Processing

Control and manage the moisture content of logs and biomass to maximise benefits along the wood supply chain

Project number: PNC400-1516

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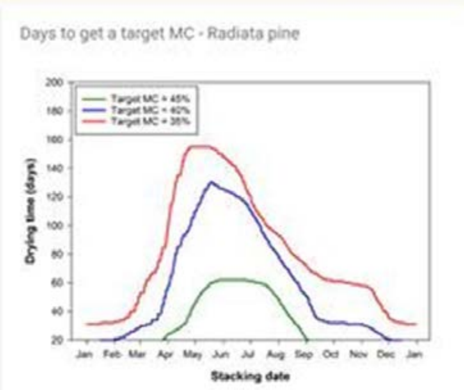

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Forest & Wood Products Australia

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Prepared for

Forest & Wood Products Australia

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1 Executive Summary

Transport costs of logs and forest biofuel can make up 50% of their delivered costs. As approximately 50% of fresh logs and forest biofuel is water, infield drying of this material presents the Australian forest industry with the opportunity to reduce delivered costs through reductions in transport costs, and increased calorific value in the case of biofuels, which will enable better cost-competitiveness with alternative building materials and wood imports and help establish a domestic and export forest biofuel industry.

The project aimed to provide forest managers with the tools to balance reduced transport costs through natural drying of roadside stocks of biofuel and of logs for chips and other wood products against quality specifications, and increased costs for storage time and processing machinery wear and tear. In order to extract the gains from infield drying, there are a number of changes that need to be made by the Australian forest industry. The key changes are:

- Moving from payment on delivered green weight to payment on delivered volume or oven-dry weight.
- Increasing the use of high volumetric capacity trucks, particularly for the transport of dried and infield chipped forest biofuel
- Using the drying models and tools developed in the study to guide planning the storage of logs and forest biofuel, in particular as part of operational planning processes.

Key recommendations

- Forest managers and growers currently managing payments for forest products on a delivered green weight basis should move to a system based on delivered volume or oven-dry weight basis to reduce the incentive to contractors to minimise infield drying
- The Australian forest industry should increase its use of higher volumetric capacity vehicles which were shown in the current study to maximise the savings from infield log and biomass drying. This change is particularly relevant to transport of dried and infield chipped LR
- Delivered cost savings identified in desktop studies of drying logs and forest biofuel should be explored in detailed case studies to examine the supply chain implications and practices required to deliver drier products of acceptable quality at minimum cost.
- Further drying trials under a range of meteorological and storage conditions are desirable to increase the robustness of drying models for logs and forest biofuel of key Australian tree species. These drying trials should make use of the automated weighing platforms used in the current study to minimise study costs.
- Drying models developed in the current study can be used directly or in spreadsheets to manage logs and forest biofuel stored infield. However, operational-level supply chain planning and decision support tools should be developed for the Australian forest industry to maximise the benefits from infield drying of logs and forest biofuel
- Testing the impacts of chipping dry material with a mobile chipper should be extended to *P. radiata* logs with a lower MC than tested in the current study and to other species and types of forest biofuel at a range of MC values

- Further testing of portable tools to measure the MC of logs and forest biofuel stored infield should be conducted and sampling protocols developed to minimise samples required to obtain a result with acceptable accuracy
- Additional Hitman HM200 tool readings for a range of MC values for *P. radiata* logs should be obtained to develop a robust model and methodology for the estimation of the MC of *P. radiata* log stacks.

Table of Contents

2 List of Figures

3 List of Tables

4 Glossary

Term	Definition
LR	Logging residue (aboveground biomass remaining after harvesting merchantable round-wood)
MC	Moisture content (green or wet basis)
Dollars	Australian dollars
t	Metric tonnes
GMt	Green metric tonnes
ODt	Oven dry tonnes

5 Introduction

Australia operates in a global forest products market and must reduce costs to remain competitive internationally against other exporting countries and domestically against imports of forest products. Log costs are the dominant cost of production for sawmills and chipmills and the cost of transporting logs to the mill can be up to 50% of their delivered price (Murphy et al. 2010). As green logs and chips contain ~50% water, ~25% of delivered costs can pay for the transportation of water. Erber et al. (2016) estimated that drying beech logs infield from 41.7% to 22.5% MC and then chipping the logs directly into a truck, increased chip volume per load by 39% when loaded to the maximum legal weight, decreasing transport costs by 22%.

Australia has the potential forest biomass resource (mainly LR, mill processing waste and biomass removed to reduce the fire hazard) to considerably increase both domestic and export energy production from forest biofuel as a means to reduce its greenhouse gas emissions. Use of forest biomass as sustainable biofuel is widely practised overseas, with Sweden and Finland producing approximately 20% of their energy needs from forestry waste (Björheden, 2017). Other countries, including the USA, Canada and Russia, have developed major wood pellet export industries based on conversion of forest biomass (Goetzl, 2015). In contrast, Australia is estimated to produce less than 2% of its energy needs from forest biofuel (Department of the Environment and Energy, 2017) and has a relatively small wood pellet production capacity. Drying forest biofuel is critical not only to reduce transport costs but also to increase its net calorific value. Forest biofuel net calorific value can increase by 50% when dried from green to 20% MC (Senelwa & Sims, 1999), increasing its value to biofuel users and exporters. Potential Australian forest biofuel sources include LR and small diameter or defective trees from thinning operations to increase growth of retained trees (Fung et al., 2002) or reduce fire hazard (Guo et al., 2007), or from plantations that have failed due to drought or pests and diseases (Barrette et al., 2017). Other potential forest biofuel sources either have higher value markets, such as larger logs and wood processing residues, or would not compete against higher value land uses, such as energy plantations (Strandgard et al., 2019).

Reducing the weight of logs and forest biofuel transported can reduce the truck fleet size needed to transport this material, decreasing road wear and tear, diesel emissions and Australia’s fuel import bill. Removal of LR that would otherwise be heaped and burnt or chopper-rolled to clear sites for replanting is estimated to reduce site preparation costs by \$500/ha to \$1000/ha in addition to the potential returns to forest owners from sale of the LR (roadside delivered cost of \$20-\$28/ODt (Strandgard and Mitchell, 2019)). Burning LR is a major contributor to air pollution in a number of major Australian cities and towns. Using woody biomass as biofuel would also reduce emissions of fine particles and volatiles generated by burning logging slash and reduce CO_2 emissions from power generators through reduced use of fossil fuels.

Infield drying of biofuel and of logs for chips and other wood products is a trade-off between the potential benefits gained from reduced transport costs and increased calorific value and potential losses from a range of sources including physical degradation, damage by biological organisms and fire (Da Silva Perez & Fauchon, 2003; Whitehead et al., 2008), increased proportions of pin chips and fines (Radiotis et al., 2008), increased chipper wear and tear (Asikainen & Kuitto, 2000), and deferment of payments (Acuna et al., 2012) and site re-establishment (Richardson et al., 2002).

Operational implementation of industrial-scale infield drying by a forest company requires three main elements to be put in place:

- Payments for logs or forest biofuel based on delivered MC or volume rather than weight
- Drying models to predict log or forest biofuel MC
- Decision support tools incorporating drying models to balance potential gains and losses from infield drying of log or forest biofuel

Payments for logs or forest biofuel based on weight create an incentive in the supply chain to minimise infield drying. However, chipped wood products typically already have their MC measured on receival, facilitating a move to payment based on MC or dry matter. In these cases, the sampling intensity may need to be increased to meet requirements for payment based on MC. Alternatively, payment on delivered log volume could be used to capture MC reductions as it creates the incentive for contractors and forest owners to dry logs infield to reduce transport costs. For companies that currently pay on delivered volume, no changes are required at the mill, but other companies will require installation of equipment to estimate delivered volume or estimate log MC, such as a laser scanner (individual logs or truck loads) or a chainsaw sawdust sampler, or similar. For example, Forico P/L recently installed a Logmeter 4000 laser scanner to change their haulage payment system from weight based to volume based to realise the benefits from infield log drying (Herd, 2018).

Log and biofuel drying models are a critical input into managing infield stocks (Bown & Lasserre, 2015). The majority of previous biofuel drying studies have been conducted in Europe due to government incentives to increase energy from renewable sources. These studies have largely been conducted in cooler and wetter climates than those typically found in Australia, and in some cases have required 12 months or longer to achieve significant levels of drying e.g. (Erber et al., 2014; Kent et al., 2010; Röser et al., 2011; Visser et al., 2014). The initial phase of FWPA infield log drying research (Strandgard & Mitchell, 2017) has shown that under the conditions in the trial, *Eucalyptus globulus* and *Pinus radiata* log piles dried much more rapidly than log piles in overseas trials, showing the drying models developed from these overseas trials were not applicable to Australia.

To determine the optimum level of infield drying that balances the costs and losses associated with infield storage against the gains associated with reduced transport costs and, in the case of biofuels, increases in net calorific value, requires the use of supply chain planning tools. A recent examination of 51 published forest biofuel supply chain tools found that only seven of the tools incorporated management of forest biofuel MC in the operation of the tool and of these, only two used a drying model (Strandgard et al., 2019).

The project aims to provide forest managers with the tools to balance reduced transport costs through natural drying of roadside stocks of biofuel and of logs for chips and other wood products against quality specifications, and increased costs for storage time and processing machinery wear and tear.

6 Development of drying models

6.1 Background

6.1.1 Drying models

Previous studies have shown that the MC, and hence the weight, of LR, logs and whole trees can be substantially reduced through infield drying which can be reflected in lower transport costs for trucks with spare volumetric capacity when loaded to their maximum weight with undried logs and forest biofuel while also increasing net calorific value of forest biofuels. However, infield drying can increase delivered costs through delayed payments for the biofuel (Acuna et al., 2012), costs to return loading and processing machines to the site (Lin et al. 2016), delays in site re-establishment (Richardson et al., 2002) and dry matter losses from decay (Whittaker et al., 2016) and physical losses, largely from handling (Nilsson et al., 2015).

To balance potential returns and costs of infield drying and calculate optimum drying times requires drying models to be developed and incorporated into forest biofuel supply chain planning and management. A considerable number of drying models have been developed in Europe and North America e.g. (Defo & Brunette, 2006; Erber et al., 2014; Filbakk et al., 2011; Gigler et al., 2000; Liang et al., 1996; Murphy et al., 2012; Simpson & Wang, 2003), but few have been developed for tree species grown in Australia drying infield under Australian conditions e.g. (Ghaffariyan, 2013b; Ghaffariyan et al., 2014; Strandgard & Mitchell, 2017). In particular, there have been no mathematical drying models developed for eucalypt or *P. radiata* LR.

6.1.2 Automated weighing platforms

Historically the most common methods used to determine MC in log and forest biofuel drying trials have been: taking samples, lifting and weighing the pile, or using a moisture measurement tool. Sampling approaches typically only measure the MC of a small part of a log or forest biofuel pile (often confined to the pile top or sides) while lifting the pile to weigh it can require the use of costly equipment, such as a forwarder or loader. These approaches also limit the frequency and length of time over which measurements can be made due to cost and practicality constraints (Kizha & Han, 2017). Weighing methods require an initial sample for MC determination to allow weight changes to be converted to MC changes.

Automated weighing platforms use a frame attached to load cells to monitor weight changes of a log or biofuel pile (and hence MC changes) over time. They have been used for a number of recent European log and forest biofuel drying studies e.g. (Erber et al., 2016; Routa et al., 2015a, 2015b). Weighing platforms are capable of taking measurements at a much higher frequency than that achievable using other approaches allowing researchers to better monitor the impact of changes in meteorological conditions on the MC of the log or biofuel pile. Once established, data collection costs using an automated weighing platform are very low compared with other approaches (Kizha & Han, 2017).

A potential problem with forest biofuel measurement approaches that involve weighing biofuel to calculate moisture changes is the limit to the size of the log or biofuel pile that can be weighed (note that this limitation also applies to piles that are lifted and weighed). Smaller piles of LR have been found to dry and rewet more rapidly than industrial-scale LR piles (Lin & Pan, 2013). Airflow under log or forest biofuel piles on weighing platforms is also greater than that for piles established directly on the ground.

Three automated weighing platforms were used to collect the drying data used to develop three of the five drying models in the current project. Each automated weighing platform consisted of two rails rested on the ground or raised on blocks. At either end of these rails were vertical “U” shaped uprights that hold the logs or biofuel (Figure 1). Approximate dimensions were L: 3m, W: 3m, H: 2m. Each weighing platform can measure log or biofuel piles with a mass of up to 12 tonnes. Wire mesh can be attached between the uprights to retain loose biofuel (Figure 2). Between the bottom rails and the uprights are four double-ended shear beam load cells[1] each with a three tonne capacity (Figure 3). Load cells measure changes in weight as changes in voltage. Voltages from each load cell are combined using a junction box and then amplified with a load cell amplifier to a voltage level that can be detected by a standard data logger.

