Resources

Reducing costs in the wood supply chain through controlling the moisture content of logs and chips:

Preliminary modelling results for air-drying Eucalyptus globulus and Pinus radiata log piles

Project number: PNC336-1314

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Forest & Wood Products Australia

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Prepared for

Forest & Wood Products Australia

by

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Executive Summary

Wood is ~50% water when harvested. Therefore, drying logs and biomass infield has the potential to produce considerable savings in transport costs for the Australian forest industry. Drying biomass produces additional gains from the increased energy content. There are a number of steps required to move from the current system of transporting green logs to a system where the moisture content of logs and biomass is managed to balance the benefits of infield drying against potential costs from degradation and increased storage duration. This project aimed to address the first step in this process through investigating the rates of air-drying of logs under Australian conditions and using the results to develop models to predict the moisture content of *Pinus radiata* and *Eucalyptus globulus* log piles stored at roadside. The models can be incorporated into other systems or used through a Smartphone app predictive tool developed as part of the project.

Log drying data were collected from small log piles (5-8 tonnes) of *E. globulus* chip logs, and *P. radiata* chip and residue logs stored at the WAPRES Diamond mill in Manjimup, Western Australia for two periods in 2014. Small numbers of individual logs were also stored to compare the moisture content of individual logs to that of the log piles. A Hitman HM200 was used to test log pile logs and individual logs to test its possible use as a tool to estimate log pile moisture content.

Log pile drying was modelled using linear and non-linear regression. The linear regression models had the best fit to the data. However, deficiencies were noted in the models when they were used to predict log pile moisture content for different commencement dates than those tested during the trial. Additional log drying trials will be needed to address these deficiencies.

Individual log moisture content values were not found to be a reliable indication of log pile moisture content, which was likely to be related to variations in drying rate related to log size. The Hitman HM200 was not able to get readings from logs in the log piles but was able to get readings from individual logs. This possibly resulted from the contact between the test logs and adjacent logs.

This project was the initial step in the research required to enable the Australia forest industry to gain the benefits from infield log drying while minimising the potential disbenefits. Further research is required in the following areas:

- Additional trials to investigate log drying rates of different log types and under different conditions and in different locations to develop further log and biomass drying models and to validate and strengthen existing models. Review of previously published studies would be advised to learn established procedures for conducting drying trials
- Investigations of value and volume loss resulting from infield log and biomass storage
- Investigations of the potential for loading trucks with additional volume of dry versus green material.
- Investigations of means of paying for logs, chips or biomass based on their moisture content or volume rather than their green weight.
- Further development of models to balance the costs and revenues from infield drying to determine optimum storage times for logs and biomass.

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Introduction

The Australian forest industry operates in a global market and has been experiencing increased competition from imported wood and wood products and from non-timber substitutes (Clancy and Jeyasingham 2012). Australia's delivered wood costs are amongst the highest in the world (Houghton 2014) and up to 20-25% of these costs result from long transport distances for logs and chips (Kemp et al. 2012). As green logs and chips contain approximately 50% water, 25% of the cost of transport is to transport water, much of which is then removed during later processing. Transport costs could potentially be significantly reduced through infield drying prior to transport. For example, Erber et al. (2016) estimated that drying beech logs infield from 41.7% to 22.47% moisture content (MC) and then chipping the logs directly into a truck, increased the volume of chips per load from 55.8 m^3 to 77.3 m^3 when loaded to the maximum legal weight, which was equivalent to a 28% reduction in transport cost per bone dry tonne of chips, all else being equal.

Overseas studies of infield log drying have shown that reductions in the MC of logs of 20% or greater are achievable (Kent et al. 2010, Röser et al. 2011, Visser et al. 2014). Most previous studies have been carried out under generally cooler and wetter conditions than those in Australia, therefore equivalent or greater levels of drying in a shorter period of time should be achievable under Australian conditions. However, consideration needs to be given to the potential deterioration of logs and chips when left infield. The nature and significance of this deterioration depends mainly on the end use of the material and whether it is in log or chip form. Sawlogs can be rapidly colonised by sap-staining fungi under favourable weather conditions (Keirle 1978) and can also undergo checking and splitting as they dry (Byrne et al. 2006), potentially reducing their value, while chips can lose significant amounts of their mass from chemical and biological degradation when stored in piles (Garstang et al. 2002) and can also undergo changes to their colour and pH that reduces their suitability for chemical pulping (Sithole 2005). In addition, pulp logs when dried can require more energy to chip (Spinelli et al. 2011) and can produce a higher proportion of undesirable pin chips and fines (Radiotis et al. 2008), though the drier chips may require less chemical treatment to convert to pulp (Rao et al. 1993). In contrast, biomass logs and chips intended for use as fuel gain not only from reduced transport costs when dried but also from increased energy content and value. Goble and Peck (2013) estimated energy content double when biomass is dried from green to 30% MC due to less energy being required to convert water in the biomass to steam. Erber et al. (2016) reported that reducing the MC of biomass chips from over 45% to less than 20% increased their value at the power plant by 11%.

Forest owners need to be able to predict the MC of logs or biomass piles stored infield in order to determine the appropriate storage duration to balance potential gains from reduced MC against potential deterioration or contamination, and increased storage costs and demand considerations. Previous drying trials have shown that weather conditions during storage have the most significant impact on the rate of drying of stored woody material (Kent et al. 2010, Röser et al. 2013, Visser et al. 2014). Log characteristics, including the species (Röser et al. 2011), log size (Visser et al. 2014) and presence or absence of bark (Röser et al. 2011), can also be important, with smaller logs and debarked logs being found to dry more rapidly (Bown and Lasserre 2015). Log piles have also been covered in wetter climates to protect them from rewetting through precipitation (Röser et al. 2011). Results of log drying trials, predominantly conducted in Europe, have been used to develop drying models to predict the MC of logs or biomass stored infield. However, there are no publically available Australian log drying models and the differences in the weather conditions and species harvested means that European drying models are unlikely to be applicable in Australia.

Currently most logs and wood chips in Australia are sold on the basis of their delivered weight which encourages minimisation of log drying along the supply chain to maximise payments. Using weight as the basis for payment post-infield drying would reduce payments. To address this issue, log and chip payments would need to be changed to a system where MC or dry matter content was used to determine payment which would require a means of accurately estimating the dry matter content or MC of wood on delivery. Wood chips are currently routinely sampled on delivery (Meyer 2011), however, it is not known if the present sampling intensity is sufficient to form the basis of payment based on MC or dry matter content. Laser scanners can be used to estimate the volume of individual logs (Oja et al. 2010) or log truck loads (Paccot 2008) as the basis for payment. Although laser scanning of logs to estimate their volume does not involve estimation of dry fibre or MC, it reduces the current incentive to minimise log drying prior to delivery. Assessing the dry matter content of non-saw logs is routinely conducted overseas through analysis of sawdust samples obtained using a modified chainsaw with a collector (Hultnäs 2012). There is also a range of handheld tools that can be used to estimate the MC of wood chips and logs. These tools fall into three categories: capacitance, conductance and acoustic tools. Capacitance and conductance based tools rely on changes in the electrical properties of wood as its MC changes, while acoustic tools rely on changes in acoustic velocity of logs related to their MC. Murphy et al. (2012) tested a range of these tools and found that results varied depending on the tool and the material (chips, logs or biomass) and species being tested. The best performing tools in that study were the Wile Bio Meter capacitance tool (www.farmcomp.fi/en/wile) testing wood chips and biomass and the Hitman HM200 acoustic tool (www.fibre-gen.com) testing small logs. Acoustic velocity varies with both MC and temperature, though based on the results of Moreno Chan et al. (2011) the impact of temperature on acoustic velocity is likely to be small over the range of temperatures typically encountered in Australia.

Implementation of infield drying models into software tools is a pre-requisite for their use in decision-making. However, few infield drying models have been incorporated into software tools, and those that have are predominantly used in strategic and tactical level tools (e.g. Acuna et al. 2012, Lin et al. 2016, Belart et al. 2017). Software apps on mobile platforms have been used for some time in forestry primarily as data collection tools (e.g. Hamilton et al. 1999, Leech et al. 1989, Rolev 1988). Recently, mobile software apps have been developed that can be used as an aid to decision-making in the field by taking advantage of the features of smartphones and tablets (internet access, camera, GPS, high-resolution display, gyroscope, accelerometer) (e.g. Amishev 2015, Riddering et al. 2015, Nascimento et al. 2016). However, there are no known implementations of log or biomass drying models as smartphone software apps.

This project aimed to assist the Australian forest industry to reduce log and wood chip transport costs through:

- Models to predict the MC of stacks of *Pinus radiata* and *Eucalyptus globulus* logs stored at roadside using meteorological data and acoustic velocity
- Software app incorporating the models to distribute the project results to industry
- Comparing chip size distributions between green and dried logs and against a chip export standard

Methodology

The study site was located at the WAPRES Diamond mill near Manjimup in south-west Western Australia (lat. -34.333943, lon. 116.108830). The site has a Mediterranean climate with warm summers and cool winters and a pronounced winter rainfall (almost 50% of the annual rainfall occurs from June to August). Long-term mean annual rainfall for the site was 997mm, long-term monthly minimum and maximum air temperatures were 6.4 degrees Celsius (July) and 27.2 degrees Celsius (January), respectively.

Log drying trial

Two log drying trials were conducted at the site to capture seasonal differences in log drying rates. The summer trial commenced on the 21st February 2014 for the *Pinus radiata* logs and 27th February for the *Eucalyptus globulus* logs and the winter trial commenced on the 30th July 2014 for the *P. radiata* logs and 5th August for the *E. globulus* logs. The summer drying trial was conducted for 159 days and the winter trial for 168 days.

Each drying trial was conducted using three log piles: one each of *E. globulus* chip logs, *P. radiata* chip logs and *P. radiata* residue logs (Figure 1). Residue logs were woody biomass logs that did not meet the specifications of sawlogs or chip logs. Log characteristics are provided in Table 1. A small number of logs of each type were laid out individually next to the log piles for destructive sampling (12-14 logs) and acoustic testing (10 logs). The eucalypt logs were debarked in the field by the harvester. The *P. radiata* logs were not debarked, although all had lost some bark during processing and handling (losses were not measured). Trial logs were delivered within 24 hours of felling to minimise moisture loss prior to the trial commencement. Log piles were bound using log truck load restraint straps to maintain the integrity of the piles during the trial. Each pile was stored so that the base of the pile rested on two parallel logs, one at each end of the pile. The log piles were approximately 1.5m tall and 2m across.

Table 1. Log pile characteristics

Trial	Log type	Initial pile weight (tonnes)	Initial pile MC (%)	Logs per pile	Mean log SED (mm)	Mean log length (m)	Mean log volume (m^3)
Summer	*E. globulus*	8.64	46	107	119	4.41	0.080
	P. radiata chip	7.92	51	149	95	4.58	0.047
	P. radiata residue	5.94	53	233	71	4.58	0.027
Winter	*E. globulus*	5.77	52	67	115	4.25	0.074
	P. radiata chip	7.35	52	78	135	5.01	0.103
	P. radiata residue	4.73	59	98	96	4.76	0.053

At the start of each trial, the initial MC of each log pile was estimated by cutting five discs along the length of one of the destructive sampling logs per log type with a chainsaw and calculating the mean MC value of the discs for each log. The MC of the discs was determined by oven-drying according to the Australian standard (AS/NZS 1080.1). MC was expressed as a percentage of the sample weight at delivery (green weight basis). The log piles were weighed by using a log grapple to carry each pile onto a weighbridge (resolution 10kg). The weight of the log grapple without the logs was subtracted from its weight with the logs to obtain the log pile weight. Changes in the weight of the log piles between weighings were assumed to represent changes in the MC of the log piles. Losses of wood and bark during the movement of the log piles for weighing were assumed to be negligible. For each trial, the log piles were weighed on delivery. For the summer trial, the piles were then weighed six times at weekly intervals, twice at two weekly intervals and once at a monthly interval. For the winter trial, piles were weighed four times at weekly intervals, four times at two weekly intervals and three times at monthly intervals (note that the differences in the frequencies of the readings between the summer and winter trials and the two week delay in the second last winter reading were due to operational constraints). Disc samples were also taken from the destructive sampling logs at each time the log piles were weighed and dried according to the AS/NZS 1080.1 standard to estimate their MC.

Fresh logs from the start of the winter trial and dry logs from the completion of the summer trial for all log types were chipped at the WAPRES Diamond mill. Six samples of chips approximately 2kg each were taken from each log type. These samples were tested to the AS NZS 1301.014rp standard to determine the percentage of chips in each size class (>28.6mm, >22.2mm, >9.5mm, >4.8mm, <4.8mm) and the percentage of bark. These values were compared with *E. globulus* and *P. radiata* export chip quality specifications used by WAPRES (Table 2).

Table 2: WAPRES *E. globulus* and *P. radiata* export wood chip specifications

>28.6mm (%)	4.8mm – 28.6mm (%)*	9.5mm – 22.2mm (%)	< 4.8mm (%)	% Bark
<5	>92	>55	<3	<0.5

* Acceptable sized chips (‘accepts’).

