Final Report on SW Timber Hub Residue-Adapted harvest trial

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Executive summary

Previous studies have suggested that extraction of logging residue (LR) from a harvest site can reduce site preparation costs through removal of obstructions to equipment, though these cost savings need to be balanced against potential nutrient losses and additional costs to extract, chip and transport the LR. There have been few studies worldwide covering the full breadth of this topic and none conducted in Australia.

This report provides an analysis of integrated harvesting methods in a mature *Pinus radiata* plantation near Margaret River, Western Australia where logs and logging residue (LR) were harvested and extracted in a single operation. The analysis was conducted primarily through a harvesting study comparing log and LR harvest and extraction, LR chipping and transport and subsequent site preparation. Initial plans were to test the following harvest systems: Control site (current harvester/forwarder harvest system), Conventional harvesting (current harvester/forwarder harvest system for logs combined with forwarder extraction of scattered LR), Fuel-adapted harvesting (Harvester felling trees forward and processing them to the side of the harvester resulting in separate log and LR piles. Forwarder extraction of logs and LR) and Whole tree to roadside (Feller-buncher and skidder to fell and extract whole trees to roadside. Processor at roadside to process trees to logs). However, the trees were too large (mean tree size >2m^3 merchantable volume) to be safely felled to the front of the harvester for the Fuel-adapted harvest system. Instead, the harvester felled each tree to the side as in a conventional harvesting operation and then heaped the LR. This approach reduced the harvester productivity and increased its cost. LR was left to dry at roadside for several months over summer prior to chipping and transport.

Productivity models for each harvest machine were developed through time and motion studies. Harvest systems were balanced to provide a consistent basis to compare costs to harvest and extract logs and LR to roadside. A balanced harvest system is one where the productivity of each machine or group of like machines is matched within the harvest system. Chipping costs were determined from a separate time and motion study of the chipper and the excavator used to feed in LR. The Whole tree to roadside LR was too contaminated with soil to be chipped due to the processor passing over the LR pile while processing trees. After screening the chipped LR from the Conventional and Fuel-adapted harvest systems met the customer's (WAPRES) requirements for size distribution and bark proportion.

Site preparation approaches and costs for each of the tested harvest systems were determined through interviews with Forest Products Commission (FPC) staff. The standard FPC site preparation approach for harvest areas such as the Control study site was to heap and burn LR followed by light chopper-rolling and line mounding. Site preparation for the study sites where LR was extracted consisted of light chopper-rolling and line mounding.

Costs were also determined using the same assumptions as those in the current study for a study comparing conventional and fuel-adapted harvest systems conducted in 2017 near Lake Muir, Western Australia with a mean merchantable tree size of 1.2m^3 in which trees were felled forward of the harvester for the fuel-adapted harvest system.

Overall costs for harvesting and extracting logs and LR, LR chipping, transport and sale, and site preparation were lowest for the Conventional harvest system for the current study site and were lowest for the Fuel-adapted harvest system for the Lake Muir site.

A literature review of the distribution of nutrients in mature *P. radiata* plantation found that the majority of the macro-nutrients (over 80%-90% in most cases) were contained in the soil and leaf

litter. For the LR, the majority of the macro-nutrients were in the needles. Nutrient and organic matter losses from burning LR were found to potentially reduce tree growth in the next rotation on sites with low soil nutrients. The current study found that approximately 50% of the LR was retained onsite following extraction and chipping for the Conventional and Fuel-adapted harvest systems. A high proportion of the retained LR was likely to have been in the form of needles and small branches. This suggested that the quantity of LR retained on the site was sufficient to maintain site productivity on fertile sites, though this was not tested.

In karri forests LR is currently primarily treated by burning with consequent limitations to timing of site preparation and re-establishment and the potential of fire escapes and agricultural smoke tainting. As such, consideration could be given to testing the approach used in the current study of extraction and sale of LR in karri forest management.

Conclusions:

- Extraction and sale of LR from clearfell harvests in mature *P. radiata* plantations can potentially reduce site preparation costs.
- For stands with a mean tree size >2m^3, a conventional harvester/forwarder harvest system combined with LR extraction by forwarder is preferred due to safety concerns falling large trees forward of the harvester
- For stands with a mean tree size <2m^3, a fuel-adapted harvester/forwarder harvest system combined with LR extraction by forwarder is preferred as it had the lowest total cost
- LR retained in the proportions in the current study is unlikely to affect site productivity on fertile sites whereas removal of LR and leaf litter through burning may reduce growth of subsequent rotations.
- The approach used in the current study to reduce site preparation costs through LR extraction and sale could be tested to determine its applicability to karri forest management.

