- A de-barking index: To assist planning for fire events, develop a difficulty of de-barking index for standing trees and stored logs by species: fire impact X stand pre condition X time since fire X de-barking methods.
- Bark adhesion:
  - Micro-organisms: The impact of micro-organisms on bark adhesion.
  - Moisture content impacts: Understanding of moisture content and de-barking effort.
  - Bark adhesion: Bark adhesion variation with the different levels of fire impact to tree stems as defined by the fire impact classification system to allow planning for salvage operations.
  - Wet storage: Impact of log wet-storage on bark adhesion and log de-barking strategies.
- Aggressive de-barking: Trade-off between bark removal and fibre loss with more aggressive de-barking (e.g. quantification of losses).

Addressing carbon

Observation 46: Methods to detect and address carbon in woodchips.

Observation 17: Explore options for reduction/removal of carbon and impurities from the supply chain.

Carbon can impact and restrict market options and supporting technology will assist.

- Carbon detection: Methods to detect and address carbon in woodchips.
- Carbon separation: Revisit and explore options for separation of carbon within resources.

Kiln drying regimes

Observation 72: Longitudinal variation in board attributes due to discrete pockets of bluestain and differential penetration of bacteria into logs under wet storage. A method is required to identify such variation within logs and how to address such variations during processing of logs and drying of boards

Observation 23: Develop a ‘fit for purpose’ kiln-drying regime for reduced homogeneity populations of boards. This should include consideration of equalisation stages as an option.

Observation 71: Whether board reconditioning will address issues associated with variation in board permeability and initial moisture content; moisture content variation between boards and within boards.

Appropriate kiln drying is critical to effective processing of fire salvage logs after storage. The following knowledge gaps were identified.

- Permeability variation: Longitudinal variation in board attributes due to discrete pockets of bluestain and differential penetration of bacteria into logs under wet storage. A method is required to identify variation within logs and to address such variations during processing of logs and drying of boards.
- Drying schedule:
  - Develop a ‘fit for purpose’ kiln-drying regime for reduced homogeneity populations of boards. This should include consideration of equalisation stages. A BCA of the different combinations (scenarios) is required.
  - Whether a ‘more gentle’ sawn timber kiln drying regime will address inherent variation in board permeability and initial moisture content; moisture content variation between boards and within boards.

- Whether board reconditioning will address issues associated with variation in board permeability and initial moisture content; moisture content variation between boards and within boards.

Source: Forestry Corporation of NSW. 2020