(a) 

(b) 

(c) 

Figure 1. Summer drying log piles (a) *E. globulus* logs; (b) *P. radiata* chip logs; (c) *P. radiata* residue logs

Acoustic testing

A Hitman HM200 acoustic tool (www.fibre-gen.com) was used to take acoustic velocity readings of ten marked logs at various positions within each log stack and of ten individual logs of each log type on the same days the log piles were weighed. Three Hitman readings were taken from each log at each time of measurement. Prior to making the initial Hitman measurements, the individual logs were trimmed to 4.5m in length to simplify Hitman readings, which require entry of log length. At each time of measurement, the individual logs were weighed using a digital hanging scale (0.1kg resolution). Weight changes were assumed to represent changes in the log's MC. Disc samples taken at the time of delivery of the logs were used to estimate initial log MCs.

Mean values for the acoustic velocity (km/s) and estimated MC (%) for the logs at each time of reading were modelled using linear regression.

Meteorological data

Meteorological data for the period of each trial were obtained from the Australian Bureau of Meteorology's (BOM) Manjimup weather station (located approximately 10km north of the trial site) (www.bom.gov.au). In previous overseas studies, a range of meteorological variables were used to model log drying. In the current study, the following variables were tested because they were found in previous studies to influence the rate of log drying and were also readily available from the Australian Bureau of Meteorology website, which is an important consideration for the potential useability of the models: wind speed (m/s), relative humidity (%), air temperature (°C), solar radiation (W/m^2), rainfall (mm) and net evapotranspiration (mm) (evapotranspiration minus rainfall).

Weekly net evapotranspiration and rainfall totals (mm) for the summer and winter drying trial periods are shown in Figure 2. Daily maximum and minimum relative humidity (%) for the summer and winter drying trial periods are shown in Figure 3. The data ranges used to develop the drying models set the valid limits for application of the models. Valid range limits for the models were set as the 10 and 90 percentiles for all meteorological variables (Table 3).

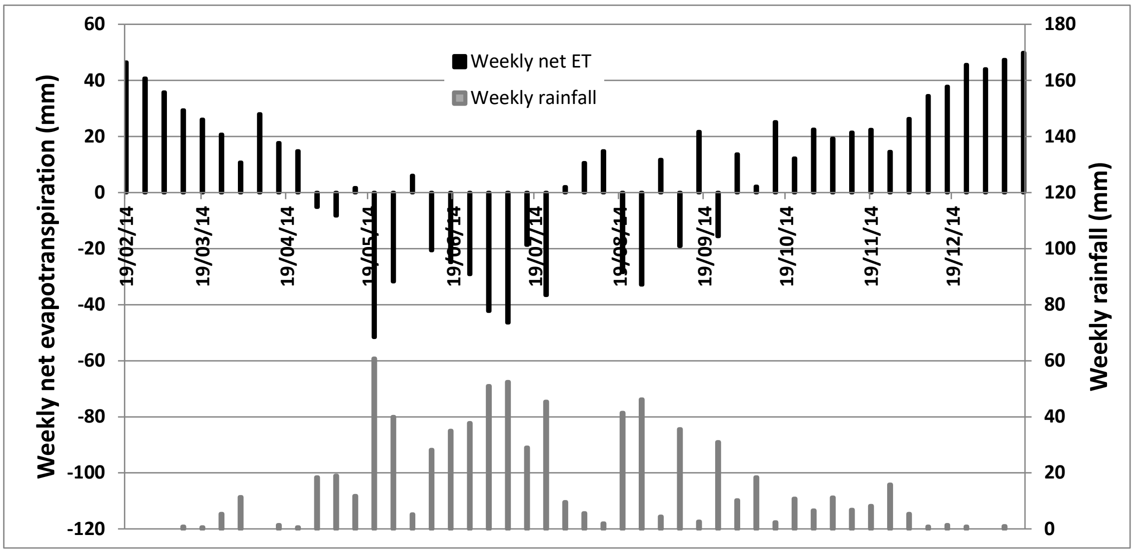


Figure 2. Weekly net evapotranspiration and rainfall totals (mm) for the summer and winter drying trial periods.

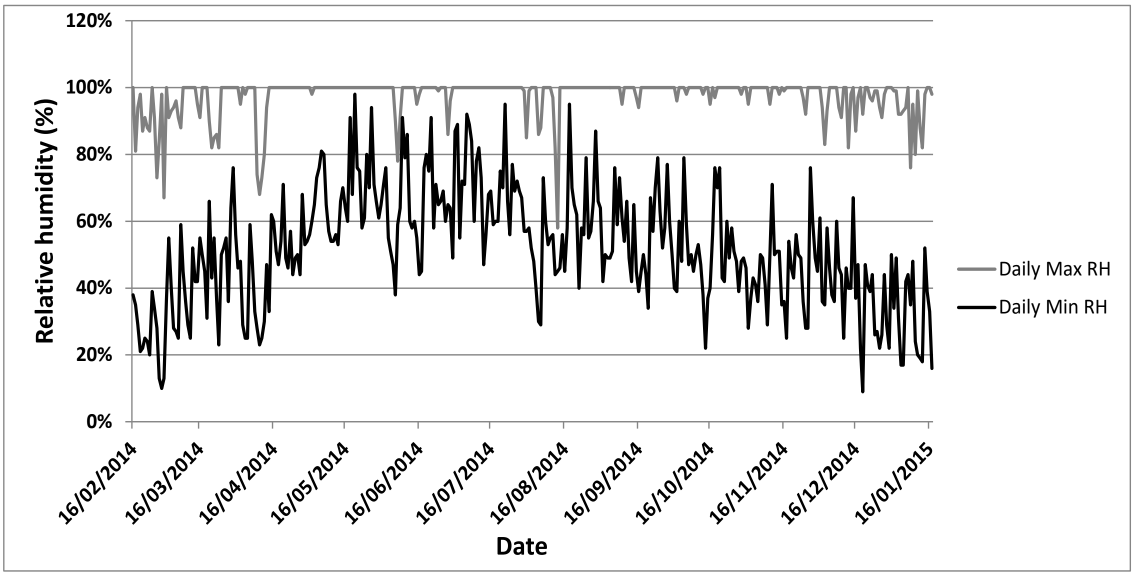


Figure 3. Daily maximum and minimum relative humidity (%) for the summer and winter drying trial periods.

Table 3. Limits for the valid ranges of the drying models: 10 and 90 percentiles on a daily basis.

Basis	Mean T (°C)	Min RH (%)	Max RH (%)	Net ET (mm)
10%	11	28	91	-4.8
90%	21	76	100	6.2

Log moisture content modelling

A number of approaches have been used in previous studies to model changes in the MC of logs in piles. Two approaches were tested in this study:

- Multiple linear regression of daily MC change against meteorological variables
- Non-linear regression of daily MC change against meteorological variables

The ability of the models to produce reliable predictions of log pile MC when extrapolated to starting dates outside those used to produce the models is critical to their successful application. To test their predictive ability, the models that best fitted the data from each approach were used to predict log pile MC values using Manjimup meteorological data for January 2014 to February 2015. Each model was tested by assuming an initial log pile MC of 50% and modelling the daily MC change for three months commencing on the 1st of each month. Plots of the predicted log pile MC values were examined to detect aberrant behaviour of the models. Predicted daily MC changes were compared with observed values from the trial data.

Multiple linear regression

The multiple linear regression was performed using the best subsets regression procedure in the Minitab (v.16) statistical software package. (www.minitab.com). Variable subsets identified by this procedure were tested to identify the regression model for each log type that had the best fit to the data in terms of its R^2(adj) and root mean square error (RMSE) values, and had the fewest variables. Variables were tested for statistical significance ($p<0.05$) and low collinearity (Variance Inflation Factor (VIF) < 5).

Non-linear regression

The non-linear model form tested was that used by Simpson and Wang (2004):

$\Delta M = aM^bT^cH^dD^e$ (Simpson and Wang 2004)

where ΔM is the daily MC change, M is the MC at the beginning of the day (%, green basis), T is the daily average air temperature (°C), H is the daily average air relative humidity (%), D is the number of logs per square metre cross-section and a, b, c, d and e are parameters to be determined by non-linear regression.

Simpson and Wang (2004) estimated M by linear interpolation between the MC values estimated on the days the trial logs were weighed. In the current trial, the value of M was modelled from the starting MC and the predicted ΔM values. Daily average air temperature and relative humidity values were estimated by calculating the mean of the daily minimum and maximum air temperature and relative humidity values, respectively. The variable D was excluded from the analysis as the current study did not include replicates with different log sizes. Parameter values for the non-linear model were determined using the non-linear modelling procedure in the Minitab (v.16) statistical software package (www.minitab.com).

Software App

A smartphone software app was developed as a proof of concept. It allows users to register the details of an infield pile of logs and to obtain an estimate of its moisture content using the log drying models provided in this report. The app was developed using Java software and will run on an Android tablet or smartphone.

Results

Log moisture content modelling

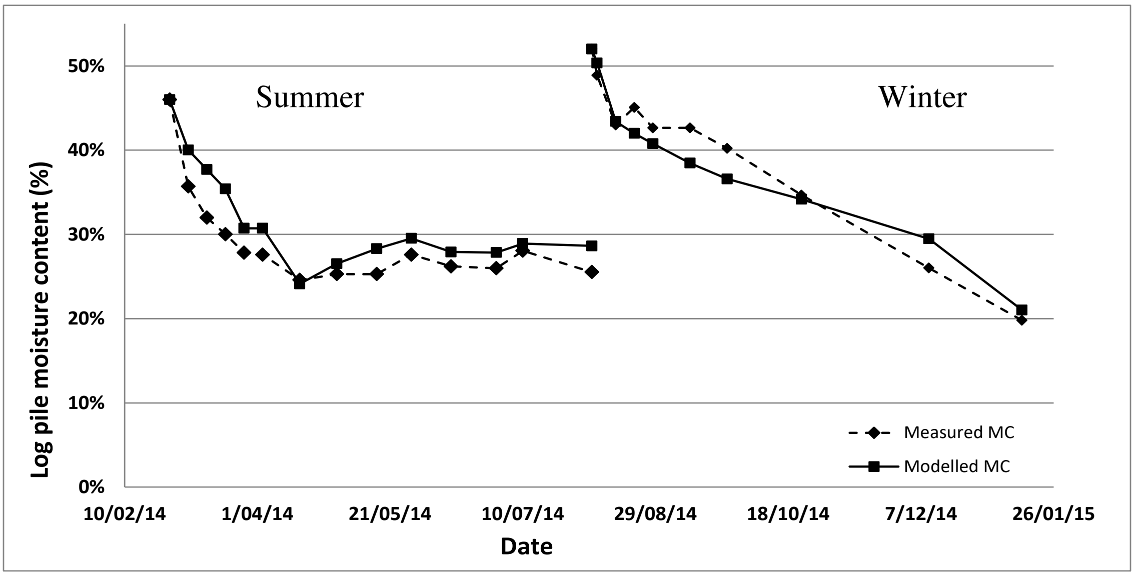
For the purposes of analysis, the datasets from the summer and winter log drying trials were combined for each log type. Daily minimum, maximum and mean log drying rates for each drying trial and log type are given in Table 4.

Table 4. Daily minimum, maximum and mean log pile drying rates for each drying trial and log type (%/day).

Study	Log type	Log drying rate (%/day)		
		Minimum	Maximum	Mean(SD)
Summer	*E. globulus*	0.26	-1.47	-0.21(0.45)
	P. radiata chip	0.29	-1.06	-0.25(0.41)
	P. radiata residue	0.63	-1.52	-0.33(0.63)
Winter	*E. globulus*	0.30	-1.56	-0.35(0.54)
	P. radiata chip	0.51	-0.48	-0.17(0.30)
	P. radiata residue	0.54	-0.69	-0.23(0.36)

Multiple linear regression

The multiple linear regression models generally fitted the log pile MC data well (Figure 4). The poorest fit was for the *P. radiata* log types when the log pile MCs dropped below 20% at the end of the winter trial (Figures 4(b) and 4(c)). At this point, the models predicted a considerably lower MC than was observed. The initial drop in MC seen in the first weeks of the winter trial for all log types reflected a short period with low rainfall and low RH at the start of August, 2014 (Figures 2 and 3).