Introduction

Reduction of LR density onsite has also been shown to have the potential to reduce site preparation costs by removing the need to windrow and/or burn residues prior to ploughing (Strandgard and Béland 2021). However, removal of LR has associated costs for extraction, chipping and transport (Smidt et al. 2012) and reduces site nutrients and organic matter (Hopman and Elms 2009).

Logging residue (LR) for use as biofuel is characterised by high supply chain costs due to its attributes: low bulk, energy and spatial densities, high moisture content and high spatial and temporal variability in quantity (Ralevic et al. 2010, Richardson et al. 2002).

Previous studies have shown potential ways to reduce LR delivered costs:

- Aggregation of logging residue infield (fuel-adapted harvesting) (Strandgard & Mitchell 2019) or at roadside (whole tree processing at roadside) (Zamora Cristales et al. 2018). These approaches reduce primary transport costs and increase LR yield and spatial density.
- Drying infield or at roadside. Drying reduces secondary transport costs and increases net energy density. Erber et al. (2016) found that drying Beech energy logs prior to truck transport reduced transport costs by approximately 28%.
- Comminution prior to secondary transport. Chipping or grinding of logging residue considerably increases it bulk density, reducing its transport costs (Routa et al. 2013).
- Trucks with a higher volume capacity may reduce secondary transport costs by allowing a greater utilisation of the truck's weight capacity when transporting dried LR chips (Strandgard et al. 2021).

European biomass users may pay a premium price for chipped forest biomass with a low moisture content and low proportions of needles and bark. Spinelli and Magagnotti (2010) reported that this premium could be ≥15%.

Objectives

To develop a commercially viable method of residue harvesting which improves utilisation of harvested wood fibre and reduces site preparation costs for subsequent rotations.

1. Improve total recoverable volume of fibre through adaptive residue harvesting techniques
2. Conduct time and motion studies on the proposed alternative methods for collecting and processing harvest residue.
3. Determine the best economic option for site management (from harvest to replant phase) for the site types investigated.
4. Quantify remaining site debris as a percentage of the Total Standing Volume (TSV)
5. Determine a harvesting method that reliably delivers product to highest of export biomass or domestic biomass specifications.
6. Document the preferred harvest methodology to inform harvest contractors.
7. Undertake a series of workshops to inform industry of new harvest methods

Deliverables

1. Outcomes of desktop analysis of previous studies covering residue adaptive harvesting.
2. Desktop analysis on existing methods in Australia for site preparation with different levels of post-harvest residue.
3. Time and motion studies on three alternative methods for collecting and processing harvest residue.

4. Cost benefit analysis of each methods
5. Interviews with FPC officers concerning additional costs that will most likely be incurred in order to bring the site to a condition capable of effective re-planting (like for like analysis that includes costs of heaping, burning, chopper rolling, Bracke plough etc
6. The best economic outcome for site harvest to replant phase for the site types investigated.
7. Identify remaining site debris as a total volume and percentage of the stands Total Standing Volume (TSV)
8. Determine a method that reliably delivers product to highest of export biomass or domestic biomass specifications.
9. Determine/estimate cost of lowest specification biomass product
10. Develop a harvest methodology to inform harvest contractors.
11. Consideration/Discussion on applicability of the studied harvest and site preparation techniques to Karri forest silviculture.
12. Review of residue left on site and implications for soil nutrition
13. Chipping time and motion study and cost

1. Desktop study of previous residue adapted harvesting studies

Residue-adapted (or fuel-adapted) harvesting refers to the harvesting technique developed in Sweden in which trees are felled in the direction of harvester travel resulting in logging residues (LR) being left in piles rather than scattered on the site (Figure 1) (Strandgard and Mitchell 2019).