Figure 1. Automated weighing platform

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[1] Hanzhong Quan Yuan Electronic Co Ltd Load cell model QH-43B

Figure 2. Automated weighing platform with mesh to retain loose radiata pine LR

Figure 3. Double-ended shear beam load cell used on automated weighing platforms

Prior to use the load cells were calibrated with a known weight and the zero point was set to exclude the weight of the uprights and any wire mesh attached to the structure to support loose biofuel.

In the current project, the load cell data were captured and recorded by a solar-powered data logger every four hours. At each measurement time, readings were taken for a minute at one second intervals to reduce the impact of brief voltage fluctuations. The recorded data were sent via the mobile phone network to a website. Voltage data were averaged for each measurement time and then converted to the equivalent weight values using the voltage recorded for the known calibration weight.

6.2 Methodology

6.2.1 Drying data collection

6.2.1.1 Radiata pine LR and chip log drying

The radiata pine LR trial was conducted from Feb-Apr 2018 and the chip log trial from Feb-Mar 2018 at Dardanup, Western Australia. Prior to conducting the LR trial, the base and sides of the weighing platform were lined with 100mm square mesh fencing wire to contain the LR on the weighing platform. Logs and LR were delivered to the trial site as soon as possible after harvest. Initial weights were approximately 3.8 t for the LR and 8.8 t for the chip logs, reflecting the considerably lower density of uncomminuted LR compared with that of logs. Initial MC values (green weight basis) were determined by obtaining two samples of 2-3 kg of LR and discs (approximately 30 mm thick) from six chip logs at 25%, 50% and 75% of the log length at the trial start. The samples were weighed green then dried at 103°C until constant weight was achieved.

Automated weight measurements of both logs and LR were made at four-hourly intervals. Changes in weight were assumed to solely result from changes in log or LR MC. The MC value used for drying model development was the mean of the MC measurements for each day. Daily MC values were chosen to match the daily frequency of meteorological data available.

Meteorological data for the trial period were obtained from the Bunbury Bureau of Meteorology weather station approximately 8km from the trial site. For all drying studies in the current project, the meteorological data collected were evapotranspiration[2], rainfall, net evapotranspiration[3], maximum and minimum daily temperature and relative humidity, mean daily windspeed and daily solar radiation.

6.2.1.2 Eucalyptus globulus whole tree drying

The trial was conducted in 2016/2017 in short-rotation *E. globulus* plantations in south-west Western Australia (within 100km of Albany) being clearfelled to produce pulp chips. The trial consisted of 12 trial sites – three sites established in each season.

At each site, two bunches of freshly harvested *E. globulus* trees were deposited by a skidder on the ground on the edge of the harvested area. Bunches were fully exposed to the sun and wind. All trees were aligned in the same direction (all tops at one end) in each bunch. Mean tree number in a bunch was 20 which was the typical bunch size brought to roadside by the skidder.

As the whole trees were too long to be placed on an automated weighing platform, MC (on a green (wet) weight basis) of each bunch of trees was estimated by destructive sampling. Initial MC measurements were made within twenty-four hours of each bunch being placed at roadside. At each site, six subsequent MC measurements were made at weekly intervals. At

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[2] Evapotranspiration is calculated by the Bureau of Meteorology from temperature, vapour pressure and solar radiation using the Penman-Monteith equation.

[3] Net evapotranspiration is Evapotranspiration minus Precipitation

each time of measurement disc samples and a two to four kg crown sample were taken from a single tree randomly selected from the top of each bunch. Discs were approximately 30 mm thick and were taken at 10, 30, 50, 70 and 90% of the tree height at the point at which the stem underbark diameter was 50mm. Discs and crown samples were weighed green then dried at 103°C until their weight stabilised. To calculate the MC for each tree, an *E. globulus* allometric model (Hingston & Galbraith, 1998) was used to weight the MC values for each tree component by the proportion of the tree before drying represented by that the component. Stem disc MC values were also weighted by disc green weight as larger discs represented more of the stem wood than smaller discs. At each time of measurement, the weighted MC values were averaged across the two bunches to give a single whole tree MC value for the site.

Meteorological data for the trial period were obtained from the closest Bureau of Meteorology weather station from each trial site.

6.2.1.3 Eucalyptus nitens LR drying

The *E. nitens* LR drying trial was conducted from late 2016 to early 2018 at the Forico Long Reach Mill, NE Tasmania. Four LR piles were established to cover seasonal weather changes. The LR was transported from the plantation as soon as possible post-harvest and placed on a truck weighbridge. Wooden pallets were placed on the weighbridge prior to the trial to allow rainwater to flow off the weighbridge. Fencing wire (100mm square mesh) was wrapped around the sides of each pile to prevent losses of material during the trial. The weight of the pallets and wire were deducted from the weighbridge readings. When each pile was established, its initial MC was obtained by weighing 3 samples of approximately 7-8kg collected from the LR at the time of collection. The MC of each residue component (bark, branches and leaves) was determined separately and weighted by the proportion that each component represented in the LR on a green weight basis. Component proportions were determined from the average of 5 random samples obtained using a 1m^2 square from the LR infield at time of collection (Table 1).

Table 1. Proportions of *E. nitens* LR components for each trial period.

Trial period	Wood (%)	Bark (%)	Branches (%)	Leaves/twigs (%)
1	32	37	16	15
2	22	34	22	22
3	24	39	18	20
4	14	53	24	8

Meteorological data for the trial period were primarily obtained from an Oregon Scientific WMR300 portable weather station adjacent to the trial site. Due to problems with the reliability of the portable weather station rain gauge, rainfall data and maximum temperature data were obtained from the Low Head Bureau of Meteorology weather station (Latitude: -41.05, Longitude: 146.79) approximately 15.8 km from the trial site.

6.2.1.4 Eucalyptus globulus chip log drying

The *E. globulus* chip log drying trial was conducted from Oct 2018-Feb 2019 at Penola, South Australia. The logs were delivered to the trial site as soon as possible after harvest. Initial chip log weight was approximately 9.1 t. To determine the initial MC values (green weight basis) discs (approximately 30 mm thick) from six chip logs at 25%, 50% and 75% of the log length were obtained at the trial start. These samples were weighed green and then dried at 103°C until constant weight was achieved.

Automated weight measurements of the logs were made at four-hourly intervals. Changes in weight were assumed to solely result from changes in log MC. The MC value used for drying model development was the mean of the MC measurements for each day.

Meteorological data for the trial period were obtained from the Coonawarra Bureau of Meteorology weather station approximately 9.5km from the trial site.

6.2.2 Drying model development

Drying models were developed from the data collected in the current study using Minitab v.17 (www.minitab.com) and Microsoft Excel (www.microsoft.com). The dependent variable in all cases was the daily change in MC between each measurement time. The independent variables tested were the MC at the end of the previous measurement period and a range of meteorological variables from the nearest Bureau of Meteorology site to each study site (evapotranspiration[4], rainfall, net evapotranspiration[5], maximum and minimum daily temperature and relative humidity, mean daily windspeed and daily solar radiation). These meteorological variables were tested because they have been found to be significant in previous studies e.g. (Bown & Lasserre, 2015; Erber et al., 2012; Strandgard & Mitchell, 2017) and because they are readily obtainable from the Bureau of Meteorology. In each case, potential candidate variables and combinations of variables were identified using the “best subsets” linear regression option in Minitab. Linear regression models with the highest R^2_{adj} and the least number of variables were selected for further testing of variables, goodness of fit (R^2_{adj}, Standard Error (S), Mean Absolute Percent Error (MAPE)) and compliance with the rules of linear regression. Variables were included in the final drying models if they were significant ($p<0.05$) and had a variance inflation factor (VIF) less than 5. VIF is a measure of the degree of multi-collinearity between the variables with a low value indicating a low degree of multi-collinearity.

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[4] Evapotranspiration is calculated by the Bureau of Meteorology from temperature, vapour pressure and solar radiation using the Penman-Monteith equation.

[5] Net evapotranspiration is Evapotranspiration minus Precipitation

6.3 Results

6.3.1 *Pinus radiata* chip log drying model

Two drying models were developed in the current study: one developed from drying data collected in the current study only and one developed from the combined data from the current study and a previous FWPA drying study of similarly sized radiata pine chip logs (Strandgard & Mitchell, 2017). These drying models and the radiata pine chip log drying model developed during the previous FWPA drying study were compared for goodness of fit to the combined dataset using the lowest MAPE value as the selection criterion. The previous FWPA drying model had the lowest MAPE (6.6%), the combined data drying model MAPE was 10.1% and the current study data only drying model MAPE was 10.8%. Figure 4 shows the MC measurements from the current study and the results for the three models modelling the current study data.

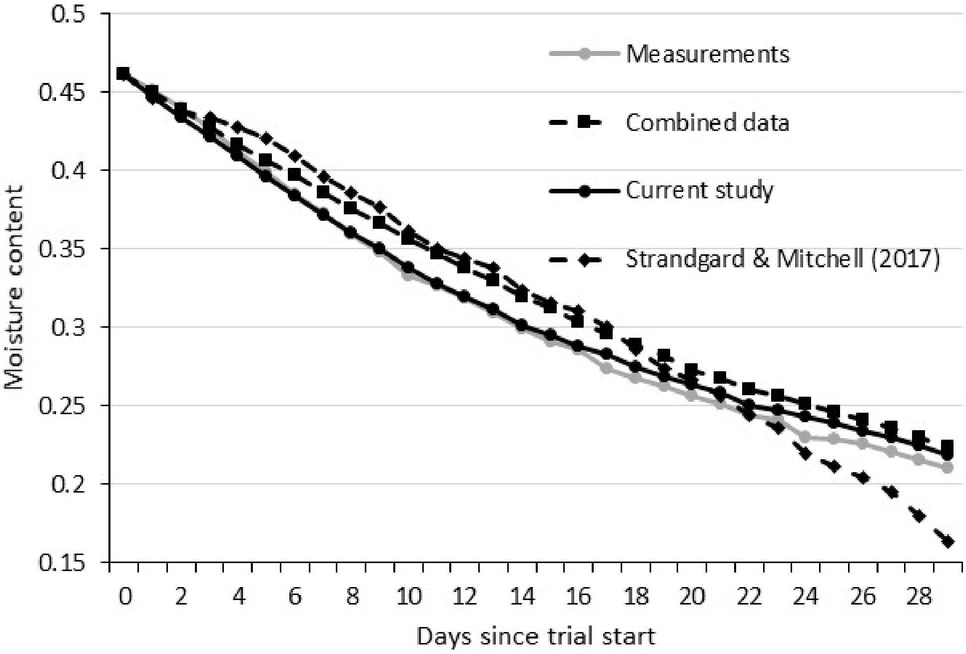


Figure 4. *Pinus radiata* chip log measured MC values and MC values modelled using models derived from current study data, current study data combined with the Strandgard and Mitchell (2017) drying data and the Strandgard and Mitchell (2017) drying data only.

Drying model fit statistics below were from the Strandgard and Mitchell (2017) radiata pine chip log drying model and data only.

$$\Delta MC = -0.0423 + 0.0327 \times Max\_RH + 0.0161 \times Min\_RH$$

$R^2_{adj} = 74.3\%$; S = 0.0019

Where:

ΔMC is the change in MC from the last measurement period

Max_RH is the maximum daily RH (%)

Min_RH is the minimum daily RH (%)

6.3.2 *Pinus radiata* LR drying model

The low R^2_{adj} and high MAPE values for the drying model developed in the study were likely to result from the model not replicating the sharp rise in LR MC that occurred 30 days after the trial started which corresponded to a rainfall event (Figure 5).

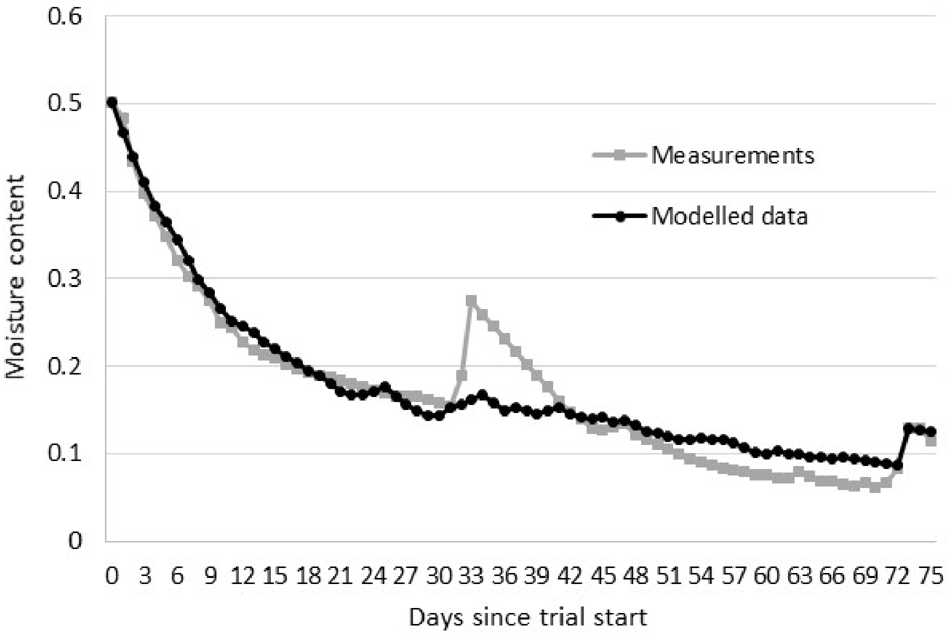


Figure 5. *Pinus radiata* LR measured and modelled MC values.

$$\Delta MC = 0.0516 - 0.0912 + \times Initial\_MC + 0.0035 \times Rainfall - 0.000493 \times Max\_RH$$

R^2_{adj} = 37.8%; S = 0.013; MAPE = 15.8%

Where:

ΔMC is the change in moisture content from the last measurement period

Initial_MC is the moisture content at the end of the last measurement period

Rainfall is the daily rainfall total (mm)

Max_RH is the maximum daily RH (%)

In order to determine the influence of the sharp rise in MC resulting from rainfall 30 days after the trial start on the regression goodness of fit, the regression was rerun after these data were removed (Figure 6). Removing these data improved the R^2_{adj} and standard error of the regression. The MAPE was lightly poorer.