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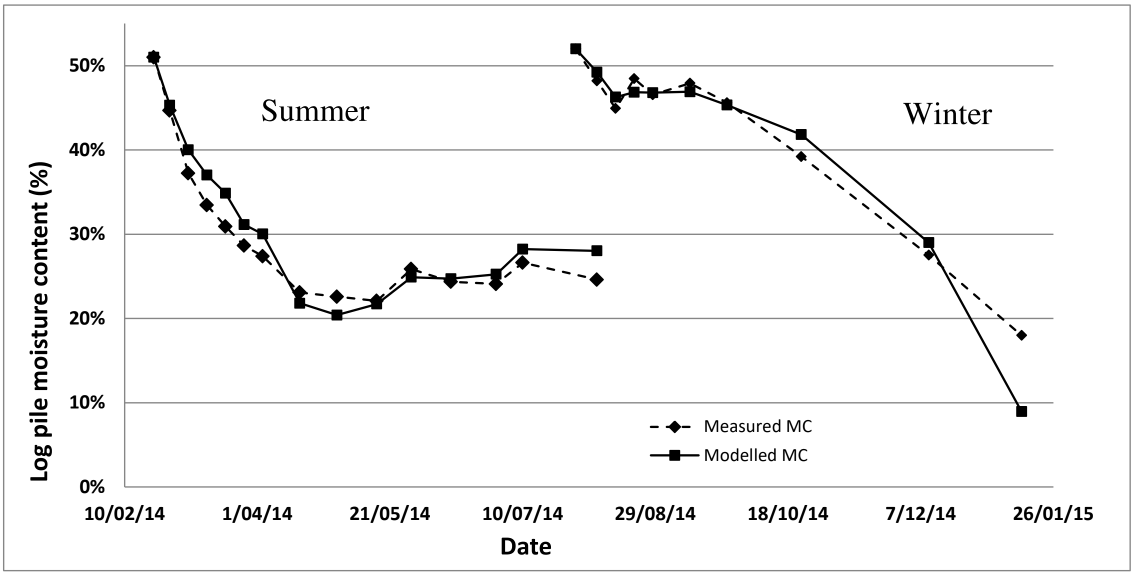

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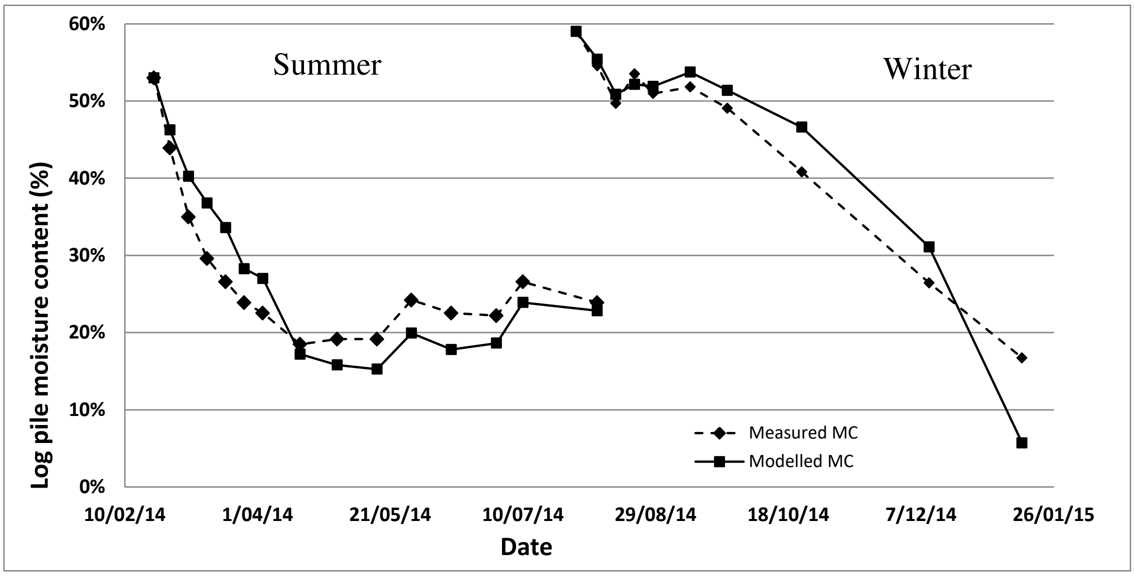


(c)

Figure 4. Measured and predicted MC values modelled using multiple linear regression for summer and winter trials. (a) *E. globulus* chip logs; (b) *P. radiata* chip logs; (c) *P. radiata* residue logs.

Best fit models for each log type were as follows:

***E. globulus* chip log model**

$\Delta M = -0.0671 - 0.0214\, x\, MC + 0.0742\, x\, Max\, RH$ (R^2_{adj} = 77.5%, RMSE = 0.26%)

Variability explained by each variable: *MC* = 13.5%; *Max RH* = 37.5%

***P. radiata* chip log model**

$\Delta M = -0.0423 + 0.0327\, x\, Max\, RH + 0.0161\, x\, Min\, RH$ (R^2_{adj} = 74.3%, RMSE = 0.17%)

Variability explained by each variable: *Max RH* = 5.4%; *Min RH* = 16.9%

***P. radiata* residue log model**

$\Delta M = -0.0552 + 0.0548\, x\, Max\, RH - 0.000623\, x\, Net\, ET$ (R^2_{adj} = 71.4%, RMSE = 0.24%)

Variability explained by each variable: *Max RH* = 11.4%; *Net ET* = 14.5%

Where:

ΔM is the daily change in MC (%)
MC is the modelled MC (%) of the log pile at the start of the day
Max RH is the maximum relative humidity (%) for the day
Min RH is the minimum relative humidity (%) for the day
Net ET is the net evapotranspiration (mm) for the day

Model F tests were significant at $p<0.0001$. All VIF values were less than 2.

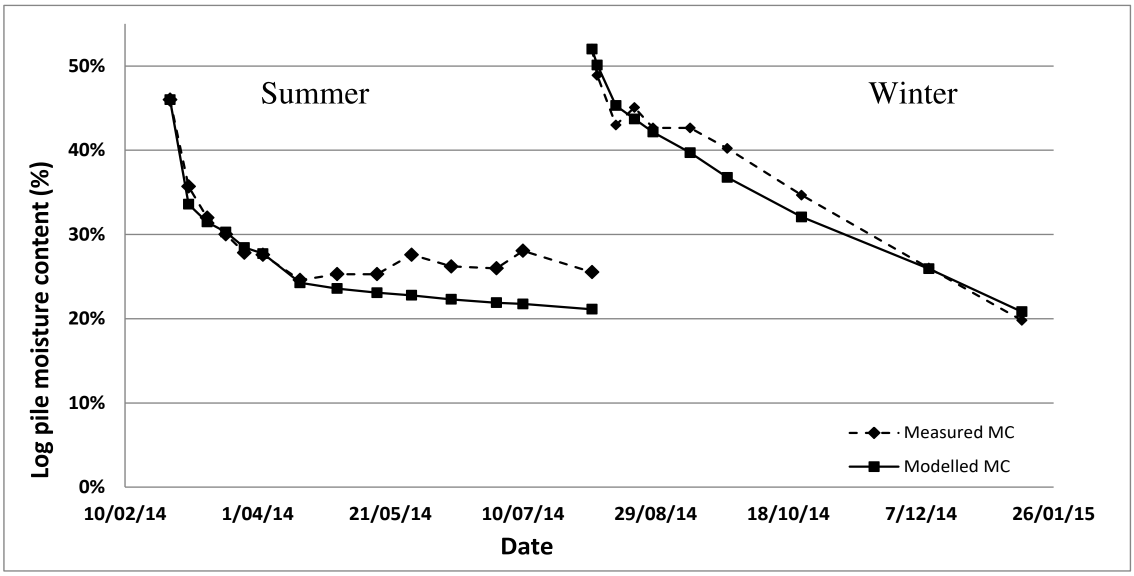
Non-linear regression

The *E. globulus* non-linear model fitted the log pile MC data well until the logs began to regain moisture at the commencement of autumn (Figure 5(a)). At this point the model predicted the MC of the log pile would fall. However, the good fit of the model when the log pile was losing moisture during both the summer and winter trials was reflected in the low RMSE value (Table 5).

During the winter trial, almost 40mm of rain fell in the week prior to the third log pile weight measurement (Figure 2). This resulted in both *P. radiata* log type piles regaining a considerable proportion of the moisture they had lost since the trial commencement (Figures 5(b) and 5(c)) (the *E. globulus* log pile was less affected). However, the non-linear models for both *P. radiata* log types predicted the MC would fall during this period. The *P. radiata* non-linear models also predicted a considerably greater initial drop in MC for these log types at the start of the summer trial than was observed. The overall poor fit of these models to the *P. radiata* log drying data was reflected in their high RMSE values (Table 5).

Table 5. Non-linear regression model parameters for each log type and RMSE (%) values.

Log type	Model parameters				RMSE(%)
	a	b	c	d	
E. globulus	-0.00103	3.043	0.895	-4.302	0.18
P. radiata chip	-0.000948	0.990	-0.102	-7.001	0.51
P. radiata residue	-0.00294	0.740	-0.847	-8.358	0.45



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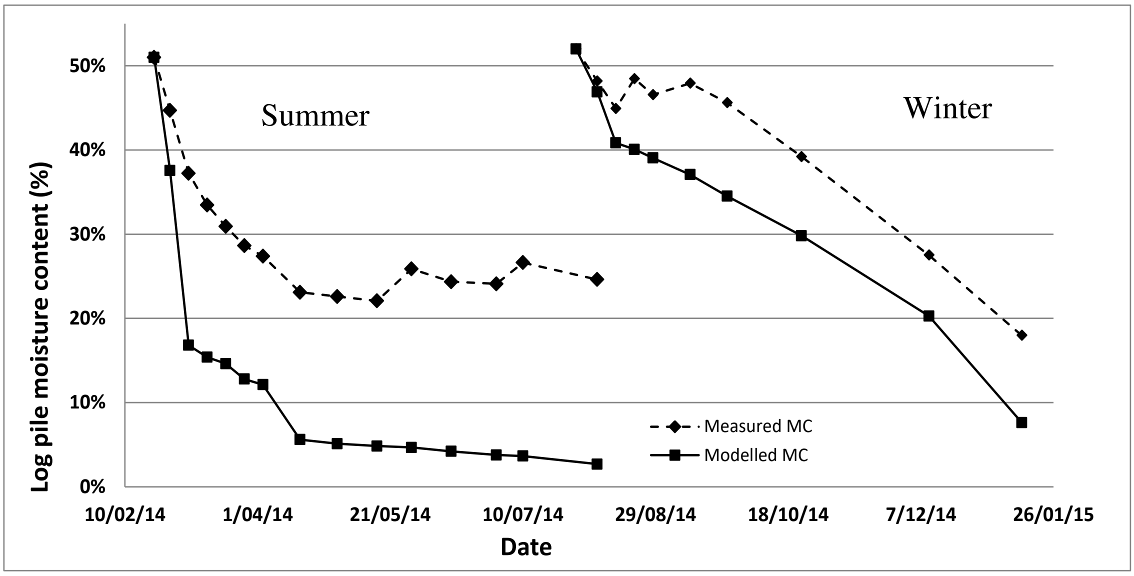

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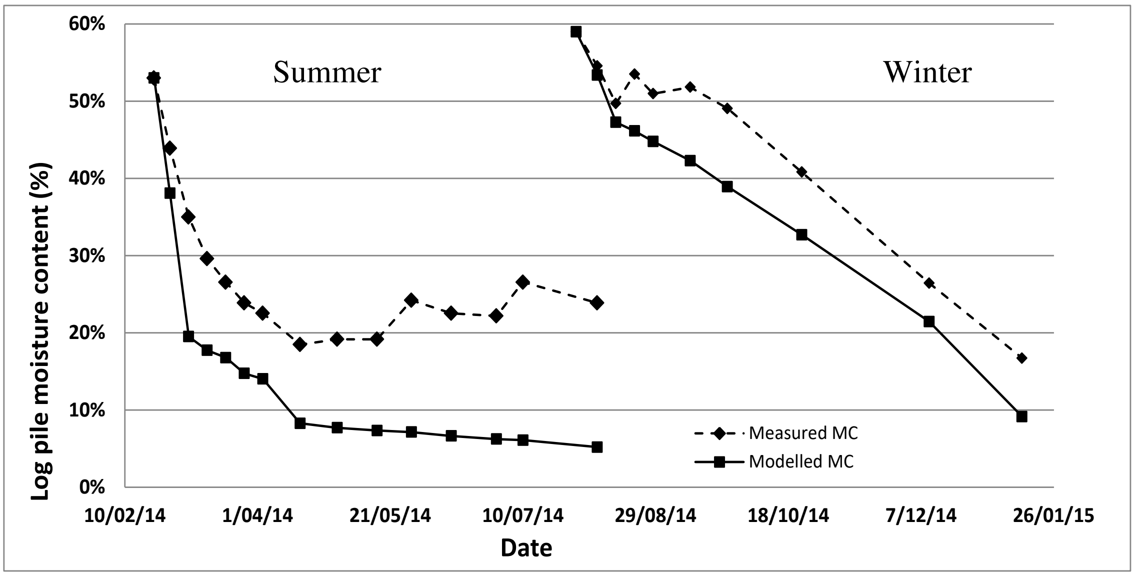
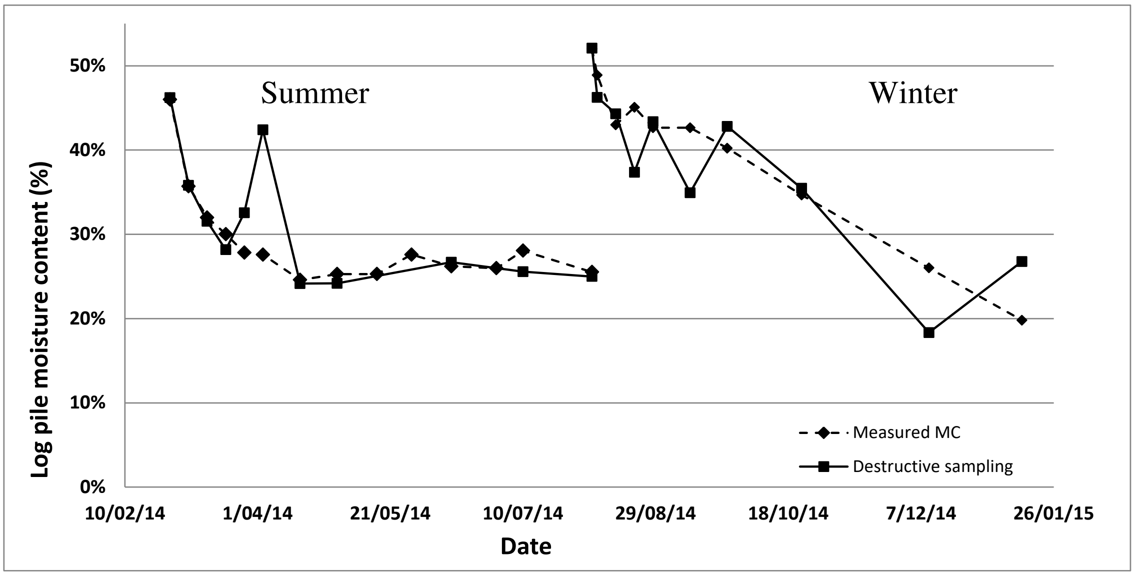


c)

Figure 5. Measured and predicted MC values modelled using non-linear regression for summer and winter trials. (a) *E. globulus* chip logs; (b) *P. radiata* chip logs; (c) *P. radiata* residue logs.