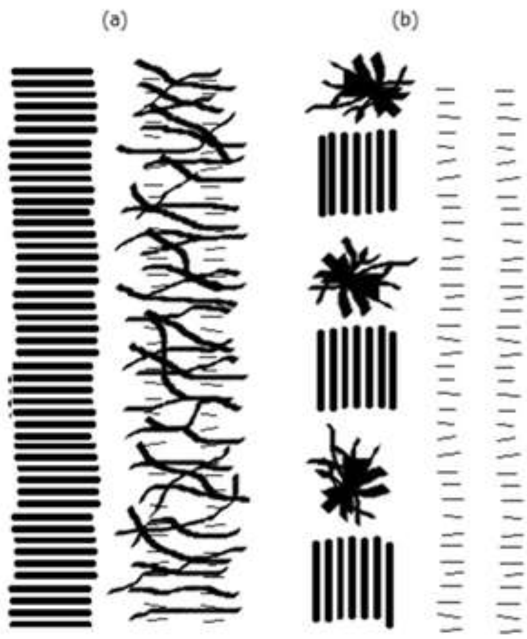

Figure 1. Log and logging residue arrangements on the (a) Conventional site; (b) Fuel-adapted site (Strandgard and Mitchell 2019).

In southern and central Sweden this approach is used for most final felling operations where LR is to be extracted. The concentration of LR in piles can considerably reduce the cost of transporting LR to roadside and increase the proportion of LR extracted (Strandgard and Mitchell 2019). The disadvantages are potential reductions in harvester and forwarder productivity when producing and extracting logs. The recent trial of residue adaptive harvesting in Australia (Strandgard and Mitchell 2019) found that harvester productivity was reduced by 15% and forwarder productivity by 11% (log extraction) for residue-adapted harvesting compared with conventional cut to length at the stump harvesting for a clearfell operation in a mature *Pinus radiata* plantation. The productivity reductions were likely to have reduced as the operators became more familiar with the fuel-adapted harvesting method. Thor and Berndt (1997) reported for a fuel-adapted final harvest in Sweden a reduction in harvester productivity of 7.5% (higher than expected), and an increase in forwarder productivity extracting logs of 2.5% compared with conventional harvesting. Published figures for forwarder productivity extracting LR showed it to be higher in the fuel-adapted harvest area than in the conventional harvest area, with corresponding reductions in extraction costs. However, the increase in productivity was considerably higher in two studies (Thor and Berndt (1997): 33%, Strandgard and Mitchell (2019): 39%) than that in the third study (Nurmi (2007): 12%). There was not enough information in the publications to determine the reason(s) for these productivity differences.

As log forwarders were not designed for logging residue transport, this is an area where changes can reduce extraction costs, such as use of different grapples (Eliasson and Nordén 2010) and larger load beds, which have achieved weight utilisation of up to 75% (Nurmi 2007; Eliasson et al. 2011). This compares with a forwarder weight utilisation of ~50% of nominal load capacity in the trial by Strandgard and Mitchell (2019). Frisch (2018) found that the productivity advantage of the residue forwarders increased with increasing extraction distance, however it may be uneconomic to extract residues where extraction distances are high (Jönsson et al. 2010).

The small piles created during fuel-adapted harvesting can dry to a lower moisture content than large stacks of LR extracted and stored at roadside (Nilsson et al. 2015). This approach can also leave more nutrient rich needles or leaves distributed on the site but can increase extraction costs and delay extraction if a machine needs to be returned to the site, reduce flexibility in the use of the LR and delay re-establishment (Nilsson 2016).

2. Desktop analysis on existing methods in Australia for site preparation with different levels of post-harvest residue.

Site preparation methods

Site preparation refers to the activities that take place after harvesting and before planting to achieve a high degree of seedling survival and high early growth rates to increase the number of potential final crop trees, rapidly achieve site occupancy and suppress weed growth. The site preparation methods appropriate for a site depends on factors including tree species, soil characteristics, slope, quantity and characteristics of LR (piece size, quantity) and weed coverage and type. The objective is to achieve the desired outcome for the least cost. Site preparation methods commonly used in *P. radiata* plantations are show in Table 1.

The first step in site preparation on most sites is to manage the LR to allow further site preparation activities and planting. The major methods to management LR include burning, windrowing, and chopper-rolling (Snowdon and James 2007). Spot cultivation can also be used to move LR from the planting lane and cultivate planting locations when LR level are not too high.

Historically, burning LR has often been the cheapest method to reduce/remove LR and provide access to planting and site preparation equipment (Turvey and Cameron 1986), though costs increase where LR is heaped or windrowed prior to burning (Costantini et al. 1997). More recently there have been considerable increases in burning costs (Dubois et al. 2001). There are many reasons for the increased costs including increased liability insurance costs and the need for detailed planning and notifications prior to burning (Anonymous 2012). Burning can cost up to $1000/ha for small areas (New Zealand Institute of Forestry 2005). Burning can also remove large proportions of a site's nutrients and organic matter (Section 12), create a smoke nuisance in populated areas and stimulate germination of some weed species (Hunt et al. 1999; Ward and Walsh 1988). The use of burning also restricts site preparation to times when the weather is suitable. Burning LR in Australia is likely to be applied to only 10% of the harvested plantation area (Snowdon and James 2008).