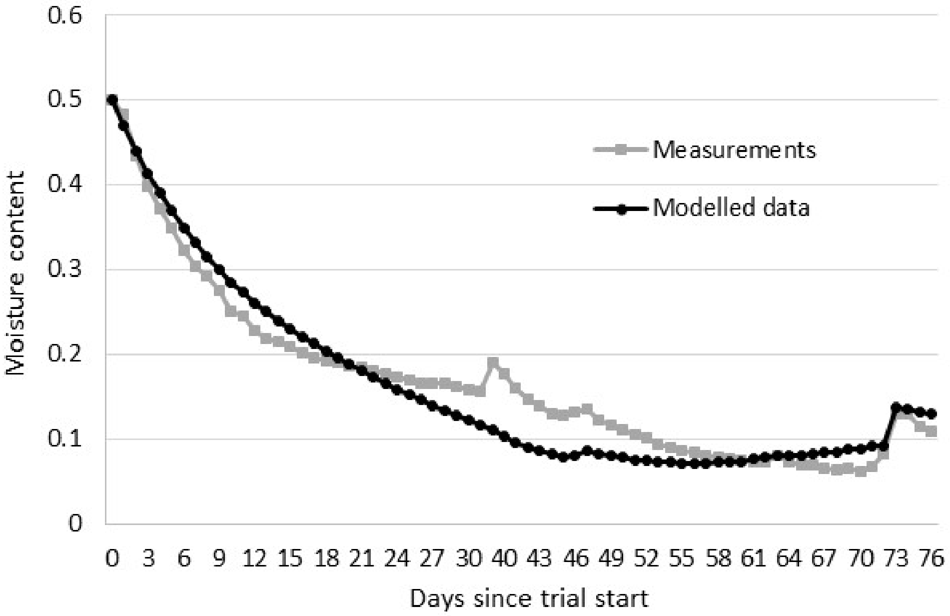


Figure 6. *Pinus radiata* LR measured and modelled MC values (sharp rise in MC data removed)

$$\Delta MC = 0.0064 - 0.075 + \times\ Initial\_MC + 0.0037 \times Rainfall$$

R^2_{adj} = 63.5%; S = 0.008; MAPE = 17%

Where:

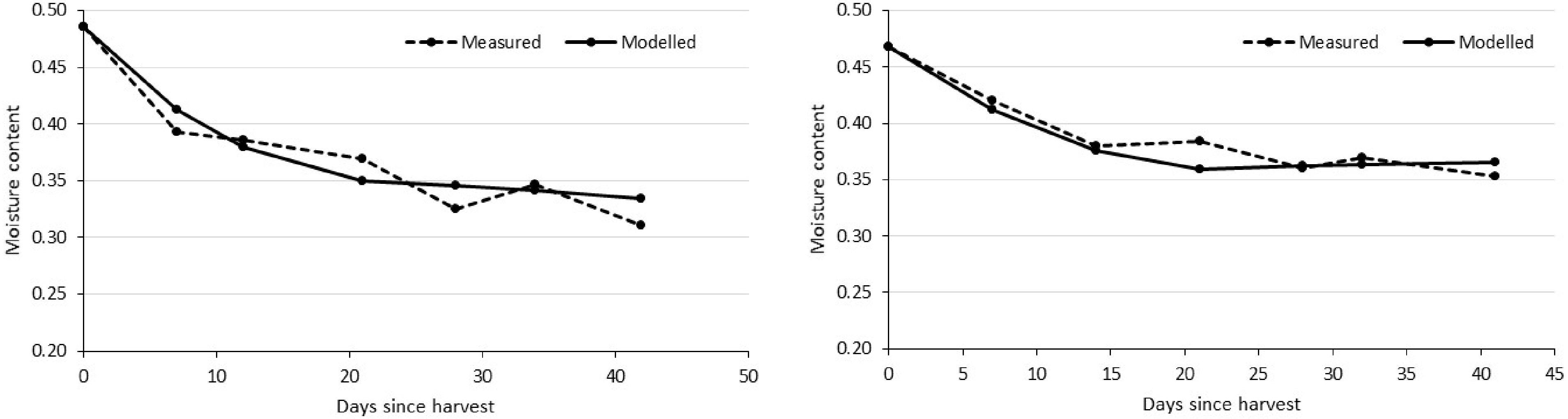
ΔMC is the change in moisture content from the last measurement period

Initial_MC is the moisture content at the end of the last measurement period

Rainfall is the daily rainfall total (mm)

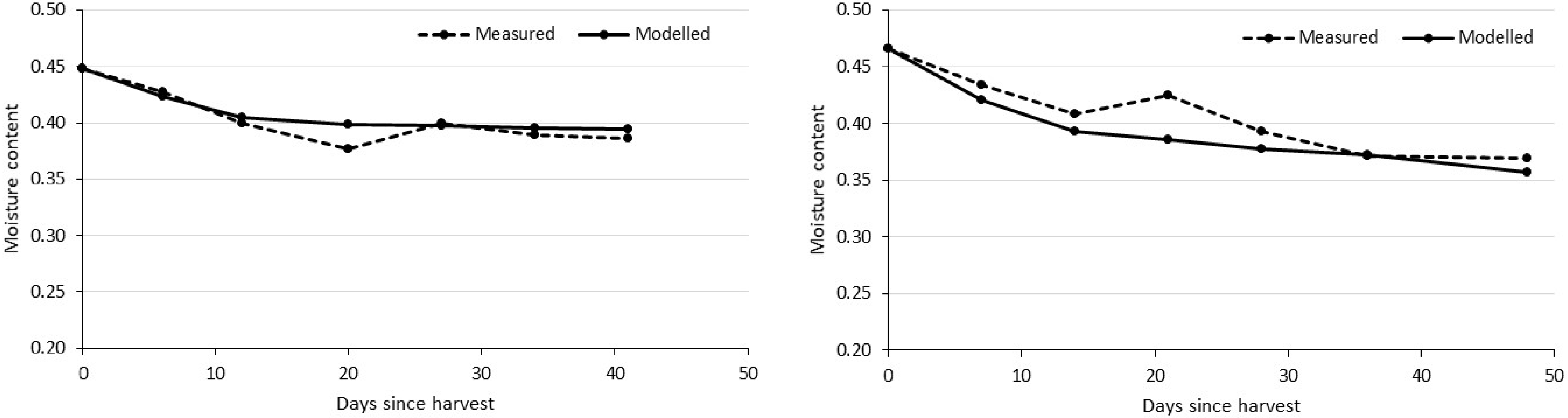
6.3.3 Eucalyptus globulus whole tree drying

Measured and modelled MC values for each season in the study are shown in Figure 6. Each value is the mean of the values for the three sites measured during that season.



(a) Summer

(b) Autumn



(c) Winter

(d) Spring

Figure 6. Measured and modelled MC values for whole *E. globulus* trees drying infield. (a) Summer; (b) Autumn; (c) Winter; (d) Spring

$$\Delta MC = 0.03 - 0.0724 \times Initial\_MC - 0.00112 \times ET$$

R^2_{adj} = 52.1%; S = 0.003; MAPE = 4.3%

Where:

ΔMC is the change in moisture content from the last measurement period

Initial_MC is the moisture content at the end of the previous measurement period

ET is the daily evapotranspiration (mm)

6.3.4 *E. nitens* LR drying model

In Figure 7, the modelled MC values for the *E. nitens* LR fitted the measured data reasonably well until approximately halfway through the drying period when the model overestimated the rate of drying of the LR.

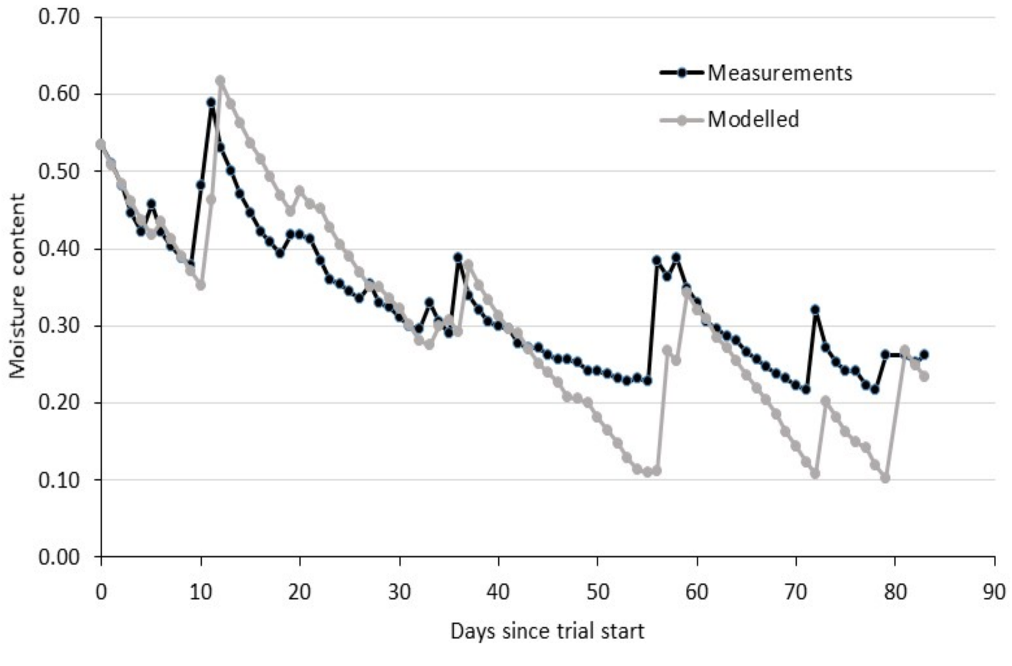


Figure 7. *E. nitens* LR measured and modelled MC values for the first of four measurement periods.

$$\Delta MC = 0.0248 - 0.0615 \times Initial\_MC - 0.00555 \times Net\_ET$$

R^2_{adj} = 54.1%; S = 0.0219; MAPE = 65.5%

Where:

ΔMC is the change in moisture content from the last measurement period

Initial_MC is the moisture content at the end of the previous measurement period

Net_ET is evapotranspiration minus rainfall

6.3.5 *E. globulus* chip log drying model

Two *E. globulus* chip log drying models were developed in the current study: one developed from the current study drying data and one developed by combining current study drying data with data from a previous FWPA drying study of similarly sized *E. globulus* chip logs (Strandgard & Mitchell, 2017). These drying models and the *E. globulus* chip log drying model developed during the previous FWPA drying study were compared for goodness of fit to the combined dataset using the lowest MAPE value as the selection criterion. The current study FWPA drying model had the lowest MAPE (4.9%), the combined data drying model MAPE was 5.3% and the previous FWPA study drying model (Strandgard & Mitchell, 2017) MAPE was 14%. Figure 8 shows the MC measurements from the current study and the results for the three models modelling the current study data.

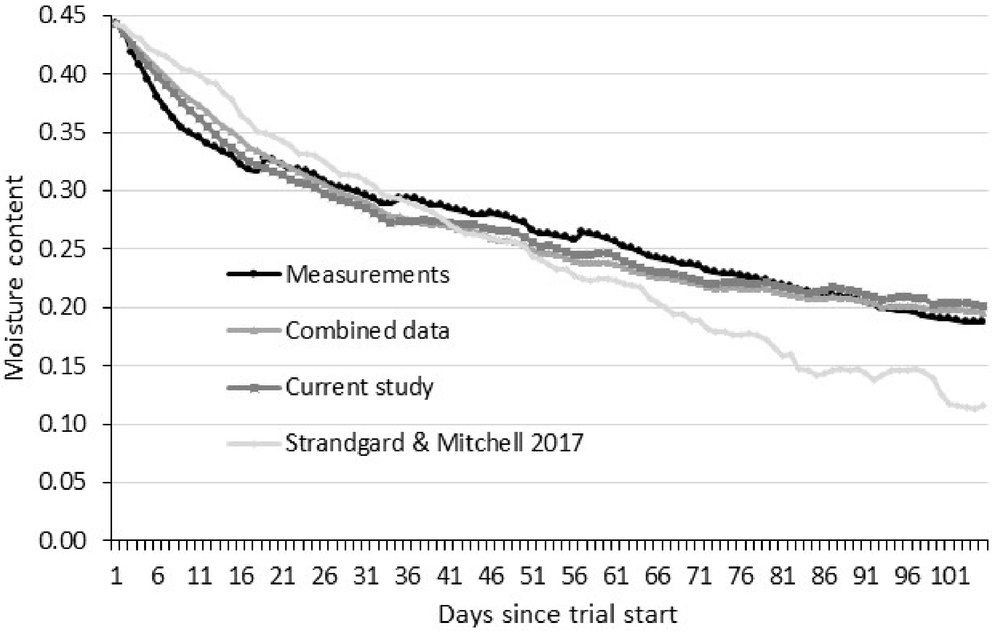


Figure 8. *E. globulus* chip log measured MC values and MC values modelled using models derived from current study data, current study data combined with the Strandgard and Mitchell (2017) drying data and the Strandgard and Mitchell (2017) drying data only.