Destructive sampling

The destructive sampling MC values for each log type were generally more variable than the corresponding log pile MC values (Figure 6). The variability in MC between measurements was likely to be related to variations in log size.



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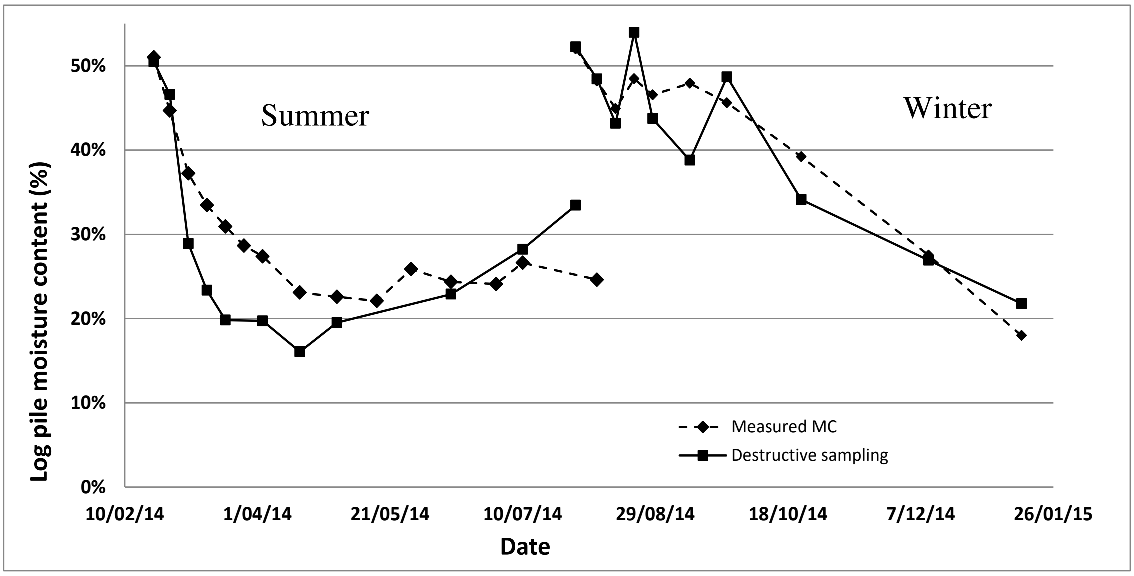

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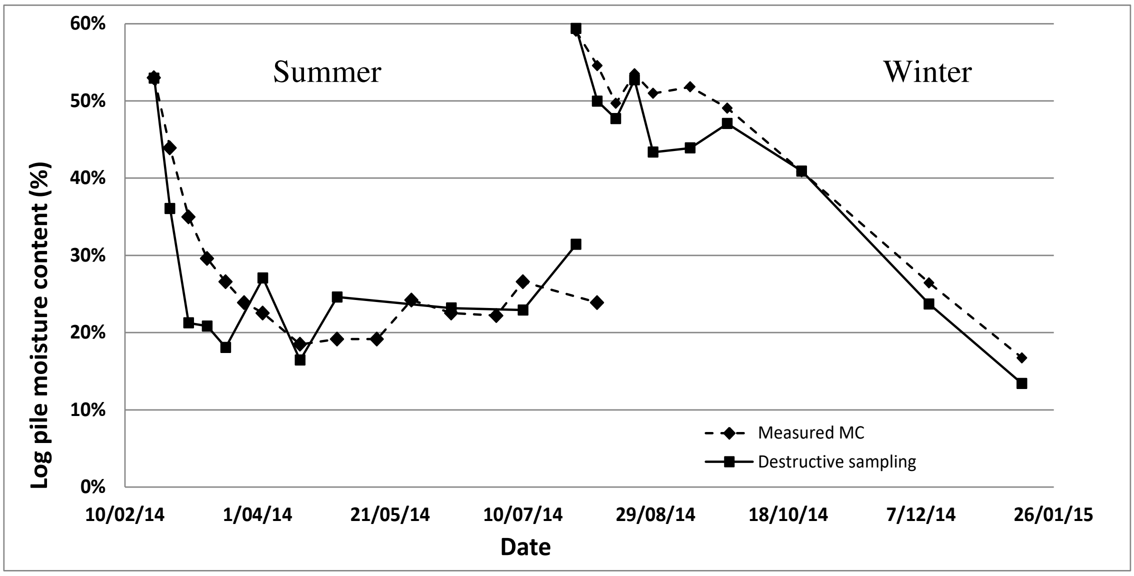


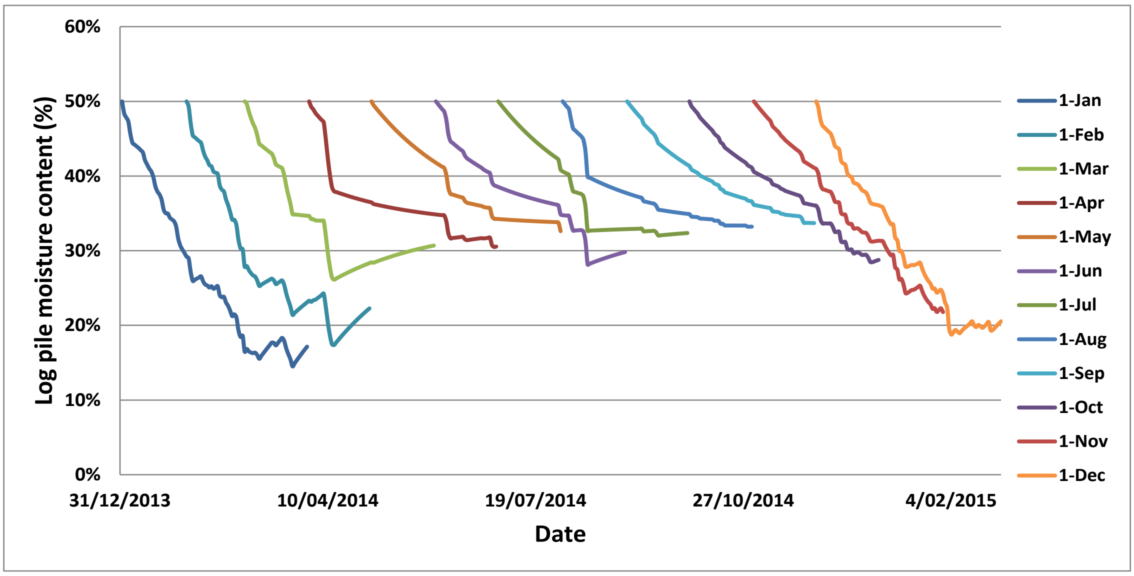
c)

Figure 6. Measured and destructive sampling MC values for summer and winter trials. (a) *E. globulus* chip logs; (b) *P. radiata* chip logs; (c) *P. radiata* residue logs.

Log drying model extrapolation testing

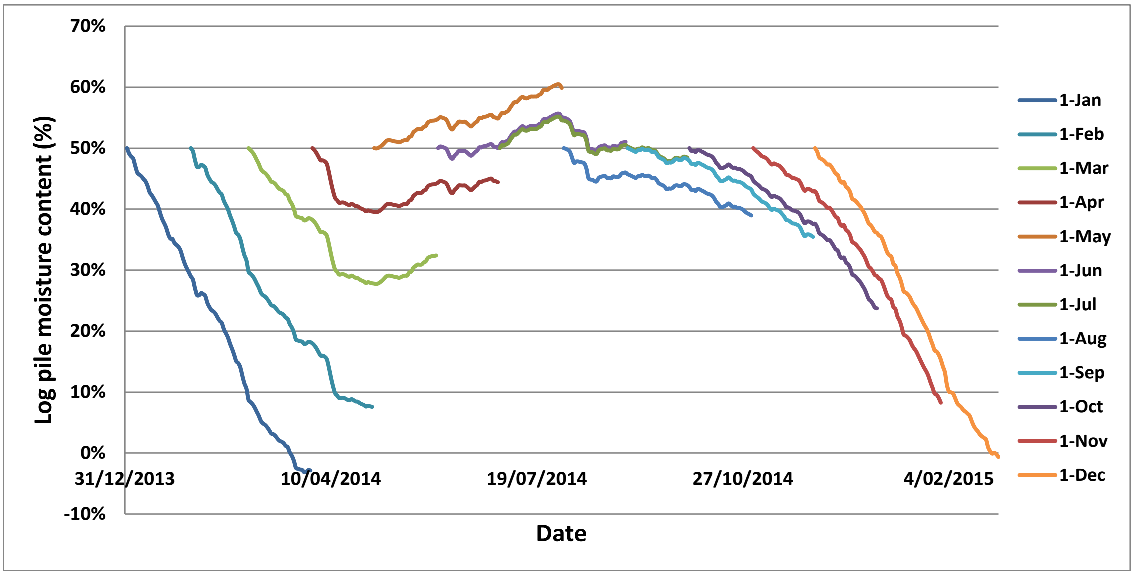
Multiple linear regression models

The log pile MC values extrapolated using the *E. globulus* linear regression model showed rapid MC reductions in summer and a decreased rate of MC loss when weather conditions were milder in Autumn, Winter and Spring (Figure 7(a)). Minimum MC values were generally close to observed minimums. The extrapolated log pile MC values for the two *P. radiata* models (Figures 7(b) and 7(c)) produced similar patterns to the *E. globulus* model for Autumn and Spring weather conditions. However, when extrapolated using the Summer weather data, the *P. radiata* models predicted MC would decline to negative values and using the Winter data the models predicted MC would increase or remain unchanged over the prediction period. For all models, the daily percentage MC changes were generally within the range observed in the log drying trials, with some minor exceptions e.g. in early April the predicted daily reductions in MC for the *E. globulus* and *P. radiata* residue log piles exceeded 2%/day.