Pushing LR into windrows with an excavator or bull-dozer can be used to remove LR from planting lanes, and may not require burning.

Chopper-rolling is performed by towing a heavy, bladed roller over a harvested site to comminute LR and incorporate it into the soil (Carlyle et al. 1998). It has been widely adopted in plantation silviculture in Australia as a replacement for burning. The comminuted LR left after chopper rolling can reduce the effectiveness of ploughing (Smith et al. 1997) and impede access by planting crews though this will be dependent on the size, quantity and degree of incorporation of material left after chopper-rolling. High quantities of LR may require an additional machinery pass to clear planting lanes, even when the LR has been comminuted. The weight of the chopper-roller can determine its effectiveness in comminuting LR but heavier chopper-rollers increase soil compaction and cost. Costantini et al. (1997) found that in Hoop pine stands with very high LR levels (>200 oven dry tonne/ha), a 10 t chopper-roller flattened but did not chop LR, weeds and regenerating Hoop pine while a 17 t chopper-roller comminuted LR up to 15 cm in diameter. Multiple passes of a lighter chopper-roller may be required to achieve the desired comminution. Leitch and Farrell (1980) found that a 12t chopper roller comminuted LR on a site with >200t of woody LR by using two passes of the chopper-roller, the first at 45 degrees to the planting rows and the second in line with the planting rows. The first pass spread the LR exposing uncomminuted LR.

Cultivation of forest sites refers to mechanical breaking up of soil and weed cover to create a favourable environment for tree establishment and growth. It is often performed to ameliorate soil compaction from machinery movements over the site during thinning and clearfell (Mason et al. 1993) or to break through a hard soil layer as soil strength above 3MPa can severely restrict root growth (Greacen and Sands 1980). Cultivation can also improve tree growth by concentrating organic matter and nutrients into the planting line (Attiwill et al. 1985), reducing weed competition and improving drainage by mounding poorly drained sites (Morris & Lowery 1988). Some type of cultivation is performed on the majority of plantation sites as many studies have found that it produces superior growth and survival compared with no cultivation (Hjelm et al. 2019; Laffan et al. 2008; Mason et al. 1993; Morris & Lowery 1988; Simcock et al. 2006; Will et al. 2002). Cultivation did not improve tree survival and growth on some study sites, such as on non hard-setting soils in Queensland (Costantini et al. 1995) and light, well-drained soils in New Zealand sites (Mason and Cullen 1986; Mason et al. 1996; Mason & Milne 1999).

In sites where conventional cultivation cannot be used or is undesirable such as steep slopes and/or erodible (Laffan et al. 2003) or stony soils (Roberts et al. 2015), spot cultivation can be performed but can be an expensive option due to its slow area coverage, particularly when LR levels are high (Hall et al. 1997). LR may be pushed away from the planting line during spot cultivation to allow safe access by planting crews. On dry, well-drained sites in the Green Triangle, spot cultivation was found to increase survival of *P. radiata* seedlings compared with mounding with no difference in growth (Forestry SA 2008, as cited in Pinkard and Bruce 2011).

Site preparation appropriate for different LR levels

There is little published information regarding suitability of site preparation methods for varying quantities of LR. A major reason for this is likely to be that differences in the characteristics of LR (including the proportion of long and/or thick pieces, species (differences in hardness and flexibility) and time since felling/moisture content) affect the performance of site preparation methods. For a given quantity of LR, the proportion of thick and/or long pieces are the most important characteristics in terms of its impact on site preparation activities as they obstruct the movement of machines and people across the site. While there is no agreed upon definition, material more than several centimetres in diameter is commonly referred to as coarse woody debris (CWD).

Berry and Sessions (2020) examined the site preparation methods suitable for three spatial densities of CWD: High, Medium and Low

High levels of CWD (>35t/ha) are commonly found after clearfell operations in mature *Pinus* plantations. The proportion of CWD is typically higher on sites with high minimum small end diameter (SED) values for pulp logs (Ximenes et al. 2012). High-levels of CWD generally require treatment to allow access for planting or other site preparation activities. Potential approaches to reduce the quantity of CWD include burning, windrowing, chopper-rolling and spot cultivation. As noted above, chopper-rolling may require an additional machine pass to clear planting lanes, incurring an additional cost.