Drying model fit statistics shown below were for the current study drying model fitted to the current study drying data.

$$\Delta MC = 0.0182 - 0.05 \times Initial\_MC - 0.00016 \times Max\_T - 0.00014 \times Solar\_Rad$$

$R^2_{adj} = 53.4\%$; S = 0.0023

Where:

ΔMC is the change in moisture content from the last measurement period

Initial_MC is the moisture content at the end of the previous measurement period

Max_T is the maximum daily temperature (°C)

Solar_Rad is the total daily solar radiation (MJ/m^2)

6.4 Discussion

In the current study, drying models were developed for five species/product type combinations: *P. radiata* chip logs and LR, *E. globulus* whole trees and chip logs and *E. nitens* LR. In two cases drying models had been developed for the same species and product type combinations (*P. radiata* and *E. globulus* chip logs) during a previous study (Strandgard & Mitchell, 2017). For these two species and product type combinations, drying models were developed using the data collected in the current study and using the combined data sets from the two studies. Models were tested for goodness of fit to the combined data sets. In the case of the *P. radiata* chip logs, the previous Strandgard and Mitchell (2017) drying model had the best fit to the combined dataset whereas for *E. globulus* chip logs the model developed in the current study had the best fit to the combined dataset.

As has been found in many previous drying model studies, meteorological variables were significant in all the drying models developed during the current study e.g. (Erber et al., 2016; Erber et al., 2014; Filbakk et al., 2011; Murphy et al., 2012; Routa et al., 2015b; Strandgard & Mitchell, 2017). However, as was observed in previous studies, there was little consistency between the meteorological variables that were significant in explaining the MC variability of the tested species and product type combinations. Erber et al. (2014) suggested differences in significant meteorological variables between drying models developed in different locations for the same species and product type combinations may result from differences in the material being tested (e.g. log size, wood density, bark coverage), in the experimental design, and in the meteorological conditions during the trial.

The log and whole tree drying models had a better fit to the measured moisture data than the LR drying models. The pattern of the drying curves for the LR was of a gradual decline in MC superimposed over strong, short-term peaks associated with rainfall events. The nature of the peaks in MC associated with rainfall events suggested that the moisture from the rainfall was at or near the surface of the LR, though this was examined in the study. Similar rapid increases in LR MC associated with rainfall events have been observed in previous overseas studies (Routa et al., 2015b). However, the responses to rainfall observed in these studies were not as large as those in the current study.

Variability of drying rates for LR piles is also likely to be affected by their high degree of heterogeneity compared with logs (Routa et al., 2015b). In the current study, there was considerable variability of the proportions of LR components between the four trial periods for the *E. nitens* LR. Eucalypt LR also contains a large proportion of bark (up to 53% in the current study) as the trees are debarked infield, whereas bark would typically be a minor component of coniferous LR. The impact of bark on eucalypt LR drying rates was not examined in the current study.

Drying models developed in this study can be used directly or in spreadsheets to estimate the MC of logs and LR drying infield or at roadside. However, the most effective use of drying models to reduce delivered costs of logs and LR is through their incorporation into supply chain planning and decision support models. However, few of these models have been developed for Australian conditions e.g. (Acuna, 2017; Acuna et al., 2012) and most current supply chain planning models developed overseas do not include drying models (Strandgard et al., 2019).

The variation between drying models developed for the same species and product type in the current study and in the Strandgard and Mitchell (2017) study suggested that additional studies would be required to develop robust drying models that can be generally applied to predict the drying of piles of key Australian species and product type combinations. This is particularly the case for the LR models. The automated weighing platforms used in the current study will allow future collection of high-resolution drying data at minimal cost.

7 Testing of moisture measurement tools

7.1 Background

MC estimation of industrial-scale drying log or forest biofuel piles by forestry staff requires the use of reliable tools that provide rapid and accurate results. Logs and forest biofuel use different tools to measure their MC, though the underlying principles are the same in some cases. Available tools to measure log MC include acoustic tools, such as the Hitman HM200 (Strandgard & Mitchell, 2017) and the IML Hammer (Becerra Ochoa, 2013) and conductance tools, such as the Humimeter BLW (Becerra Ochoa, 2013) Available tools to measure biofuel and wood chip MC include: conductance tools such as Humimeter BLL (López, 2012), capacitance tools such as the Humimeter HM1 and Wile Bio Meter (Becerra Ochoa, 2013), Near Infra-Red (NIR) tools such as the Prediktor Spektron Biomass (Fridh et al., 2017) and Magnetic Resonance tools such as the Metso MR Moisture Analyzer (Fridh et al., 2014).

In the current project, two field tools were selected for testing based on results of previous published and unpublished trials by AFORA staff e.g. (Strandgard & Mitchell, 2017) and studies found during a literature search: the Hitman HM200 and the Wiltronics ME2000 Fine Fuel Moisture Meter.

7.2 Methodology

7.2.1 Hitman HM200

The Hitman HM200 was selected for testing to estimate log MC. The Hitman HM200 tool's primary function is to use acoustic velocity to sort logs in the forest or sawmill yard on the basis of their stiffness which can be used to improve value recovery at sawmills by identifying logs that can produce a higher proportion of structural grade timber (Walsh et al., 2014) and it is already widely used for this purpose in the Australian forest industry.

The Hitman HM200 study was carried out on 19 *Pinus radiata* logs stored in a sawmill logyard (Table 2). Strandgard and Mitchell (2017) identified in a previous FWPA study that different results could potentially be obtained for logs tested with the Hitman HM200 when the logs were laid out individually or stacked. In the current trial, readings obtained using the procedure documented in the Hitman HM200 User Manual[6] were taken both with the logs stacked and laid out individually (Figure 9). Three Hitman HM200 readings (each taking several seconds) were taken from the end of each log and the mean of the three readings was used in subsequent analysis. Separate linear regression models were developed for the stacked and individual logs using Minitab v. 17 and the models were compared using an F test (Motulsky & Christopoulos, 2004). Each model was checked for compliance with the linear regression assumptions and for goodness of fit. Goodness of fit measures used were R^2_{adj}, RMSE and residual plots. Probability was $p<0.05$.

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[6] https://www.dropbox.com/sh/d5cn22vs1ure8dz/AAB8F29uAzQx0TX16WhH8eaya?dl=0&preview=HM200+User+Manual_2018.pdf

Table 2. Hitman test log characteristics. Mean and range (in brackets).

Log characteristic	Value
Length (m)	4.7 (3.0 – 5.4)
Small end diameter (mm)	285 (94 – 463)
Large end diameter (mm)	327 (162 – 493)

Figure 9. Taking a Hitman HM200 reading.

To determine the actual MC of each log, sample discs approximately 25mm thick were cut 300mm from the end of each log following the Hitman HM200 testing and oven-dried at 105°C until constant weight was achieved. MC values were expressed on a green (wet) basis.

7.2.2 Wiltronics ME2000

The Wiltronics ME2000 Fine Fuel Moisture Meter was used to estimate the MC of forest biomass. Its intended use is to estimate fine fuel MC to predict fire behaviour (Chatto & Tolhurst, 1997) and it is already widely used in Australia for this purpose. The Wiltronics ME2000 uses the electrical resistance of the sample to estimate its MC as resistance increases as the biomass dries.

The Wiltronics ME2000 study was conducted at two *Eucalyptus globulus* short-rotation plantation sites in Western Australia. Forest biofuel has a much higher potential for variability in MC than logs because of its heterogeneous composition (bark, leaves and various size branches). This increases the number and size of the samples required to achieve a reasonable estimate of the MC of a forest biofuel stack (Sjöström, 2011). Differential drying rates between forest biofuel components (finer material dries more rapidly than thicker material) can increase MC variability in a stack.

To measure a sample with the Wiltronics ME2000 it is first finely ground with a mincer (Figure 10) and then placed into a small chamber in the Wiltronics ME2000 (Figure 11) and compressed. This process takes several minutes plus the time required to collect the sample material from the stack. Additional samples were collected and oven-dried at 105°C until they had achieved a constant weight to determine the actual MC of each biofuel stack. Samples were taken on four occasions on one site and three at the other site over a period of three months as the stacks were drying to check the Wiltronics ME2000 performance over a range of MC values. At each site and time of measurement the MC of 16 to 20 forest biofuel samples were measured using the Wiltronics ME2000.

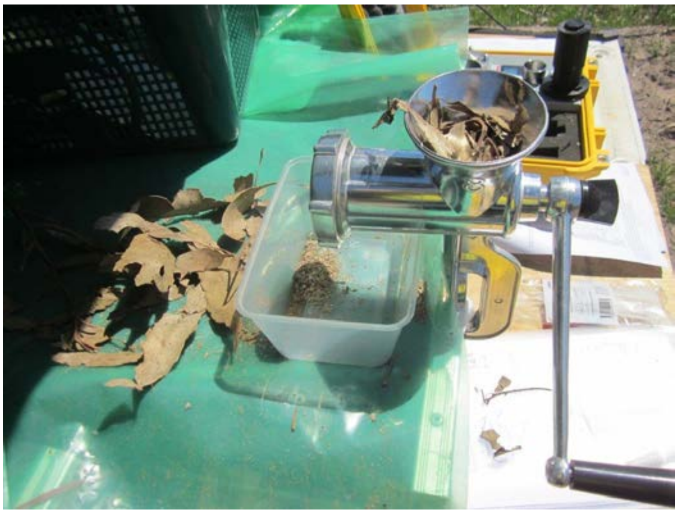


Figure 10. Mincing sample prior to testing in the Wiltronics ME2000.

Figure 11. Biofuel sample being tested using the Wiltronics ME2000.

7.3 Results

7.3.1 Hitman HM200

One outlier was removed from the stacked log dataset and two from the individual log dataset. The linear regression models and goodness of fit measures are shown in Table 3. All variables were significant. Plots of MC against acoustic velocity for stacked and individual logs are shown in Figure 12.

Table 3. Log MC linear regressions for stacked and individual logs and goodness of fit measures. (MC = moisture content expressed as a proportion; AV = acoustic velocity (m/s)).

Log arrangement	Regression	R^2_{adj}	RMSE
Stacked	$MC = 1.005 - 0.1692 \, x \, AV$	0.624	0.01
Individual	$MC = 0.991 - 0.1676 \, x \, AV$	0.648	0.01

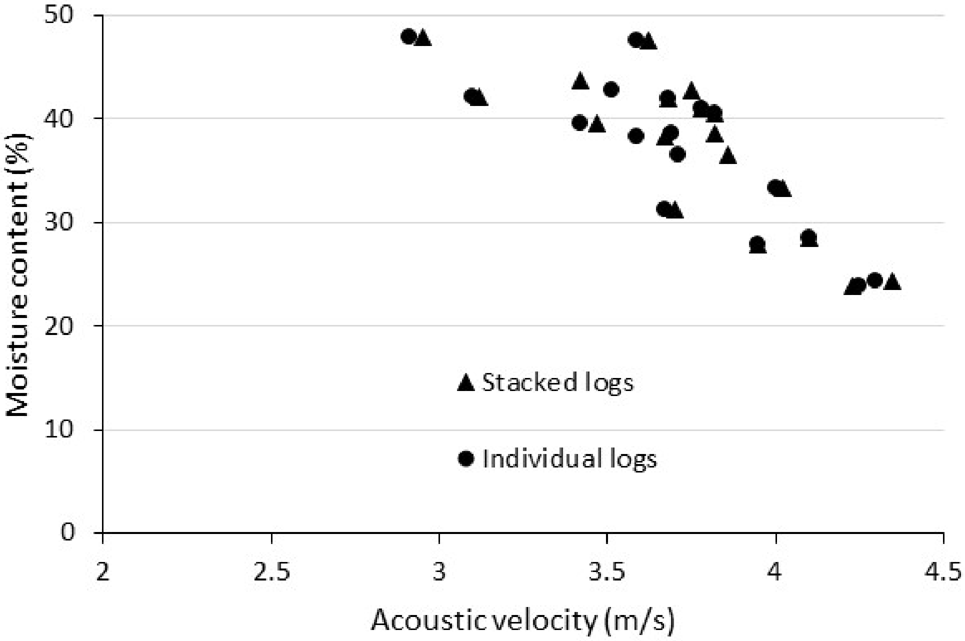


Figure 12. Plots of MC (%) against Acoustic velocity (m/s) for stacked and individual logs

The models were found to not be significantly different using an F test (Motulsky & Christopoulos, 2004) allowing either model to be used to estimate the MC of a *P. radiata* log from Hitman HM200 acoustic velocity readings.