60%
50%
40%
30%
20%
10%
0%
Log pile moisture content (%)
31/12/2013
10/04/2014
19/07/2014
27/10/2014
4/02/2015
Date
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec

(a)



70%
60%
50%
40%
30%
20%
10%
0%
-10%
Log pile moisture content (%)
31/12/2013
10/04/2014
19/07/2014
27/10/2014
4/02/2015
Date
1-Jan
1-Feb
1-Mar
1-Apr
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1-Jun
1-Jul
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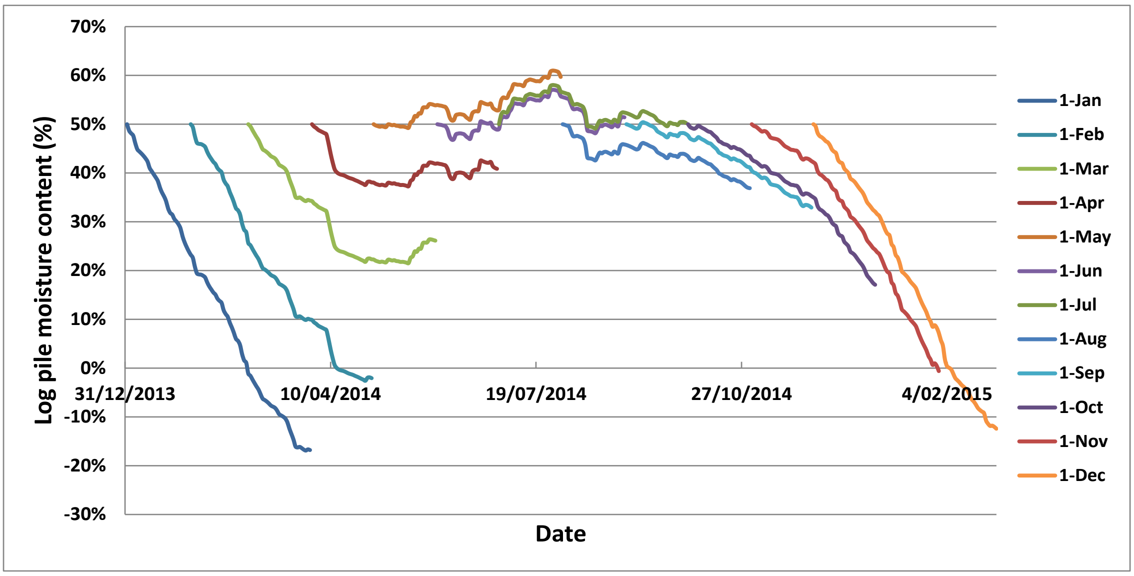
1-Sep
1-Oct
1-Nov
1-Dec

(b)



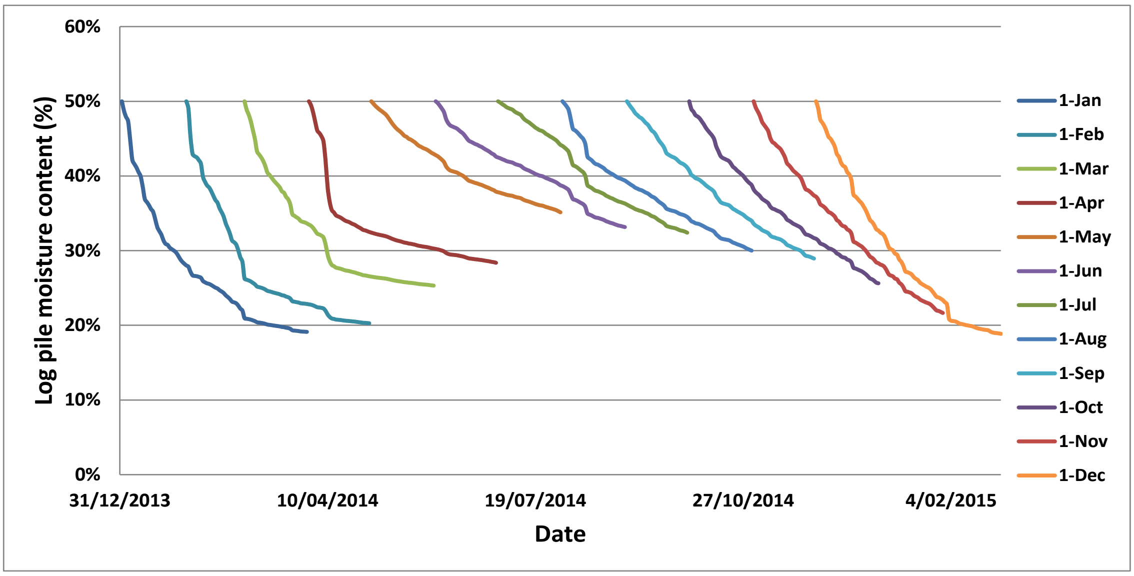
70%
60%
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
Log pile moisture content (%)
31/12/2013
10/04/2014
19/07/2014
27/10/2014
4/02/2015
Date
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec

(c)

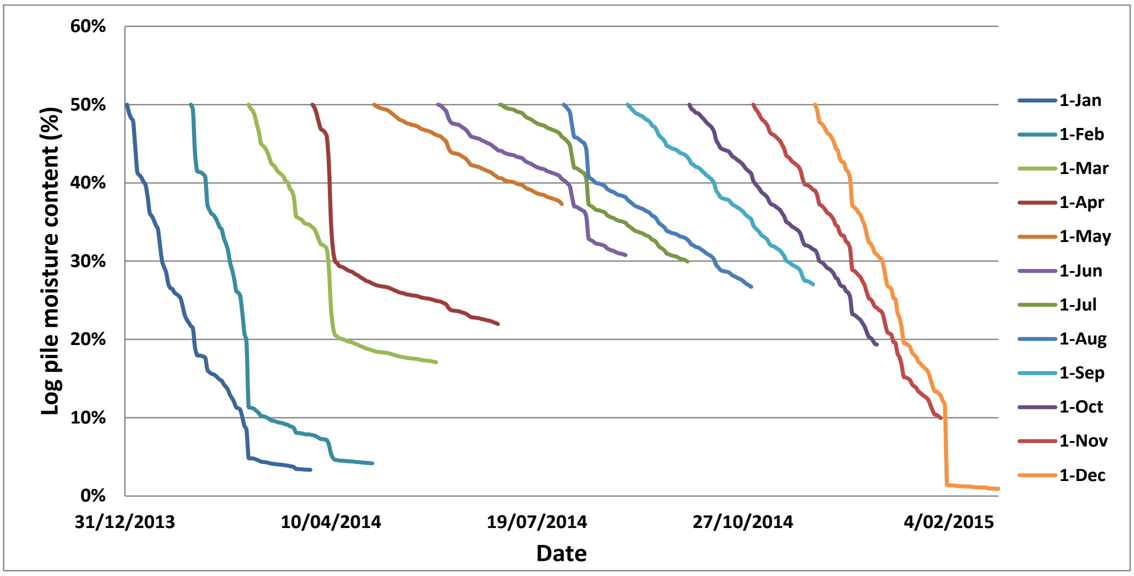
Figure 7. MC values modelled using multiple linear regression extrapolated for three months from the start of each month in 2014. (a) *E. globulus* chip logs; (b) *P. radiata* chip logs; (c) *P. radiata* residue logs.

Non-linear models

The log pile MC values extrapolated using the *E. globulus* non-linear regression model were similar to those for the linear model, showing rapid MC reductions in summer and a decreased rate of MC loss when weather conditions were milder in Autumn, Winter and Spring (Figure 8(a)). The daily percentage MC changes for the *E. globulus* model were generally within the range observed in the log drying trials, with some minor exceptions similar to those for the linear regression model, and the minimum MC values were generally close to observed minimums. The *P. radiata* non-linear models (Figures 8(b) and 8(c)) predicted daily MC reductions of up to 11%/day which was considerably in excess of the observed values. This resulted in the *P. radiata* models predicting MC would decline to low values not seen in the observed data or to negative values.



(a)



(b)

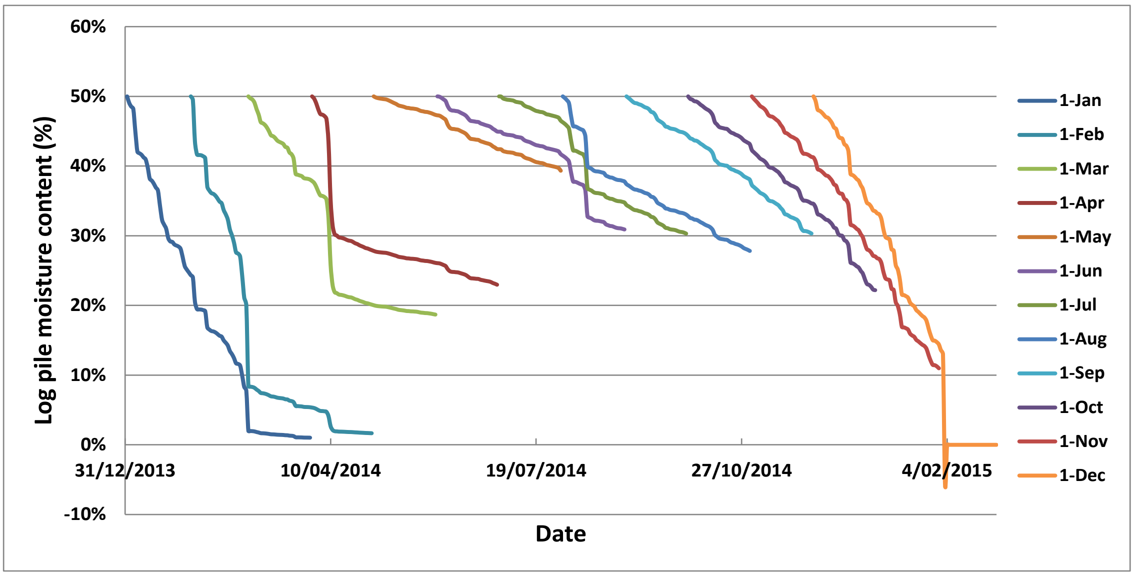
(c) 

Figure 8. MC values modelled using non- linear regression extrapolated for three months from the start of each month in 2014. (a) *E. globulus* chip logs; (b) *P. radiata* chip logs; (c) *P. radiata* residue logs.

Acoustic testing

The Hitman HM200 was not able to obtain acoustic velocity readings from the logs tested in the log piles at any time of measurement, possibly from the transfer of the sound waves generated by tapping the log ends to adjacent contacting logs. However, readings were obtained from the individual test logs. Models were developed using the mean MC values for the ten test logs of each log type at each time of measurement. Using mean values can considerably decrease the variability in the data and inflate the R^2 values (Martinez-Vara de Rey et al. 2001), as was found in the current study. However, the individual log data could not be used as the starting MC value for each log was not known. Data for the summer and winter trials were combined for modelling purposes.

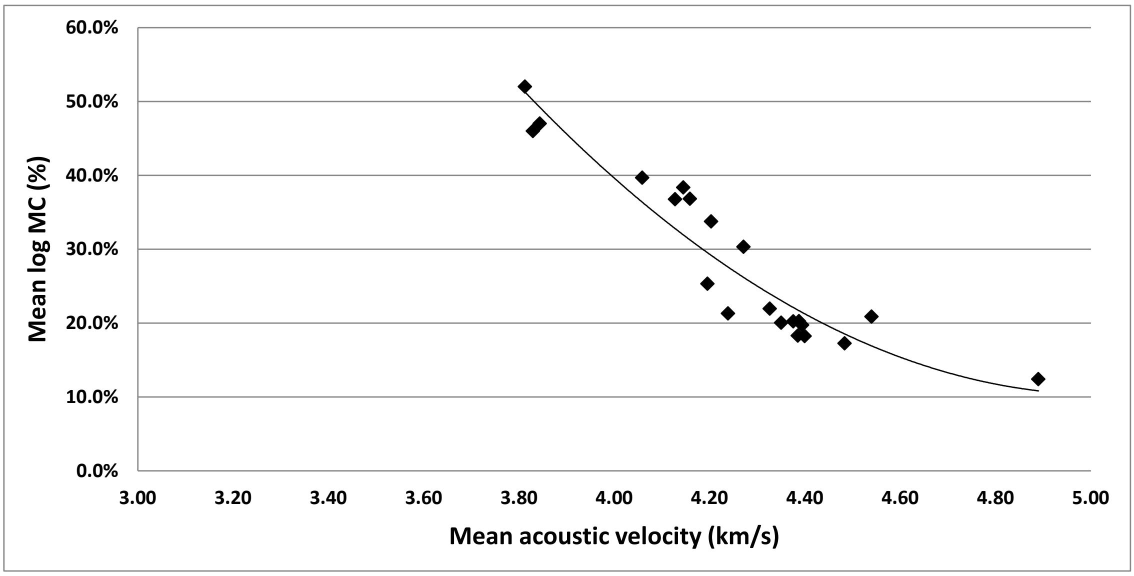
The model form that best fitted the data for mean log MC (%) against mean acoustic velocity (AV) (m/s) was a 1st order polynomial for all log types:

$$MC \; = \; a + \; b\,x\,AV + c\,x\,AV^2$$

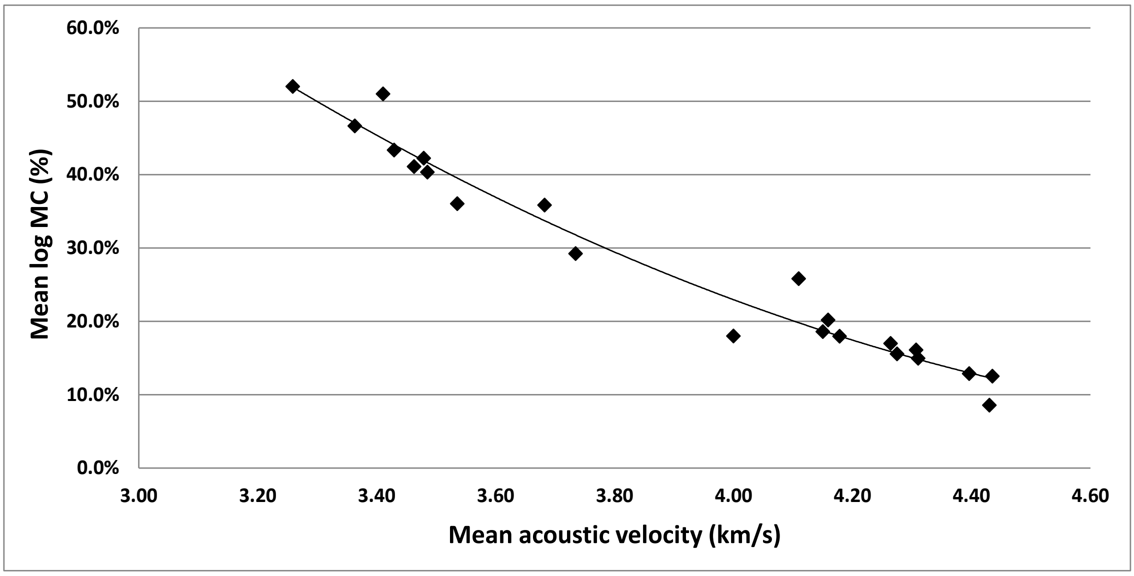
Model parameters, RMSE(%) and R^2_{adj} are given in Table 6. Figure 9 shows plots of mean log MC (%) against mean acoustic velocity (km/s) for each log type.