High levels of CWD may also result from legacy native forest CWD that was originally broadcast burnt. In some cases, it may be necessary to heap and burn this CWD to allow machine access (Snowdon and James 2008).

Medium levels of CWD (15-35t/ha) are common for *P. radiata* sites with a low minimum SED value for pulp logs and on cut to length at the stump plantation eucalypt sites. Treatment options include windrowing, chopper-rolling (potentially with additional clearing of planting lanes) and spot cultivation.

Low levels of CWD (<15t/ha) are common for whole tree to roadside operations. For small diameter, brittle CWD, these sites could be cultivated without further treatment (Strandgard and Béland 2021). Roadside LR can be heaped and burnt or cleared from the planting lanes.

Table 1. Site preparation methods commonly used in *P. radiata* plantations (Mead 2013).

Methods[a]		Slope	Soil factors ameliorated						Frost	Vegetation type				Cost[b]
			Shallow hard pan	Compact surface	Poor drainage	Very dry sands	Erodible	Fertility		Herbs and pasture	Bracken fern	Woody weeds	Logged site	
Hand	Clear	Any										* S, B		H
	Release/ line-cut	Any									*S	* S		M
	Fertilizer – individual tree	Any						**						L[b]
Mechanical	Towed roller (R)	<20°										** S, B	*** S	M
	Gravity roller (R)	>15°										** S, B	*** S	M/H
	Root-rake windrow (V)	<30° c										*S	** S	M/H
	V-blade (V)	<20°			* [d]				*S[d]				S	M
	Line or V-rake (V)	<25° c											** S	M
	Rotary slash	<20°										*S		M
	Discing (D)	<20°		**						*S	*S			H
	Ripping (R)	<15°	*** [e]	*** [e]	** [ef]						*S			M
	Rip/mound (R)	<15°	*** [de]	*** [de]	***[def]				***S[d]	**S	* S	*S	* S	L to H
	Spot clear/ cultivate	<30°	** [e]	*** [e]	** [ef]		**						** S	M
	Line furrow (F)					**S[e]								M
Chemical	Aerial spray (S)	Any							*	* [g]	**D	** R, V	** R, V	L[b]
	Band spray (S)	<15°				***				***	**D	** R, V	** R, V	M[b]
	Spot spray (S)	<70°				***				*** [g]	**D	R,V	** R, V	L[b]
Burn	(B)	Any										** R, S	R, S	L to H
Graze		Any								**S [g]		S		L
Over-sow		Any					**					** S, R, B	** S, R, B	L/M

Note: a = asterisks suggest suitability, and capital letters indicate likely combinations of establishment techniques. * = some suitability, ** = moderately suitable, and *** = very suitable. For example, rollers are moderately suitable for woody weeds such as gorse, but are very suitable for macerating logging slash. Likely combinations with other treatments are given using capital letters. For example, spraying for weeds (S) is often combined with other site preparation treatments; b = cost, where L = low cost (< US$300/ha), M = moderate cost ($US300–600/ha), H = high cost (>US$600/ha). The chemical cost of fertilizer or weedicide is not included; c = slope limitations: bulldozer – <25° degree slope; excavator – < 35° slope. Excavators are usually cheaper and do less soil damage; d= trees planted on mound; e = if there is heavy logging slash, there may also be a need for a V-rake or V-blade or similar. An alternative may be to use an excavator for spot cultivation; f = drainage is improved if hardpan is broken; g = including pampas grass (*Cortaderia* species).

3. Time and motion studies on three alternative methods for collecting and processing harvest residue

Results are presented for:

- Productivity of each harvest machine in each harvest system
- Shift-level productivity of “balanced” harvest systems
- Cost per tonne or m^3 of logs loaded on trucks and LR delivered to roadside
- Chipping productivity and cost

Methodology

Harvest machine productivity

Time and motion studies were conducted to compare three harvesting systems (cut to length at the stump (Conventional), fuel-adapted harvesting and whole tree to roadside) producing logs and LR on adjacent sites in a mature *P. radiata* plantation near Margaret River (latitude -33.922, longitude 115.074) in SW Western Australia. A further time and motion study was conducted of the excavator and chipper used to chip the recovered LR directly into trucks.