7.3.2 Wiltronics ME2000

The comparative MC values for the Wiltronics ME2000 and for the oven-dried method are shown in Table 4. The Wiltronics ME200 MC values are the mean of the 16-20 samples measured at each location and time of measurement.

Table 4. Mean MC values (%) for the Wiltronics ME2000 and oven-drying at two *E. globulus* sites and four times of measurement

Measurement time	Location 1		Location 2	
	Wiltronics	Oven-dried	Wiltronics	Oven-dried
1	68.6%	42.5%	71.3%	43.4%
2	-	-	23.9%	20.5%
3	14.9%	23.6%	11.2%	22.8%
4	9.2%	14.6%	8.8%	8.8%

7.4 Discussion

Acoustic velocity readings from the Hitman HM200 were well-correlated with the MC values of the tested logs. This suggested that the models developed in the study could be used to estimate the MC of a stack of radiata pine logs drying infield by calculating the mean of MC values calculated from acoustic velocity readings taken from a sample of logs in the stack. The appropriate sample size would depend on the required level of precision and the degree of variability in MC values between the logs. Potential sources of variability in MC identified in previous trials include the size of the logs as larger logs dry more slowly than smaller logs because smaller logs have a higher surface area to volume ratio and a shorter distance from the log centre to its surface (Visser et al., 2014) and the position of logs in the stack as logs nearer the surface of the stack can have a higher MC than those further into the stack (Kofman & Kent, 2009).

The increased spread in acoustic velocity values for logs with MC values above approximately 40% suggested that for these logs, other wood properties, such as wood stiffness, were having a greater influence on acoustic velocity values than was MC resulting in reduced accuracy predicting MC of *P. radiata* logs with the Hitman HM200 above ~40%.

Advantages of the Hitman HM200 as a tool for log MC measurement include that it is non-destructive, easy to use, and can rapidly collect the required sample of MC values.

The Wiltronics ME2000 readings were less accurate for higher MC values than for lower MC values. Similar findings were reported by Massaiu (1998). The higher MC values for the 3rd and 4th measurement times for the oven-dried method compared with the Wiltronics method (Table 4) were the result of a small number of higher MC oven-dried readings in each case. These higher values were for samples that contained a high proportion of bark and woody material. This material cannot be ground with the manual grinders supplied with the Wiltronics ME2000. Removal of these higher values resulted in mean oven-dried MC values that were closer to those for the Wiltronics ME2000. This heavier material is not sampled in a fine-fuel MC study to predict fire behaviour but would be sampled as part of the estimation of the MC of a forest biofuel stack, which suggests that the Wiltronics ME2000 method is unsuitable for forest biofuel MC prediction unless a method can be developed to grind heavier material without affecting its MC.

The test chamber of the Wiltronics ME2000 limited the sample size that could be tested, increasing the number of samples required for a reliable MC reading.

The Wiltronics ME2000 is one example of a class of moisture meters that use the resistance or capacitance of logs, biofuel or wood pellets to determine their MC. Some of these devices may overcome the limitation of the Wiltronics ME2000’s small sample size. However, this may increase sampling times if comminution of larger samples is required. Indicative pricing for these meters is US$1200 - $2200.

Although the current study was not conducted for sufficient time to accurately judge the mechanical reliability of each tested tool, anecdotal evidence suggests that both tested tools have a high degree of mechanical reliability.

7.5 Conclusion

The Hitman HM200 was found to be a suitable tool to estimate the MC of *P. radiata* sawlogs stored in piles infield, particularly for MC values less than 40%. Given that the acoustic velocity within a log is dependent on the wood stiffness as well as the MC, further research is required to determine whether a single model relating MC and acoustic velocity can be developed or whether additional parameters need to be added to the model to accommodate variations in wood stiffness associated with age, site or genotype. Research could also be conducted to examine the suitability of the Hitman HM200 to estimate the MC of larger eucalypt logs. Other moisture content sampling techniques for logs could be examined, such as analysis of sawdust collected using a chainsaw.

The Wiltronics ME2000 was found to be unsuitable to estimate the MC of *E. globulus* forest biofuel. This was related to the inability of the accompanying grinder to grind thicker material, which may be addressed by using a different grinder, and the small size of each test sample. Other moisture meters could be tested in future research to examine their suitability to determine the MC of forest biofuel. Future studies should test forest biomass meters that use different measurement principles (e.g. capacitance) and with larger sample capacities. However, these MC meters are designed to test comminuted biomass so a small chipper would also be required to prepare samples of uncomminuted forest biomass.

8 Assessment and modelling of moisture changes during roadside storage on log and LR chip delivered costs

This is a summary of a paper submitted to the *Forests* journal “Use of modelling to compare the impact of roadside drying of *Pinus radiata* logs and LR on delivered costs using high capacity trucks in Australia”.

8.1 Background

- Interest has increased worldwide in use of forest residues as biofuels to reduce greenhouse gas emissions (International Energy Agency, 2017). Unmerchantable logs and post-harvest LR represent two potentially important forest biofuel sources (Hakkila, 1989)

- Drying logs and LR reduces their weight with little change in volume hence reducing their bulk density which can substantially reduce transport costs (Talbot & Suadicani, 2006). Australian forest growing areas have the potential for rapid MC reductions through roadside drying (Strandgard & Mitchell, 2017)

- The Australian National Transport Commission (NTC) recently proposed increasing the volumetric capacity of commonly used truck configurations in Australia without change to their gross vehicle mass in response to reports that many Australian trucks operate below their mass limits due to volume constraints (National Transport Commission, 2016). This approach would allow trucks to comply with existing mass limits on roads and bridges while being able to transport larger quantities of low-density materials.

- The study compared delivered costs of *P. radiata* residue logs (logs not suitable for a merchantable product) and LR chips for five existing and proposed Australian truck configurations under two scenarios: with and without roadside storage.

8.2 Methodology

8.2.1 Study description

- The study was based on supplying chipped *P. radiata* logs or LR to a hypothetical 10 MW_e gasification plant located in south-west Western Australia to produce electricity.

- The gasification plant required 25,000MWh of energy input per month supplied using up to 100,000m^3 of *P. radiata* pulplogs currently exported and up to 150,000m^3 of *P. radiata* LR from cut-to-length at the stump harvesting operations.

- Five truck configurations were studied: 6 axle semi-trailers, 9 axle B-doubles, the proposed higher volumetric capacity versions of these trucks (semi HV and B-double HV) (National Transport Commission, 2016) and 11-axle pocket road trains (PRT) (commonly used in Western Australia) (Table 5). Volumetric capacity for logs was estimated to be 80% of the chip volumetric capacity.

Table 5. Truck length, weight (gross, tare and load), volumetric capacity and transport rate.

Truck type	Semi-trailer	Semi-trailer HV*	B-double	B-double HV*	PRT
Overall length (m)	19	20	26	30	27.5
Gross vehicle mass (tonnes)	42.5	42.5	62.5	62.5	79
Tare weight (tonnes)	16	16.5	21	22	26
Load weight (tonnes)	26.5	26	41.5	40.5	53
Volumetric capacity (chips) (m^3)	75	82	120	160	140
Volumetric capacity (logs) (m^3)	60	66	96	128	112
Transport rate ($/t-km)	0.15	0.15	0.13	0.13	0.10

* National Transport Commission (2016).

- The supply chain was modelled from the tree at harvest to delivery at the gasification plant for LR chips and delivery and chipping for logs. The study assumed there were no limitations for truck numbers and chipping and unloading capacities and no delays along the supply chain. MC was expressed on a green (wet) weight basis.

- Two scenarios were modelled in the study: Scenario 1 – a “hot-deck” system with no infield storage or drying; Scenario 2 – a “cold deck” system where logs and LR were stored to dry at roadside for a period determined by the optimal solution of the linear programming model.

- For each scenario, five truck configurations (Table 1), two products (*Pinus radiata* logs and LR) and a single supply point and demand destination were modelled. Logs were chipped upon delivery while LR was chipped directly into trucks infield. LR chipping cost was higher than that for logs because LR was chipped infield whereas logs were chipped at a static chipmill, which have lower costs per tonne chipped and because chipping cost was expressed in dollars per tonne requiring a greater volume of lower density LR to be chipped than of logs to produce the same weight of chips. Chipping costs for both products were also higher for lower MC to reflect the reduced chipper productivity and greater wear and tear when chipping forest biofuel with a lower MC.

- In Scenario 2, costs were applied to reflect delays in receiving income from selling the logs and LR and physical and biological losses. It was assumed that no losses or drying occurred during transport of logs and LR to the gasification plant. Storage times for logs and LR in Scenario 2 were determined separately.

- LR chip density in a truck load was calculated from chip bone-dry bulk density adjusted by MC and for logs from their basic density multiplied by their solid content adjusted by MC. Log and LR chip volumes were assumed to remain constant with changes in MC.

- Storage costs were calculated as a percentage (0.5%/mth) of the harvest and extraction costs to reflect the costs borne by the harvest contractor while the material was stored.

8.2.2 Optimisation tool

- MCPlan (Acuna, 2017) is a software tool developed to optimize timber and biofuel supply chains. The mathematical model implemented in MCPlan is detailed in Acuna (2017).

- For the study, MCPlan was used to determine the optimal least-cost solution to deliver the quantities of logs and/or LR required to meet the monthly energy requirements for each Scenario/truck configuration combination. MCPlan decisions on the volume of logs and LR to be harvested (years 1 and 2) and transported (year 2) were made monthly. Model parameter values for each scenario are shown in Table 6.

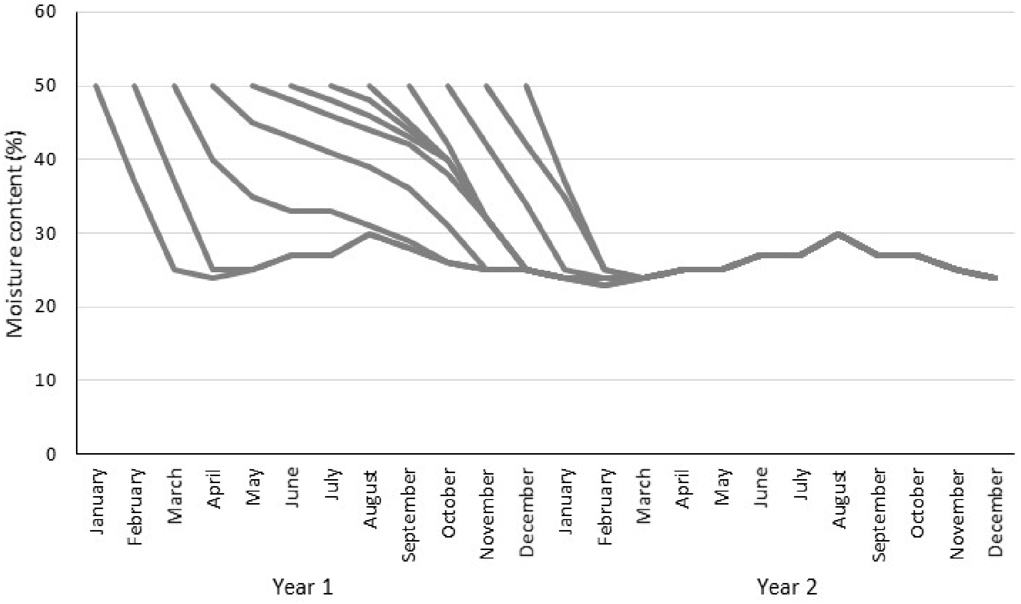
Table 6. Model parameters for Scenarios 1 and 2

Parameter		Logs	LR
Basic density (bone dry kg/solid volume m^3)		430	360
Bulk density (chips)(bone dry kg/bulk volume (m^3)		181	151
Bulk volume (m^3) to solid volume (m^3) ratio		1.59	2.38
Solid content		0.63	0.42
Delivered MC range (%) Scenario 1		MC at harvest	MC at harvest
Delivered MC range (%) Scenario 2		≤35	≤35
Material loss rate (%/month)		0.1	1.0
Harvest age (years)		30	-
Biomass expansion factor		-	0.19
Energy content @ 0% MC (GJ/t)		19.0	19.9
One-way distance (km)		50	50
Interest rate (%/month)		0.5	0.5
Harvest and extraction to roadside ($/t)		14.4	-
Extraction to roadside ($/t)		-	17.3
Transport rate ($/t-km)	Semi-trailer	0.15	0.15
	B-double	0.13	0.13
	PRT	0.10	0.10
Chipping cost ($/t)	MC >50%	4.7	9.5
	MC 36-50%	4.9	9.7
	MC ≤35%	5.0	10.0

8.2.3 Drying curves

- Generalised natural drying curves used in the study were based on recent infield *P. radiata* drying studies (Strandgard and Mitchell (2017) and the current study) (Figure 13). Drying can commence in any month across the two years modelled in MCPlan. For clarity, only drying curves for drying commencing in the 1st year are shown.