Table 6. Parameters, RMSE(%) and R^2_{adj} for the models of MC against acoustic velocity for each log type.

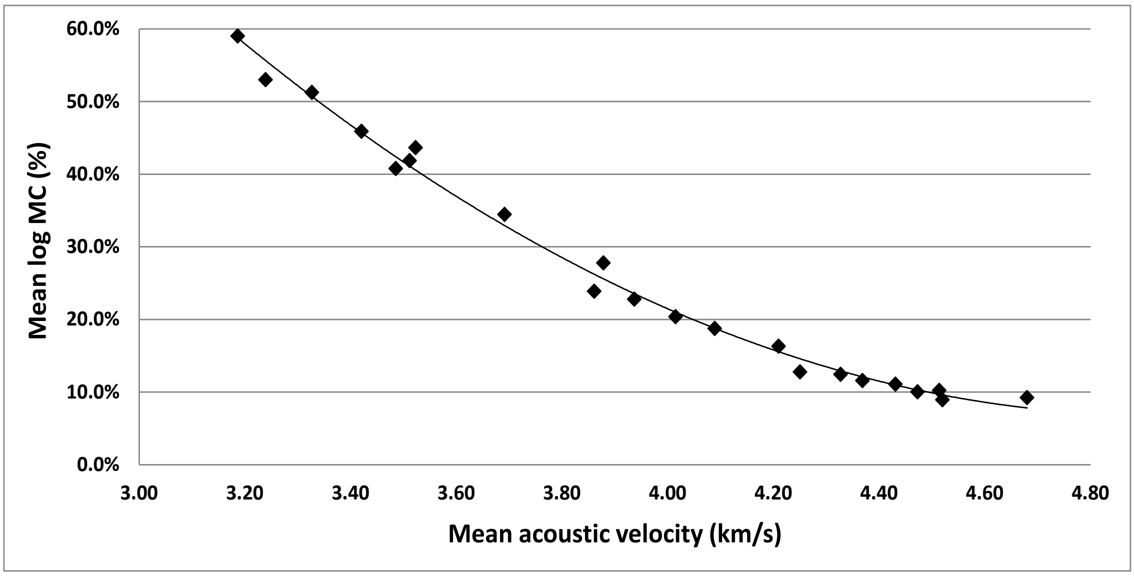
Log type	Model parameters			RMSE(%)	R^2_{adj}
	a	b	c		
E. globulus	7.1105	-2.7873	0.2772	3.7	88.2
P. radiata chip	3.3933	-1.282	0.1228	2.6	96.1
P. radiata residue	4.245	-1.6973	0.1724	1.4	99.2



(a)



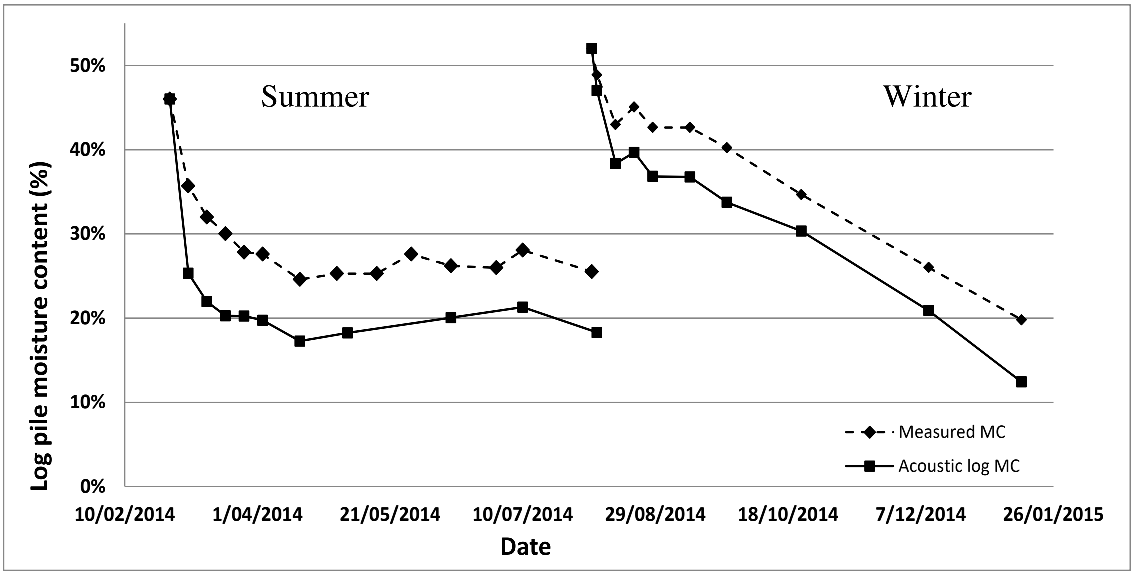
(b)



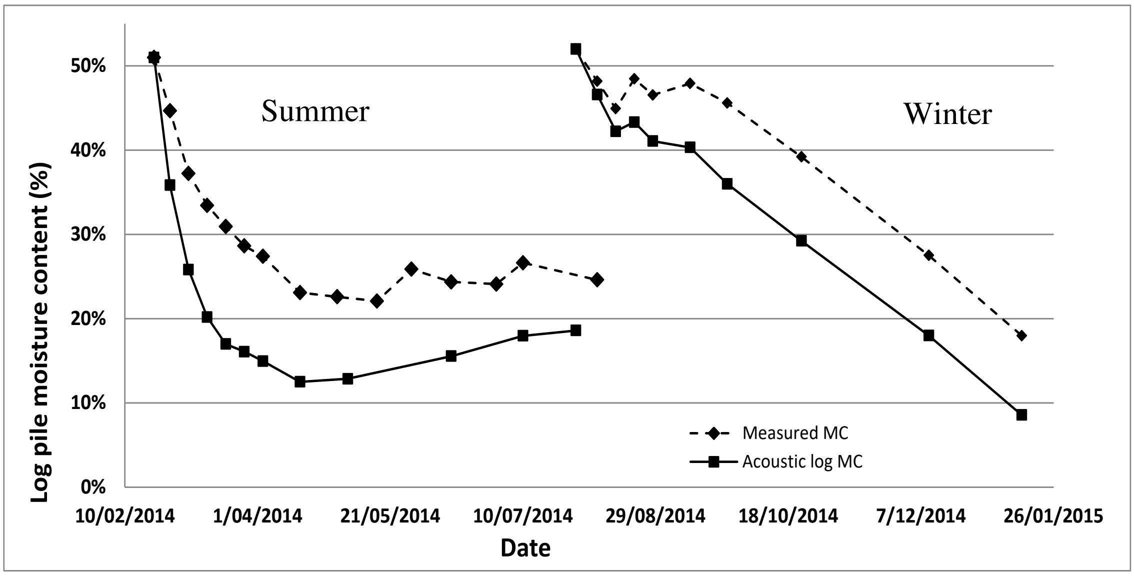
(c)

Figure 9. Mean acoustic test log MC (%) plotted against mean acoustic velocity (km/s). (a) *E. globulus* chip logs; (b) *P. radiata* chip logs; (c) *P. radiata* residue logs.

Mean MC values from the ten acoustic test logs and the measured log pile MC values both plotted against measurement date were compared for each log type (Figure 10). In all cases, the acoustic test logs dried more rapidly and to a lower MC than the log piles. The MC of the *P. radiata* acoustic test logs also increased more rapidly in response to rain and cooler conditions at the end of the Summer trial. The response of the *E. globulus* acoustic test logs to the cooler, wetter conditions was similar to that of the *E. globulus* log pile.



(a)



(b)

(c)

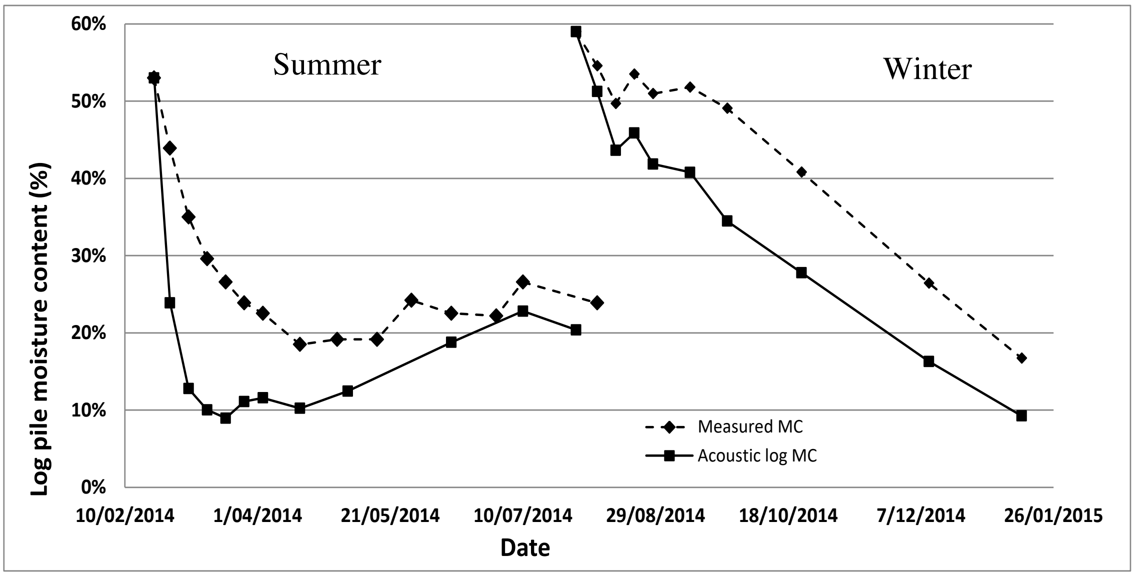


Figure 10. Measured log pile MC and mean acoustic test log MC values for the summer and winter trials. (a) *E. globulus* chip logs; (b) *P. radiata* chip logs; (c) *P. radiata* residue logs.

Wood chip size and bark percentage

The chip size distribution and bark percentage for each log type for fresh and dry logs are shown in Table 7. The *P. radiata* logs had a higher bark percentage than the *E. globulus* because the *P. radiata* logs had not been debarked prior to the trial. The percentage of chips >4.8mm for the dry *E. globulus* logs was statistically significantly greater than that for the fresh logs. There were no significant differences between the fresh and dry *P. radiata* chip log chip and bark proportions while for the *P. radiata* residue logs, there was a significant increase in the percentage of chips over 22.2mm and a commensurate significant decrease in the percentage of chips over 9.5mm. There was also a significantly lower bark percentage for the dry *P. radiata* residue logs compared with the fresh logs.

Table 7. Mean wood chip percentages by size class and bark percentage for each log type for fresh and dried logs

Log type	Wood age	% >28.6mm	% > 22.2mm	% > 9.5mm	% > 4.8mm	4.8-28.6mm (%)	% < 4.8mm	% Bark
E. globulus	Fresh	1.0	55.7	40.5	2.1*	98.3	0.3	0.07*
	Dry	1.6	48.4	45.9	3.0*	97.3	0.4	0.00*
P. radiata chip	Fresh	5.0	53.0	34.5	3.0	90.5	0.7	2.95
	Dry	7.5	66.4	20.6	2.1	89.1	0.4	2.49
P. radiata residue	Fresh	3.2	40.2*	46.5*	4.5	91.2	1.0	3.24*
	Dry	4.7	63.9*	25.2*	3.0	92.1	0.7	2.09*

* Denotes the chip size percentages or bark percentages were significantly different between fresh and dry logs for that log type

The chip samples for all log types (fresh and dry) failed to satisfy the export chip specifications (Table 2):

- None of the log types (fresh and dry) met the requirement for >55% of the chips to be between 9.5-22.2mm in size
- Only the fresh and dry *E. globulus* logs and the dry *P. radiata* residue logs met the requirement for >92% of the chips to be between 4.8 – 28.6mm in size.
- The fresh and dry *P. radiata* chip logs exceeded the specification of <5% of chips being >28.6mm.
- None of the *P. radiata* chip samples met the allowable bark percentage specifications.

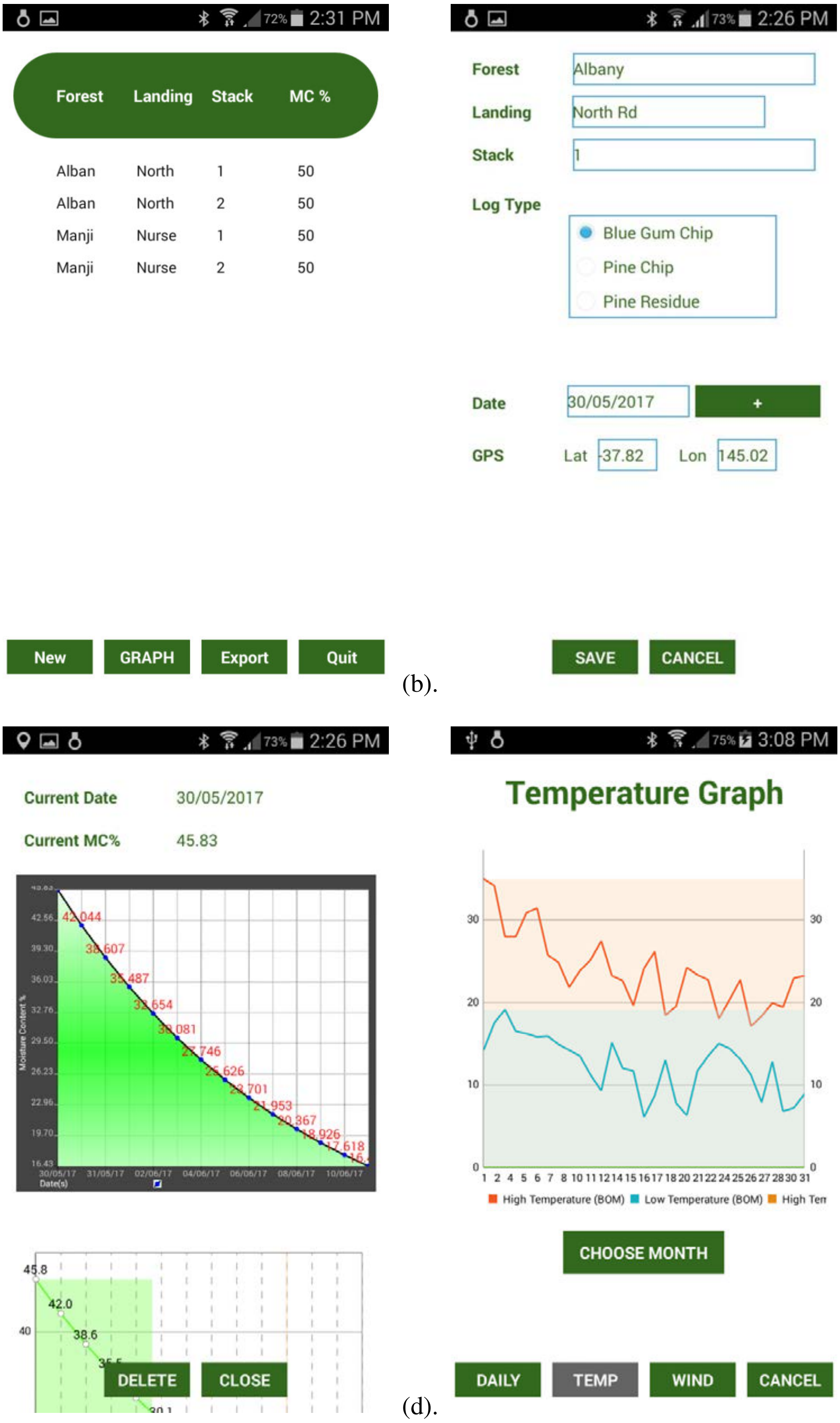
Software App

To install the log drying proof of concept app the apk file first needs to be copied to the Downloads directory on the device. Next the following changes must be made in Settings on the device:

Settings > Security > Unknown services > ticked
Settings > Security > Verify apps > unticked (this may not be present on all devices)

Click on the apk file to install the app. Before using the app switch on the device's Location services.

To use the log drying app, the user first creates a new log pile instance (Figure 11a) and inputs the administrative area information applicable to the pile's location ("Forest" and "Landing") and the pile id to allow entry of multiple log piles per administrative unit (Figure 11b). The log type is then selected ("Blue gum chip", "Pine chip", or "Pine residue"). The app supplies the log pile coordinates using the smartphone's internal GPS and the log pile creation date (current date). The date can be changed if the pile was created prior to the current day. When the new log pile is saved, the app extrapolates the drying curve from the current day using the multiple linear regression models provided in this report (Figure 11c). The model used is based on the log type selected by the user. Plots of the underlying meteorological data can also be displayed by selecting the "GRAPH" option on the opening screen (Figure 11d). As the app is proof of concept at this stage it currently uses a fixed set of meteorological data to estimate the log pile moisture content. Future versions of the log drying app will use data from the nearest meteorological station to the location of the log pile or input user-provided meteorological data files which will allow use of portable weather station data.



(a). (b). (c). (d).

Figure 11. Screenshots of the log drying app. (a). Main screen; (b). New log pile data entry; (c). Log drying curve; (d). Meteorological data display.

Discussion

The initial drying rates of the log piles in the summer trial (>1%/day) were considerably higher than those seen in most previous log drying studies and were comparable to the summer drying rates for *E. globulus* log piles in Chile reported by Bown and Lasserre (2015). As would be expected, initial drying rates of the log piles in the winter trial were lower than those in the summer trial. In the summer trial, the times required for each log pile to reach its lowest MC were 8 weeks for the *E. globulus* chip logs (25% MC) and the *P. radiata* residue logs (19% MC) and 12 weeks for the *P. radiata* chip logs (22% MC). Though not tested in the current study, the relatively small size of the logs and the removal of bark from the *E. globulus* logs in the study were likely to have increased their rates of drying (Visser et al. 2014, Bown and Lasserre 2015). By way of comparison, log pile drying times and final MC values reported in a number of published studies were: approximately 11 weeks for debarked *E. globulus* logs in Chile to reach 20% MC (Bown and Lasserre 2015); 24 weeks for small *P. radiata* logs to reach 21% MC in New Zealand (Visser et al. 2014), and; 37 weeks for small diameter softwood logs to reach 24% MC in Ireland (Kent et al. 2010).

Previous studies have used a variety of meteorological variables to model rates of infield log drying. In the current study, the meteorological variables found to have the most significant relationship with log pile MC changes were relative humidity and net evapotranspiration. This was similar to the findings of Erber et al. (2012) who reported that relative humidity and precipitation were the most significant variables influencing log pile drying rates in their study. Other meteorological variables found to be significant in previous studies, including air temperature and wind speed, were not found to be significant in the current study.

Two model forms were used in the study to develop models relating log pile MC changes with meteorological conditions: multiple linear regression and non-linear regression. The multiple linear regression models fitted the log drying data well, explaining over 70% of the variability in daily MC changes. The poorest fit occurred when the MC of the *P. radiata* residue and chip logs fell below 20%, at which point the models predicted a greater drop in MC than was observed. Although not tested in the study, this may have resulted from the logs being at or below fibre saturation point (FSP) (approximately 20-25% MC (green basis) for *P. radiata* (Herritsch 2007)). The rate of air drying of wood slows considerably below the FSP because most of the free water has been removed (Jankowsky and Santos 2005). The *E. globulus* logs in the study did not dry to the same degree as the *P.radiata* logs and hence may not have reached FSP.

The non-linear log drying model form tested (Simpson and Wang 2004) was unable to model an increase in the MC of a log pile. This explained the poor fit of the non-linear models for each log type in the current trial when the log pile MCs increased in response to rainfall and cooler conditions. Previous studies have reported conflicting results for the impact of rainfall on log pile MC. Bown and Lasserre (2015) found that rainfall during their trials had no impact on log pile MC, Nurmi and Hillebrand (2007) and Visser et al. (2014) reported increases in log pile MC in response to rainfall, while Gigler et al. (2000) found that rainfall had a short-lived effect on log MC as it only superficially wetted the outside of the logs and Kokkola (1993) found that rainfall only affected the MC of logs at the top of the log stack. The non-linear models also predicted a greater decrease in the log pile MCs for both *P. radiata* log types than was observed at the commencement of the summer trials. Different variable combinations may have improved the fit of the non-linear models, though this was not tested in this study.

The value of log drying models lies in their ability to predict log pile MC based on actual or predicted meteorological conditions as an input into management decisions. The extrapolated MC values and rates of MC change for the *E. globulus* linear and non-linear regression models were generally within the range of values observed during the trial. However, for a large proportion of the extrapolated results for the *P. radiata* log drying models, the predicted MC values and rates of MC change were outside the ranges observed during the trial and in some cases were impossible (negative MC values). Reducing the extrapolation period from three months to one month, reduced, but did not eliminate, these issues. The problems with the values predicted by the *P. radiata* log drying models may have reflected the limitations of the current study, which included disparities between the trial log piles and commercial-scale log piles (small size and elevation from the ground of the trial log piles) and the limited nature of the trial (one replication of each log type, two drying periods, and a single location) and the hotter, drier conditions experienced during the trial compared with those in overseas trials. The relatively small size of the log piles relative to commercial log piles was an issue shared with most previous log drying trials and was a consequence of using changes in the log pile weight to estimate changes in log pile MC, which puts an upper limit on the maximum practical size of the log pile. Small log piles are likely to be less representative of commercial log drying operations due to their high surface to volume ratio which may affect their rate of drying (Klepac et al. 2014, Visser et al. 2014) and increase the effect of rainfall on the stack (Gigler et al. 2000). Drying trial log and biomass piles are typically elevated from the ground for ease of measuring weight changes. However, elevating log piles may increase their rate of drying by allowing airflow under the stacks. Routa et al. (2015) placed paper on the sides and bottom of their trial biomass piles to emulate the trial piles being part of larger piles, but there is no evidence of the effectiveness of this approach. Replicating drying trials in different locations and seasons would allow the drying responses of logs and biomass to be examined under a greater range of meteorological conditions and starting dates resulting in the development of more robust drying models.

Two tests of the potential of individual logs stored near a log pile to be used to estimate the log pile MC were conducted during the trial. The MC values for the destructive sampling logs showed the same overall patterns of change in MC over time as did the log piles but with a greater degree of variability, which would make them a poor indicator of the MC of a log pile. The variability in MC was likely to be related to variations in log size, as several studies have found smaller logs dry more rapidly than larger logs (Visser et al. 2014, Bown and Lasserre 2015). The mean MC values of the ten acoustic test logs were more consistent than those of the individual destructive sampling logs. However, the acoustic test logs dried more rapidly and to a lower MC value than the log piles of the same log type, which would make them also poor indicators of the MC of a log pile. The greater degree of drying experienced by the acoustic test logs was likely to have resulted from their increased exposure to weather conditions compared with logs in the log piles.

The Hitman HM200 acoustic tool used in the current study was not able to obtain acoustic velocity readings for individual logs in log piles for any log type. This was believed to result from the transfer of the sound waves generated by tapping the log ends to adjacent contacting logs resulting in multiple reflected signals that could not be resolved by the Hitman HM200 (Peter Carter pers. comm.). Previous studies (e.g. Green and Ross 1997, Tsehaye et al. 2000) have been able to measure acoustic velocity of individual logs in stacks, however the logs in these trials were larger in diameter than the logs in the current study, which would have reduced the area of contact with adjacent logs relative to the log volume, and had not been debarked which may have helped acoustically isolate the logs (Peter Carter pers. comm.). In contrast, a strong relationship was found between acoustic velocity and log MC for the individual logs stored adjacent to the log piles, which was consistent with the findings of other studies (e.g. Kang and Booker 2002, Liu et al. 2014). The strength of these relationships suggests acoustic velocity tools have potential to be used to estimate MC of log piles non-destructively. Further research is required to determine whether acoustic velocity readings can be obtained from larger eucalypt and *P. radiata* logs in piles.

The chip samples produced from the logs in the study (fresh and dry) failed to meet the WAPRES export chip specifications. The main cause was the high percentages of chips in the larger size classes (>22.2mm and >28.6mm). Rechipping the oversize chips (>28.6mm) in the study chip samples (as would occur in a chipmill) would have been likely to enable the chip samples to meet the requirements for 92% of the chips to be between 4.8-28.6mm and for the proportion of chips >28.6mm to be less than 5%. However, the chip samples would still fail to meet the export chip specification for 55% of the chips to be between 9.5-22.2mm in size. The *P. radiata* chip samples for both log types also failed to meet the allowable bark percentage specification. However, Walsh and Strandgard (2014) reported that *P. radiata* woodchips with a similar bark percentage to those in the current trial, were acceptable for kraft paper making when mixed with chips with a lower bark percentage. The chip samples from the dried logs in the study generally had a greater proportion of smaller chips than the fresh log chips for the *E. globulus* logs and a greater proportion of larger chips than the fresh log chips for the *P. radiata* logs, though few of the differences in chip size class percentages were statistically significant. However, unlike the findings of Radiotis et al. (2008), chipping dried logs in the current trial did not produce significantly greater proportions of pin chips and fines compared with chipping green logs. The bark percentage was lower in all cases for the dried *P. radiata* logs, though only significantly so for the *P. radiata* residue logs. Bark losses may have resulted from bark falling off the dried logs or being knocked off during transport of the logs for weighing. All chip samples met the ISO 17225 standard P31.5 chip size class for biomass, which is acceptable for use in small scale domestic or industrial boilers. Small chips with low MC, such as produced in this study, would fetch higher prices for biomass than coarser, wetter chips. However, bark has a lower energy density than wood and produces more ash when burnt (Hakkila 1989) which may make the *P. radiata* chips less desirable as biomass intended for use as fuel.