(a). *P. radiata* logs



(b). *P. radiata* LR

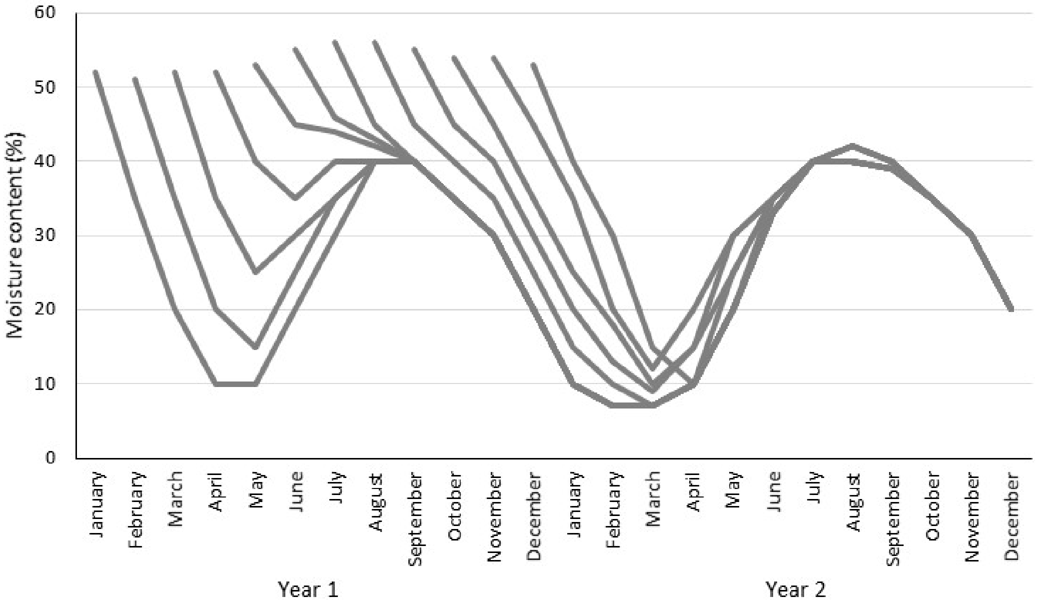


Figure 13. Natural drying curves for *P. radiata* (a). logs and (b). LR harvested at different months of the year

8.3 Key findings

- High volume semi-trailer and B-double truck configurations were of little or no benefit compared with the standard capacity trucks when transporting undried logs and LR (Scenario 1). In comparison, in Scenario 2 the B-double HV was able to transport 27% more oven-dry tonnes of logs and 34% more oven-dry tonnes of LR than the standard B-double while the semi-trailer HV transported 11% and 10% greater quantities of logs and LR in oven-dry tonnes, respectively, than the standard semi-trailer.

- Roadside drying reduced transport and chipping costs through log and LR weight reductions and increased log and LR net calorific values which reduced the quantity of logs and LR required to meet the gasification plant’s requirements. Delivered cost savings resulting from roadside drying were up to 16% for logs and up to 27% for LR for mean MC reductions of approximately 23% for logs and 42% for LR.

- Logs in the study had a lower delivered cost ($/MWh) than LR. This reflected lower log harvest, extraction and chipping costs relative to those for LR due to the lower basic density of uncomminuted LR. The optimum solution used the maximum available quantity of logs due to their lower delivered cost.

- Storage costs were 4-6% of delivered costs.

- The PRT truck configuration had the lowest delivered costs for logs and LR in both Scenarios due to it having the lowest transport rate ($/tonne-km). The PRT truck configuration also required the fewest truck trips to transport logs and LR without drying (Scenario 1) and second fewest with drying (Scenario 2) due to its combination of high load weight and volumetric capacities. This suggested that wider use of PRTs should be considered within Australia.

9 Modelling of supply chain cost/benefit ratios based on operational impacts and observed degrade in drying trials

9.1 Background

Benefits from infield drying of logs and forest biofuel in terms of reduced transport costs from weight reduction (Erber et al., 2016) and increased quality from increased net calorific value (Pettersson & Nordfjell, 2007) need to be balanced against increased costs from a number of sources including payment delays (Acuna et al., 2012) and site re-establishment (Richardson et al., 2002) and losses from biological degradation and physical losses of stored logs and forest biofuel (Thörnqvist, 1985).

The harvest system used can influence the primary transport cost of LR (extraction cost) and consequently the impact of storage on costs associated with payment delays. Cut-to-length at the stump harvest systems are the predominant harvest system used in Australian *P. radiata* plantations. However, limited trials have shown that LR extraction costs when processing whole trees at roadside can be substantially lower than those for cut-to-length at the stump harvest systems (Hall et al., 2001).

Physical losses of forest biofuel are largely the result of foliage and small branches falling onto the ground as the biofuel dries (Jirjis, 1995; Thörnqvist, 1985) or during handling (Pettersson & Nordfjell, 2007) and hence are typically greater for stored LR or whole trees. Thörnqvist (1985) reported stored LR losses ranging between 0.1% to 5.5% per month with higher losses occurring for small piles in warmer weather. Although these losses represent a reduction in the total forest biofuel removed from a site, the lost material typically has a higher ash (Thörnqvist, 1985) and nutrient content (Nurmi & Hillebrand, 2001) than the material removed from the site resulting in retention of a greater proportion of site nutrients and a reduction in ash requiring disposal following combustion of the biofuel. Reported physical losses for logs are lower than those for LR and whole trees. Golser, Pichler, and Hader (2005) reported dry matter losses for stored logs in Austria of <2% per year for *Picea abies* and *Pinus sylvestris* while Erber et al. (2012) reported a 5% loss over 14 months for stored *Pinus sylvestris* logs.

Biological degradation of logs and forest biofuel is mainly the result of attack and infestation by microorganisms or insect larvae. For softwoods a major concern is colonisation of wood by sapstaining fungi, which can occur rapidly under the right conditions (Keirle, 1978). Sapstain fungal spores are found widely in forested areas and can also be spread by harvesting equipment (Uzunovic et al., 2004) or by certain beetle species. The bark beetle *Ips grandicollis*, which carries a sapstain fungus (*Ophiostoma ips*) has been recorded in Queensland attacking logs within days of felling (Wylie et al, 1999). Sapstaining fungi cause minimal reduction in wood strength but can reduce wood value due to the change in its appearance (Schirp et al., 2003). Decay organisms can cause losses of dry matter as they break down forest biofuel. Rates of biological degradation can vary greatly, with a major factor determining loss rates being the temperature and biofuel MC during storage (Krigstin & Wetzel, 2016). Value losses can be considerably higher than dry matter losses for logs.

McLean (1985) estimated losses resulting from Ambrosia beetle damage to outer clearwood on stored logs in British Columbia, Canada were tens of millions of dollars per year due to downgrade of potential veneer and appearance grade logs.

End-splitting of logs can occur rapidly after felling and during subsequent storage and handling, particularly for some eucalypt species (Malan, 1979). End-splitting can reduce the value of logs if the intended product is sawn timber or poles as the split end must be docked (Malan, 1979).

9.2 Methodology

The forest biofuel supply chain optimisation tool, MCPlan (Acuna, 2017) was used to model the impact on delivered costs of *P. radiata* logs and LR (branches, needles and unmerchantable stems and stem section remaining post-harvest) for a range of loss rates and storage periods. In all scenarios, the objective was to minimise the combined delivered costs for logs and LR while meeting a requirement to deliver exactly 25,000m^3 of logs per month. No limits were placed on the quantity and timing of LR produced. The base case was a "hot" system with no infield storage and no losses. Loss rates and storage periods tested were based on observations of forest biofuel and log degradation in the current trial and in previous (unpublished) trials. Standard industry practice is to leave logs infield for no more than one to two months as a 'rule of thumb' approach to minimising physical losses and degradation. To test the impact of restricting the storage time of logs infield on delivered costs, each combination of log and LR loss rates was tested when the maximum storage time infield was one, two or six months and also with no restriction on the length of infield storage time. Tested log loss rates were 0.1%, 0.5% and 1% per month and tested LR loss rates were 0.5%, 1% and 2% per month.

P. radiata log and LR drying models used in MCPlan were derived from drying models developed in the current study. The drying models used in MCPlan for this study are shown in the previous chapter.

In MCPlan, logs are transported from the field and chipped using a static chip mill at the end-use facility whereas LR is chipped with a mobile chipper directly into trucks at roadside. Logs and chips are transported to the same facility. Transport of both logs and LR was modelled based on a 6 axle semi-trailer with a 27.5t load capacity and a 75m^3 volumetric capacity transporting chips and 56 m^3 volumetric capacity transporting logs.

MCPlan parameters used in the study are shown in Table 7.

Table 7. Parameters used to model supply chain costs/benefits of infield storage of P. radiata logs and LR using MCPlan

Parameter		Logs	LR
Basic density (bone dry kg/solid volume m^3)		430	360
Bulk density (chips)(bone dry kg/bulk volume (m^3)		181	151
Bulk volume (m^3) to solid volume (m^3) ratio		1.59	2.38
Solid content		0.63	0.42
MAI (m^3/ha/year)		20	-
Harvest age (years)		30	-
Energy content @ 0% MC (GJ/t)		19.0	19.9
One-way distance (km)		50	50
Interest rate (%/month)		0.5	0.5
Harvest and extraction to roadside ($/t)		14.4	-
Extraction to roadside ($/t)		-	17.3
Transport rate ($/t-km)		0.15	0.15
Chipping cost ($/t)	MC >50%	4.7	9.5
	MC 36-50%	4.9	9.7
	MC ≤35%	5.0	10.0

The study assumed there were no limitations for truck numbers and chipping and unloading capacities, no delays along the supply chain. Loss rates were assumed to be constant across the modelling period.

9.2.1 Sensitivity analysis

Sensitivity analyses were conducted on the impact of varying MC and LR extraction costs on log and LR delivered costs.

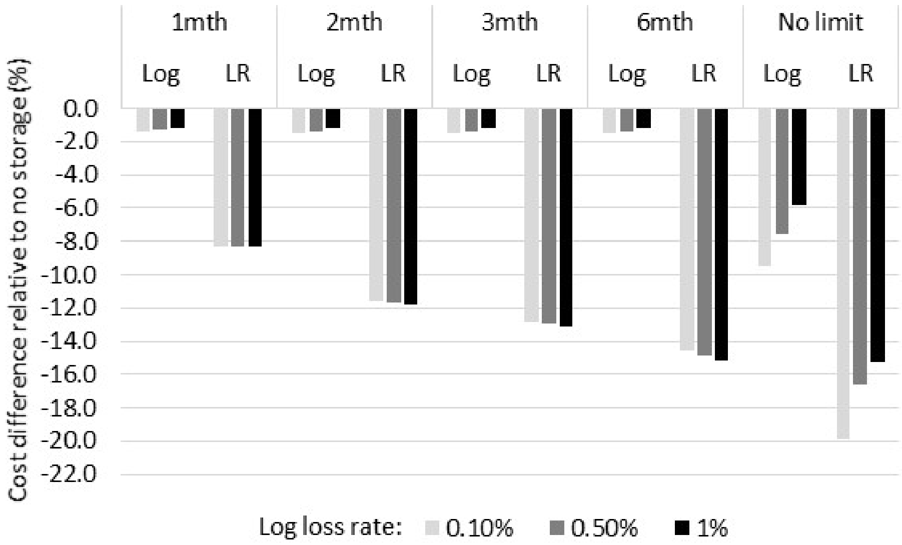
Log and LR MCs and drying rates are key variables in determining the trade-off between storage gains and losses. The drying curves used by MCPlan were altered by ±5% to analyse the impact on the delivered costs of logs and LR.

Changes in LR extraction costs can affect storage costs as MCPlan calculates interest costs on total costs prior to storage. LR extraction cost in the study was based on a cut-to-length at the stump harvest system. To examine the potential impact on delivered LR costs of using a whole tree to roadside harvest system it was assumed that LR was moved from close to roadside to the infield chipper with an excavator for $8/tonne. Log harvest costs were assumed to be the same for both harvest systems.