Conclusions

Reducing MC of logs and biomass through infield drying prior to transport offers an opportunity for the Australian forest industry to make significant cost savings in the supply chain. However, drying logs or biomass infield is a trade-off between the potential reduction in costs from reducing MC, and potential cost increases from longer storage time and from biological, chemical or physical degradation. To determine the optimum time to transport the logs and biomass for further processing requires a means to estimate its current and future MC.

Three approaches to estimating the MC of log piles drying infield were tested during the trial (models, individual log tests and acoustic velocity tests). The linear regression models developed from the trial log drying data generally fitted the log drying data well. However, the non-linear regression model form tested was unable to model increases in log MC which resulted in the modelled results deviating from the trial results when the log pile MC increased following rain. This limitation would limit the applicability of this model form. Neither of the individual log tests was able to be used to estimate the log pile MC values. The individual destructively sampled log MC values produced occasional MC results that showed large deviations from the log pile MC values, while the acoustic test logs dried faster and to a lower MC than the log piles of the same log type. Acoustic testing of logs in the log piles with the Hitman HM200 was unsuccessful in the current trial but acoustic tools have been used successfully in other studies. Acoustic testing of individual logs showed a strong relationship between acoustic velocity and log MC, which suggested this approach has potential if further trials can identify conditions (log size, species, bark, etc) under which acoustic readings can be taken from logs within log piles.

Extrapolation of log pile MC estimates for starting dates other than those in the study, was used to test the general applicability of the models developed in the trial. The *E. globulus* models (both linear and non-linear regression) generally performed well, but results were less satisfactory for the *P. radiata* models. Reducing the extrapolation period reduced but did not eliminate the problem. This reflects the limited nature of the drying trials in this study (one replication of each log type, two drying periods, and a single location). Further log drying studies in different locations and seasons would be required to refine the models and increase their applicability to meteorological conditions and locations other than those encountered in this trial.

The chipped samples from the study logs did not meet the WAPRES export chip requirements. However the chips were likely to have been acceptable when mixed with chips from other sources. Drying the logs produced generally smaller chips than for the fresh *E. globulus* logs and larger chips than for the fresh *P. radiata* logs, though few of the size differences were statistically significant. All chip samples met the ISO 17225 standard P31.5 chip size class for biomass.

Recommendations

This project was the initial step in the research required to enable the Australian forest industry to gain the benefits from infield log drying while minimising the potential disbenefits. Further research is required in the following areas:

- Additional trials to investigate log drying rates of different log types and under different conditions and in different locations to develop further log and biomass drying models and to validate and strengthen existing models. Review of previously published studies would be advised to learn established procedures for conducting drying trials
- Investigations of value and volume loss resulting from infield log and biomass storage
- Investigations of the potential for loading trucks with additional volume of dry versus green material.
- Investigations of means of paying for logs, chips or biomass based on their MC or volume rather than their green weight.
- Further development of models to balance the costs and revenues from infield drying to determine optimum storage times for logs and biomass.

References

Acuna, M., Anttila, P., Sikanen, L., Prinz, R. and Asikainen, A. (2012). Predicting and controlling moisture content to optimise forest biomass logistics, Croatian Journal of Forest Engineering 33: 225–238.

Amishev, D. (2015). New Zealand Steep Terrain Harvesting Technologies with Potential Application in Western Canada. FPInnovations Technical Report 52.

Belart, F., Sessions, J., Leshchinsky, B. and Murphy, G., 2017. Economic implications of moisture content and logging system in forest harvest residue delivery for energy production: a case study. Canadian Journal of Forest Research 47(4): 458-466.

Bown, H.E. and Lasserre, J-P. (2015). An air-drying model for piled logs of *Eucalyptus globulus* and *Eucalyptus nitens* in Chile. New Zealand Journal of Forestry Science 45:17.

Byrne, T., Stonestreet, C. and Peter, B. (2006). Characteristics and utilization of post-mountain pine beetle wood in solid wood products. In: Safranyik, L., Wilson, B. (Eds.), The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine. Natural Resources Canada, Victoria, Canada, pp. 233-253.

Clancy, T.F. and Jeyasingham, J.K. (2012). Risk analysis of the Australian timber industry, ABARES report to client prepared for Climate Change Division, Department of Agriculture, Fisheries and Forestry, Canberra.

Erber, G., Kanzian, C. and Stampfer, K. (2012). Predicting moisture content in a pine logwood pile for energy purposes. Silva Fennica 46(4): 555–567.

Erber, G., Kanzian, C. and Stampfer, K. (2016) Modelling natural drying of European beech (Fagus sylvatica L.) logs for energy based on meteorological data. Scandinavian Journal of Forest Research, 31:3, 294-301.

Garstang, J., Weekes, A., Poulter, R. and Bartlett, D. (2002). Identification and characterisation of factors affecting losses in the large-scale, non-ventilated bulk storage of wood chips and development of best storage practices. FES B/W2/00716/REP. DTI/Pub URN 02/1535.

Gigler, J.K., van Loon, W.K.P., van den Berg, J.V., Sonneveld, C. and Meerdink, G. (2000). Natural wind drying of willow stems. Biomass and Bioenergy 19: 153-163.

Goble, D. And Peck, M. (2013) .Opportunities for Using Sawmill Residues in Australia. Report PRB280-1112, Forest and Wood Products Australia.

Green, D. W. and Ross, R. J. (1997). Linking log quality with product performance. Role of wood production in ecosystem management : Proceedings of the Sustainable Forestry Working Group at the IUFRO All Division 5 Conference, Pullman, Washington, July 1997. Madison, Wis. : USDA Forest Service, Forest Products Laboratory, 1997. General technical report FPL ; GTR-100.:p. 53-58.

Hakkila P. (1989). Utilization of residual forest biomass. Springer Series in Wood Science. Springer. Heidelberg, New York. 568 p.

Hamilton, F., Penny, R., Black, P., Cumming, F. and Irvine, M. (1999). Victoria's Statewide Forest Resource Industry—an outline of methods, Australian Forestry 62(4): 353-359.

Herritsch, A. (2007). "Investigations on wood stability and related properties of radiata pine," PhD thesis, University of Canterbury, Christchurch, New Zealand.

Houghton, J. (2014). FWPA Statistics and Economics Program. FWPA webinar presented 27 March 2014.

Hultnäs, M. (2012). Weight Scaling Methods to Determine the Quantity of Pulpwood. Doctoral Thesis Swedish University of Agricultural Sciences Faculty of Forestry Uppsala 2012.

Jankowsky, I. and Santos, G. R. (2005). Drying behaviour and permeability of *Eucalyptus grandis* lumber. Maderas Ciencia y tecnología 7(1):17-21.

Kang, H. and Booker, R.E. (2002). Variation of stress wave velocity with MC and temperature. Wood Science and Technology 36 (1): 44–54.

Keirle, R.M. (1978). Effect of Storage in Different Seasons on Sapstain and Decay of Pinus radiata D. Don in N.S.W. Australian Forestry 41(1):29-36.

Kemp, A., O'Fallon, C. Counsell, K. and Chow, M. (2012). Transport's proportion of total costs for New Zealand businesses. NZ Transport Agency research report 495. 59pp.

Kent, T., Coates, E. and Kofman, P. (2010). Moisture Content Variation in Forest Biomass During Storage. Proceedings of the COST FP902 Conference, Trento, Italy, 8 October 2010.

Klepac, J., Mitchell, D. and Thompson, J. (2014). The Effect of Pile Size on Moisture Content of Loblolly Pine while Field Drying. 37th Council on Forest Engineering Annual Meeting. June 22-25, 2014. Moline, Illinois.

Kokkola, J. (1993). Drying of pulpwood in northern Finland. Silva Fennica 27(4): 283-293.

Leech, J.W., Sutton, M.W. and Archer, G.R. (1989). Recording field measurements on Husky Hunter microcomputers. Australian Forestry 52(2):68-73.

Lin, Y., Pan, F., and Srivastava, A. (2016). A linear programming optimization model of woody biomass logistics integrating infield drying as a cost-saving preprocess in Michigan. Forest Products Journal 66(7): 391-400.

Liu, H., Gao, J., Chen, Y. and Liu, Y. (2014). Effects of Moisture Content and Fiber Proportion on Stress Wave Velocity in Cathay Poplar (*Populus cathayana*) Wood. BioResources, 9(2), 2214-2225.

Martinez-Vara de Rey, C.C., Galindo, M.P.G. and Velarde, M.A.A. (2001). Effects of Using Mean Scores in Regression Models: An Example From Environmental Psychology. Quality and Quantity 35(2): 191-202.

Meyer, R. (2011). Accuracy of Chip Sampling Techniques May Vary. Forest Operations Review. Technical Release 11-R-12.

Moreno Chan, J., Walker, J.C. and Raymond, C.A. (2011). Effects of moisture content and temperature on acoustic velocity and dynamic MOE of radiata pine sapwood boards. Wood Science and Technology. 45(4): 609-626.

Murphy, G.E., Belart, F., Kent, T. and Kofman, P.D. (2012). Forecasting and monitoring moisture content of woody biomass in Ireland and Oregon to improve supply chain economics. COFE Annual Conference, New Bern, North Carolina. September 2012.

Nascimento, D.A., Anunciação Jr., R.M., Arnhold, A., Ferraz Filho, A.C., dos Santos, A., Zanuncio, J.C. (2016). Expert system for identification of economically important insect pests in commercial teak plantations, Computers and Electronics in Agriculture, Volume 121, February 2016, Pages 368-373

Nurmi, J. and Hillebrand, K. (2007). The characteristics of whole-tree fuel stocks from silvicultural cleanings and thinnings. Biomass and Bioenergy 31: 381–392.

Oja, J., Skog, J., Edlund, J. and Bjorklund, L. (2010). "Deciding log grade for payment based on X-ray scanning of logs," Proceedings of the Final Conference of Cost Action E35; The Future of Quality Control for Wood and Wood Products, http://cte.napier.ac.uk/e53.

Paccot, C. (2008). LOGMETER 4000. An example of whole-load scanning technology applied to Wood Measurement. Timber Measurements Society. Fall meeting. October 28-29 2008. Reno, Nevada.

Radiotis, T., Berry, R., Hartley, I.D. and Todoruk, T.M. (2008). Kraft Pulp and Paper Mill Utilization Options for Grey-Stage Wood Mountain Pine Beetle Working Paper 2008-09 MPBI Project # 8.50.

Rao, M., Wang, Q. and Cha, J. (1993). Integrated Distributed Intelligent Systems in Manufacturing. Chapman & Hall, London. 325 pp.

Riddering, J., Holden, Z.A., Jolly, W.M. and Warren, A. (2015). Smartphone applications for data collection, dynamic modelling and visualization in the wildland fire environment. Fire Management Today 74(3): 10-14.

Rolev, AM. (1988). SIWORK3, Version 1.1. Work study and field data collection system based on Husky Hunter handheld computer. Danish Forest and Landscape Research Institute, Lyngby, Denmark.

Röser, D., Mola-Yudego, B., Sikanen, L., Prinz, R., Gritten, D., and Emer, B. (2011). Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. Biomass and Bioenergy 35(10):4238–4247.

Routa, J., Kolström, M., Ruotsalainen, J., Sikanen, L. (2015). Precision Measurement of Forest Harvesting Residue Moisture Change and Dry Matter Losses by Constant Weight Monitoring. International Journal of Forest Engineering 26(1): 71–83.

Simpson, W.T. and Wang, X. (2004). Estimating air drying times of small-diameter ponderosa pine and Douglas-fir logs. Forests Products Journal 54(12): 24-28.

Sithole, B. (2005). New Method of Measuring the pH of Wood Chips [online]. In: Appita Conference and Exhibition (59th : 2005 : Auckland, N.Z.). 59th Appita Annual Conference and Exhibition: Incorporating the 13th ISWFPC (International Symposium on Wood, Fibre and Pulping Chemistry), Auckland, New Zealand, 16-19 May 2005: Proceedings. Carlton, Vic.: Appita Inc., 2005: 391-395.

Spinelli R., Magagnotti N., Paletto G. and Preti C. (2011). Determining the impact of some wood characteristics on the performance of a mobile chipper. Silva Fennica 45:85–95.

Tsehaye, A., Buchanan, A.H. and Walker, J.C.F. (2000). Sorting of logs using acoustics. Wood Science and Technology 34(4): 337-344.

Visser, R., Berkett, H. and Spinelli, R. (2014). Determining the effect of storage conditions on the natural drying of radiata pine logs for energy use. New Zealand Journal of Forestry Science 44(3).

Walsh, D. and Strandgard, M. (2014). Productivity and cost of harvesting a stemwood biomass product from integrated cut-to-length harvest operations in Australian *Pinus radiata* plantations. Biomass and Bioenergy 66: 93-102.

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