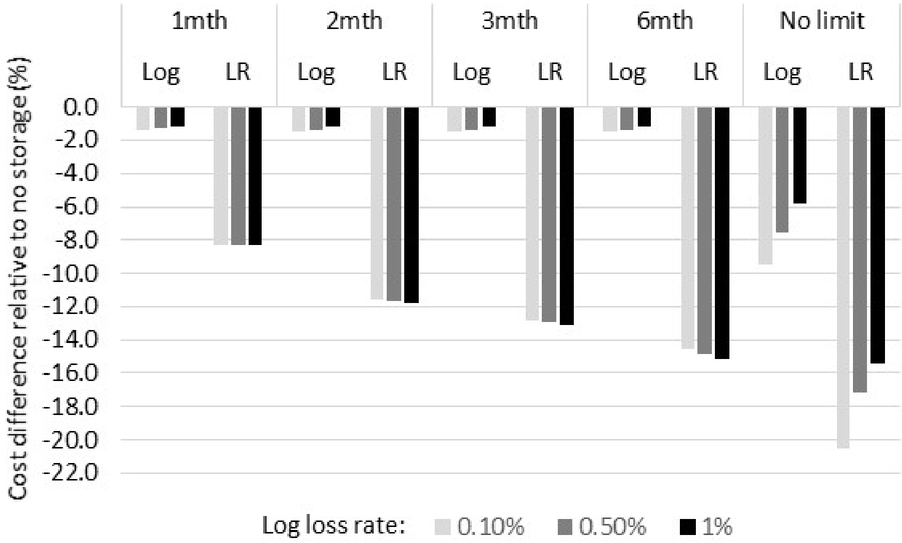
9.3 Results

Results are shown as the percentage difference between the delivered log and LR costs for each combination of storage time and loss rate and the base case (no storage) delivered log and LR costs, respectively (Figure 14).

(a). LR 0.5% loss rate



(b). LR 1.0% loss rate



(c). LR 2.0% loss rate

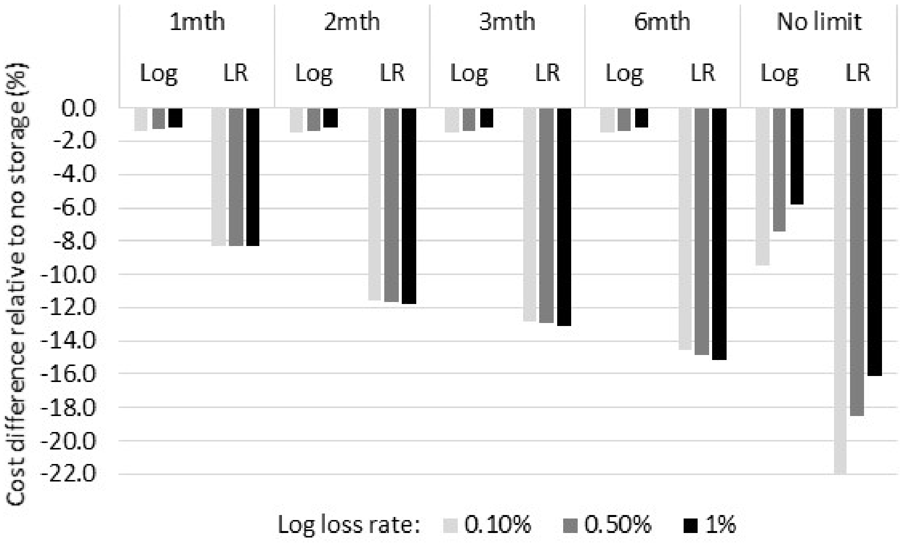


Figure 14. Percentage difference between the delivered log and LR costs for log loss rates of 0.1%, 0.5% and 1% and LR loss rates of 0.5%, 1% and 2% and the base case delivered log and LR costs for a range of storage periods.

For maximum storage periods of one to six months the delivered cost savings from storing logs infield were small (≤1.5%) and decreased slightly as the log loss rate increased. For the same storage period range, LR delivered cost savings were considerably greater than those for logs and increased with length of storage. For maximum storage periods of two to six months there was a slight decrease in delivered costs for LR for increasing log loss rates but no change in delivered costs for LR when LR loss rates changed for a given log loss rate.

Under the no storage time restriction scenario, delivered costs of both LR and logs were lower than for all scenarios with storage time restrictions. With no storage time restrictions, logs were predominantly stored for periods of zero to four months while 30% of the logs were stored for periods of five to thirteen months. Delivered costs for both logs and LR increased as the log loss rate increased. The LR delivered cost also decreased as the LR loss rate increased.

9.3.1 Sensitivity analysis

Increasing log and LR MC by 5% increased delivered costs of both products and decreasing the MC by 5% decreased delivered costs of both products. Proportionally the largest changes in delivered costs were for logs, though these were mostly from low initial delivered cost values (Figure 14).

Reducing LR extraction costs reduced its delivered costs by 40-60%. The largest delivered cost reductions were for scenarios with no storage time limits. In these scenarios, MCPlan harvested a greater proportion of the logs (and hence also LR) earlier which reduced LR transport and chipping costs due to their lower weight from greater drying. LR storage costs were also lower because they are based on harvesting and extraction costs.

9.4 Discussion

For all scenarios tested in the study, infield storage resulted in a saving in delivered costs compared with the base case. This resulted from reduced transport and chipping costs of logs and LR from infield drying-related weight reduction exceeding storage costs. In contrast, Hall et al. (2001) found increasing LR loss rates from 1.5% to 2% increased its delivered costs by 2%. This reflected the very low drying rate (3%/mth) used in their study which resulted in storage costs and losses outweighing drying gains. Increasing drying rates to 5%/mth reduced delivered costs by 4%. Similarly, Sosa et al. (2015) reported supply chain costs were reduced through reducing length of infield storage with consequent reductions in storage costs and losses. In the current study, delivered cost savings increased with increased drying rates and decreased with decreasing drying rates. The effect was proportionally greater for logs than LR.

In the study, for short-term storage periods (one to six months), delivered cost reductions for logs were minimal (1.2-1.5%). The impact of fixed storage periods on delivered costs was compounded by the lack of flexibility in log drying times associated with the fixed monthly log supply requirement. In contrast, the lack of a supply requirement for LR allowed MCPlan increased flexibility in the length of LR drying times to reduce its weight and hence its delivered cost. The faster drying rates for LR compared with that for logs increased this effect. Acuna et al. (2012) found that constraints on storage period length had no overall effect on supply chain costs, however in that study the biofuel supplied to a power plant was a mix of stemwood, whole trees and LR with the mix changing with changes in length of storage period.

As would be expected, increasing log loss rates reduced delivered cost savings for all tested scenarios compared with the base case because a greater quantity of logs needed to be harvested to meet the monthly supply requirement increasing harvest and storage costs. Asikainen et al. (2001) also noted increased log demand due to storage losses could increase transport costs as logs may need to be harvested from a broader area. This effect was not modelled in the current study. For the scenarios with a maximum one to six-month storage time, LR delivered cost savings increased as log loss rates increased. This resulted from the increased log loss rates resulting in a greater proportion of logs, and hence LR, being harvested earlier allowing increased LR drying time.

Removing storage restrictions considerably increased delivered cost savings for both logs and LR compared with those from scenarios with storage time limits due to greater drying weight losses and hence larger reductions in chipping and transport costs. LR delivered cost savings decreased as log loss rates increased and increased as LR loss rates increased. The decreased LR delivered cost savings as log loss rates increased were caused by MCPlan harvesting a greater proportion of the logs in the second year to reduce log losses, which reduced the time available for the LR to dry in storage and hence reduced its weight losses and transport and chipping savings. The increased savings as the LR loss rate increased resulted from a reduction in the delivered quantity of LR which reduced chipping and transport costs.

A limitation of the study was the assumption that loss rates were constant across the modelled period. In practice this is likely to only be accurate for storage periods of several months. Over longer storage periods, losses can vary considerably due to seasonal changes in insect and microorganism activity (Keirle, 1978) and initial physical losses of more readily detached material such as leaves/needles, fine branches and bark (Nilsson et al., 2015).

Operational management of log and LR piles stored at roadside to minimise delivered costs while meeting supply commitments is considerably more complex than the traditional ‘hot deck’ harvest system used in Australia whereby most harvested material is removed during harvesting. However, there is currently a paucity of systems available to assist with this task suggesting further research is required in this area.

The sensitivity analysis suggested that roadside processing could substantially reduce delivered costs of LR due to the considerably lower extraction costs. Further research is required in this area in Australia to investigate the impact of roadside processing on harvesting costs, log volume and value and potential contamination of LR by dirt and stones during tree extraction to roadside.

9.5 Conclusion

In the study, costs related to log and LR losses were less than the gains from reduced transport and chipping costs resulting from drying weight reductions for all combinations of loss rates and storage periods. However, the lack of flexibility in drying times associated with maximum storage time periods of 1 to 6 months resulted in minimal gains for logs, particularly when the drying curve MC values were increased by 5%.

The considerably greater savings from flexible storage periods for both logs and LR compared with savings from fixed storage periods suggested that companies should move away from current arrangements that set a maximum infield storage period. However, the complexities associated with determining the optimum balance between gains and losses associated with infield storage require investment in the development and use of supply chain planning tools such as MCPlan and operational decision support tools or at a minimum information storage and retrieval systems to manage the operational aspects of chipping and transporting logs and LR stored infield.

10 Mobile app to allow industry to interact with drying models

10.1 Background

To facilitate the use of the drying models developed in this study a proof of concept forest biofuel infield drying app (MC Calculator) was developed for mobile devices (phones or tablets) with Android version 6.0 or later. The app uses the drying model for small diameter radiata pine residue logs stored in a pile infield, which was detailed earlier in this document. It predicts the number of days of infield storage commencing from the user-selected date required to achieve the user-selected final MC. The user can select either 35%, 40% or 45% as the target final MC value.

10.2 Installation of MC Calculator

To install the MC Calculator proof of concept app copy the installation file (McCalculator.apk) to the Downloads directory on the mobile device (Android 6.0+). As the app is not installed from the Google Play Store, the device Settings will need to be changed to allow installation of apps from ‘unknown sources’. The procedure required to make this change will depend on the version of Android on the device. Instructions to make the required change can be found on the device manufacturer’s website.

After the device settings have been changed to allowed installation of apps from unknown sources, open the Downloads directory using the device’s file manager and click on the McCalculator.apk file to install the app. Answer ‘Yes’ or ‘Ok’ if you are asked to confirm the installation of the app.

10.3 Using MC Calculator

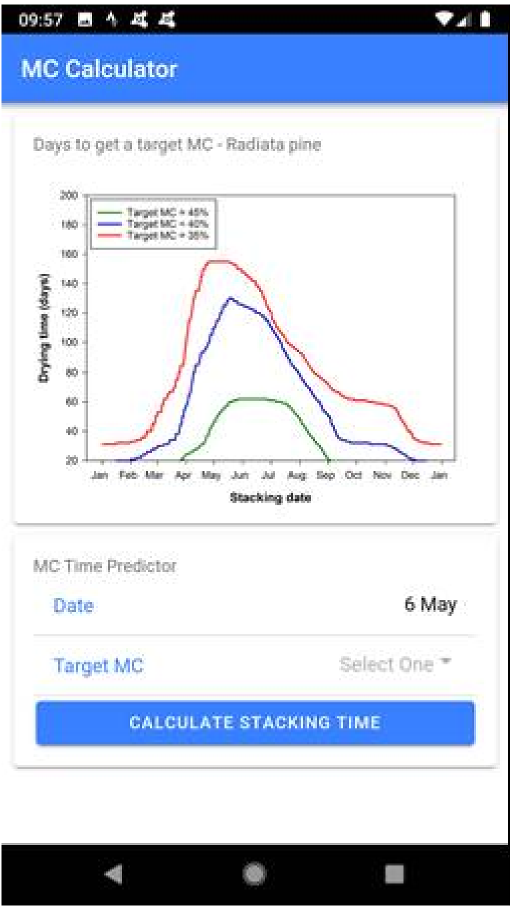
1. **Start MC Calculator.** Tap on the MC Calculator icon to start the app. This will display the app splash screen and then the app main screen (Figure 15(a) & (b)).

2. **Change date.** The default date is the current day. To change the date, tap on the displayed date and select the desired day and month (Figure 15(c)). When finished tap ‘Done’. To abort the changes, tap ‘Cancel’.

3. **Change target MC.** To change the Target MC, tap the ‘Target MC’. This will bring up the 3 available options (45%, 40%, and 35%) (Figure 15(d)). Tap the circle to the left of the desired target MC value to select it. Then tap ‘Ok’. To abort the changes, tap ‘Cancel’.

4. **Display stacking time.** To display the stacking time required to achieve the target MC value, tap the ‘Calculate Stacking Time’ button. This will bring up a window displaying the stacking time required to achieve the desired target MC in days from the selected day (Figure 15(e)).

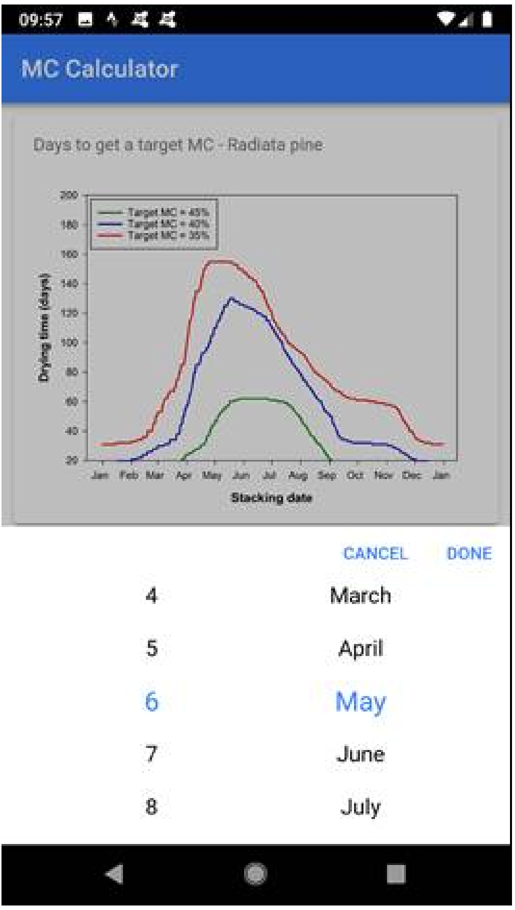
(a)



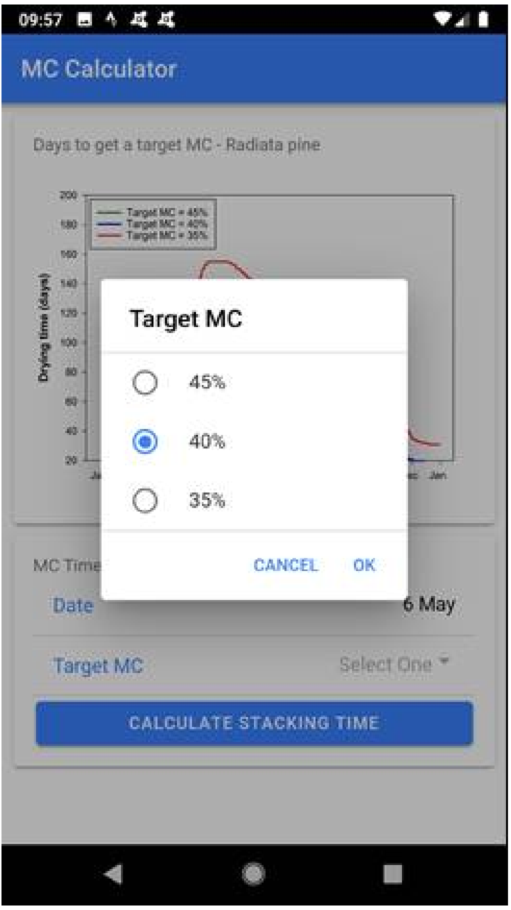
Date 6 May

Target MC Select One

(b)



(c)



Target MC

○ 45%

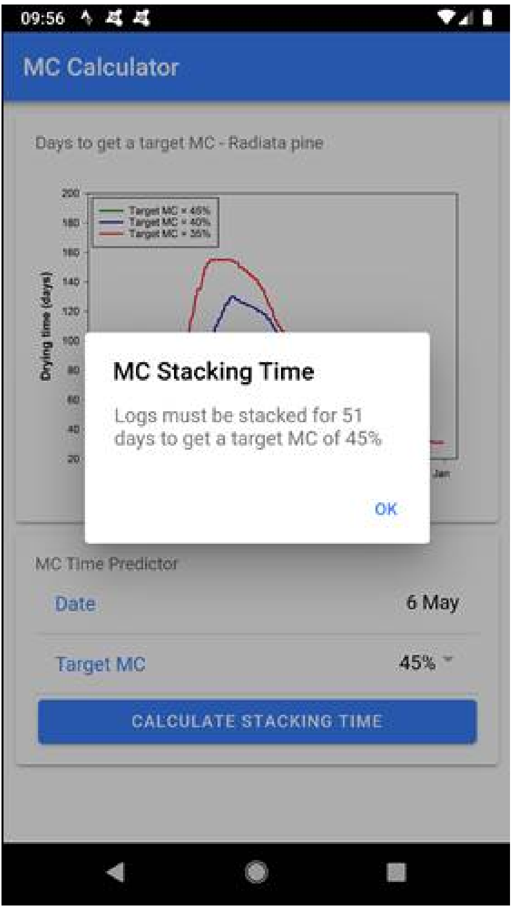
● 40%

○ 35%

Date 6 May

Target MC Select One

(d)



MC Stacking Time

Logs must be stacked for 51 days to get a target MC of 45%

Date: 6 May

Target MC: 45%

(e)

Figure 15. MC Calculator screen shots. (a). Splash screen; (b). Main screen; (c). Change date screen; (d). Change Target MC screen; (e). Display MC Stacking time screen.

11 Infield chipping trials

11.1 Background

Drying logs and biofuel infield can reduce supply chain costs by increasing the log and biofuel net calorific values and reducing their transport costs (Strandgard et al., 2019). However, the performance of mobile chippers can be significantly impacted when chipping dry logs or forest biofuel compared with chipping green material. Pochi et al. (2015) reported that chipper productivity dropped by over 20% when chipping dried poplar material compared with chipping fresh material while Asikainen and Kuitto (2000) found that chipping dried LR can increase chipper knife costs by 10-20%. However, there have been no published studies comparing the performance of a mobile chipper chipping green and dry logs or biofuel in Australia.

Discussions with Australian forest industry representatives identified that there was little difference in terms of productivity or wear and tear for static chippers (those located at a chip mill) between chipping green or dry logs or forest biofuel. This is likely to be because of the higher power of the engine driving a static chipper compared with a mobile chipper and the relative ease of maintaining a static chipper in an indoor environment with an onsite workshop.

The objective of the study was to compare the productivity of a mobile chipper chipping dried *Pinus radiata* logs with chipper productivity results from previous trials chipping fresh *P. radiata* logs.

11.2 Methodology

The chipper trial was conducted in south-west Western Australia on the 18th and 19th of September 2018. The company purchases small *P. radiata* logs and transports them whole to a depot where they are stored in piles. The logs are then chipped and transported as required to meet customer demand. The chipper studied was a Peterson 4310 drum chipper with 6 knives (Engine power 570kW) loaded by a Cat 322C excavator base with a fixed grapple head. The loader operator operated the chipper remotely. The material chipped in the study was small diameter *P. radiata* logs (Log volume ~0.1m^3, SED <120mm, Random length (minimum 5m)) that had been harvested in July 2018 and then stacked in piles infield. The chipping system was a “hot deck” system where chipping only occurred when a truck was available to receive the chips.

A summary of the meteorological conditions during the period the logs were stored infield is shown in Table 8.

Table 8. Meteorological data summary for log storage period

Total rain (mm)	Mean net ET (mm)	Mean max T (°C)	Mean min T (°C)	Mean max RH (%)	Mean min RH (%)

298	-1.1	16.9	7.6	96.1	57.2

The productivity of the chipper was calculated by dividing the quantity of chips (expressed as green metric tonnes (GMt)) produced during a chipper cycle by the chipper cycle time (expressed as Productive Machine Hours without delays (PMH_0)). Chipper cycle time was defined as the time required to fill a truck, excluding delays. Each chipper cycle involved the time elements listed in Table 9, though not all elements were included in every cycle.

Table 9. Definition of chipper time elements

Work element	Definition
Move truck move to chipper	Starts when truck moves to chipper and ends when chipping starts
Chipping	Starts when operator starts picking up logs and feeding them into the chipper and ends when van is full
Change vans	Starts when first van is full and ends when loading second van commences
Planned refuelling and maintenance	Any planned time to refuel or maintain the chipper
Relocate to next pile	Starts when chipper/loader starts moving to new pile and ends when first truck starts moving to be loaded
Delay	Any interruption to performing one of the above work elements

The trucks used to transport the chips in the studied operation did not pass over a weighbridge on every trip. Therefore, the weight of the chips was estimated from the known volumetric capacity of each chip van and an estimate of the proportion of the van that was filled with chips for each load. Loaded volume was converted to loaded weight using chip loose bulk density (kg/m^3) calculated from four truckloads of chips which were passed over a weighbridge prior to and after unloading to determine the weight of chips being transported. Mean chip loose bulk density calculated from the truck data was 318 kg/m^3 (green) and 165 kg/m^3 (bone dry). Loose bulk density was also calculated by loading chips from the logs in the study into a steel container of known volume (73l) and then loading additional chips after the container was repeatedly dropped from a height of 150mm and topped up with additional chips following the procedure documented in Mozammel et al. (2006). This test was repeated 15 times during the study. The loose bulk density results from the container trial (313 kg/m^3 (green) and 167 kg/m^3 (bone dry)) were in close agreement with those obtained from the truck data.

The MC of the logs chipped in the study was estimated by taking 15 chip samples across both days of the study, each of 300g. These samples were weighed at time of collection and then after heating in an oven at 103°C until constant weight was reached. The weight loss from drying was assumed to be entirely the result of moisture loss. MC was expressed on a green weight basis.

11.3 Results

Details of the studied chipper operations and performance are shown in Table 10. The majority of the delays recorded in the trial resulted from the chipper waiting for a truck.

Table 10. Chipper operation and performance results

Characteristic	Value
Total time (hrs)	13.37
Working time (hrs)	5.91
Delay time (hrs)	7.46
Utilisation (%)	44
Vans loaded	22
Weight chipped (tonnes)	412
Productivity (GMt/PMH_0)	70

Mean MC of the chipped logs was 46%. Although the initial MC of the trial logs was unknown, similarly sized logs in a previous FWPA trial had an initial MC of 51-52% (Strandgard & Mitchell, 2017).

11.4 Discussion and Conclusion

Chipper productivity is affected by a range of factors, including the chipper power, piece size being chipped, type of chips being produced and location of chip discharge (Ghaffariyan et al., 2013). The productivity of the chipper in the current trial was higher than that reported for chippers of similar power and chipping similar piece size material e.g. Spinelli and Hartsough (2006): chipper productivity 54.8 GMt/PMH_0 and 59 GMt/PMH_0; McDonald and Stokes (1994) 57 GMt/PMH_0, and was also higher than the chipper productivity estimated using the model in Ghaffariyan et al. (2013) (62 GMt/PMH_0). A contributing factor to the higher productivity of the studied chipper may have been that most studied chipper systems have a flail delimber/debarker in front of the chipper which limits the chipper productivity. Hartsough et al. (2002) found that delimbing poplar trees prior to passing them through a flail combined with a chipper increased the flail/chipper productivity by 8% compared with processing intact trees. Drum chippers have also been found to be more productive than the equivalent disc chipper as drum chippers are able to cut with the same energy along the length of its knives whereas disc chipper rotational speed varies across the disc (Spinelli et al., 2013).

The results of the study suggested that chipping dried small diameter *P. radiata* logs did not have a significant effect on the productivity of the chipper. The high engine power of the chipper may have been a factor in this result. Watson et al. (1986) tested two Morbark infield chippers (models 20 and 27) and found that the MC of the material being chipped was a significant variable in modelling the productivity of the smaller chipper (260kW) but did not affect the productivity of the larger chipper (485kW). However, chipping dry material considerably increased knife wear and hence knife costs for the larger chipper which required knife changes every 3 van loads compared with changes every 10 van loads for green material. Another factor may have that the Janka hardness of *P. radiata* wood is relatively low when green and dried (2.1kN green, 3.3kN dried).

Further tests need to be carried out to determine whether drying *P. radiata* logs to a lower MC than tested in the current study or use of a lower power chipper has an impact on chipper productivity. Chipping other species, particularly eucalypts (which can have considerably higher Janka hardness values after drying), may also impact chipper productivity, though Mola-Yudego et al. (2015) did not find species (including a number of pine and eucalypt species) to be a significant factor in their study of infield chipper productivity.

13 Key recommendations

- Forest managers and growers currently managing payments for forest products on a delivered green weight basis should move to a system based on delivered volume or oven-dry weight basis to reduce the incentive to contractors to minimise infield drying
- The Australian forest industry should increase its use of higher volumetric capacity vehicles which were shown in the current study to maximise the savings from infield log and biofuel drying. This change is particularly relevant to transport of dried and infield chipped LR
- Delivered cost savings identified in desktop studies of drying logs and forest biofuel should be explored in detailed case studies to examine the supply chain implications and practices required to deliver drier products of acceptable quality at minimum cost.
- Further drying trials under a range of meteorological and storage conditions are desirable to increase the robustness of drying models for logs and forest biofuel of key Australian tree species. These drying trials should make use of the automated weighing platforms used in the current study to minimise study costs.
- Drying models developed in the current study can be used directly or in spreadsheets to manage logs and forest biofuel stored infield. However, operational-level supply chain planning and decision support tools should be developed for the Australian forest industry to maximise the benefits from infield drying of logs and forest biofuel
- Testing the impacts of chipping dry material with a mobile chipper should be extended to *P. radiata* logs with a lower MC than tested in the current study and to other species and types of forest biofuel at a range of MC values
- Further testing of portable tools to measure the MC of logs and forest biofuel stored infield should be conducted and sampling protocols developed to minimise samples required to obtain a result with acceptable accuracy
- Additional Hitman HM200 tool readings for a range of MC values for *P. radiata* logs should be obtained to develop a robust model and methodology for the estimation of the MC of *P. radiata* log stacks.

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