The trial was conducted between October 2020 and February 2021. Details of the study sites are shown in Table 2. Site slope was <5°.

Table 2. Study site characteristics

Attribute	Conventional	Fuel-adapted harvest	Roadside processing
Area (ha)	1.93	1.90	1.18
Mean tree height (m)	34.8	35.5	36.3
Mean tree dbhob* (mm)	472	504	487
Mean tree merchantable volume (m^3)#	2.1	2.5	2.4

* Diameter at Breast Height Over Bark

Calculated from the approximately 100 trees used to determine harvest machine productivity on each study site

Balanced system productivity and cost

Balancing harvest systems refers to adjusting the number and/or utilisation of the machines in each harvest system to match their productivity at a shift level within ±10%. This takes into account that harvest systems in a trial may not represent a production harvest system for the mean tree size of the study site and hence allows a more realistic comparison of the cost and productivity of each harvest system.

Shifts were assumed to be 10 hours in length and utilisation rates were generally between 60%-85%. The exception was the feller-buncher which was assigned a utilisation rate of 39% due to its very high productivity. Shift level productivity was set to that of the machine or machine type in each harvest system with the lowest productivity.

As the LR was removed independently of the logs and left at roadside for later chipping and transport, there were no machine interactions. As such, the forwarders were assigned a utilisation rate of 75% for performing LR extraction.

The chipper study period was too short to accurately determine its utilisation rate. Therefore, a utilisation figure of 75% was used based on Spinelli and Visser (2009).

Cost calculations were based on the method described in Miyata (1980).

Trial machines

Details of the machines used in the trial are in Table 3. All operators were experienced in the operation of their machines. Productivity for the harvester/feller-buncher/roadside processor was determined from samples of approximately 100 numbered trees. The harvester used on the Conventional and Fuel-adapted harvest sites was used in the role of a feller-buncher on the whole tree to roadside site. Whole trees were transported to roadside by skidder and logs and LR by forwarder. LR was chipped at roadside directly into trucks.

Table 3. Trial machine details

Machine type	Make and model	Engine hours
Harvester, feller-buncher, roadside processor	Cat 541 (tracked) with a Waratah 624c harvester head	22500
Forwarder	John Deere, 1910e, with Intelligent Boom Control (IBC)	2900
Skidder	Tigercat 620c	14000
Chipper	Peterson 4310	9500
Excavator (feeding chipper)	Volvo EC240CL	u/k

Analysis

Machine cycle and elemental times were determined using tablet-based time and motion study software (www.laubrass.com/umtplus). Definitions of each element are provided in Appendix 1. The sum of the elemental times that cannot be assigned to a particular cycle (Travel, Brush and clear and Stacking) was divided by the number of study trees and added to each cycle time.

Productivity for the harvester, feller-buncher and roadside processor was determined by dividing the merchantable tree volume for each study tree by the corresponding cycle time excluding delays (cubic metres per productive machine hour without delays (m^3/PMH_0)). For the harvester and roadside processor merchantable tree volume was determined by summing merchantable log volumes from StanForD stm or pri files for each study tree. The tree volumes estimated from the supplied tree volume model were significantly lower (~10%) than those obtained by summing merchantable log volumes obtained from StanForD data files. Therefore, for the feller-buncher a model was developed relating dbhob and tree height from inventory data on the Conventional and Fuel-adapted harvest sites with the corresponding StanForD merchantable tree volumes

$$MerchVol = -4.548 + 0.008847 \times DBHOB + 0.0709 \times Ht \quad R^2_{adj} = 94\%$$

Where:

MerchVol is merchantable tree volume (m^3)

DBHOB is tree diameter measured at breast height over bark (mm)

Ht is total tree height (m)

Forwarder LR load weights were determined by summing grapple load weights determined using grapple scales.

Forwarder productivity was determined by dividing the load weight for each cycle (green metric tonnes (GMt)) by the corresponding cycle time excluding delays. Load weights were obtained for a number of the cycles using the forwarder's grapple scale. Load weights for the remaining cycles were estimated using the mean log volumes for the sawlog length categories used at the harvest sites (long (0.58m^3), medium (0.32m^3) and short (0.31m^3)) and chiplogs (0.11m^3) calculated from log volume data in StanForD data files. Log weight was estimated using a 1:1 ratio of log volume and weight. There was close correlation between the measured load weights and the corresponding estimates from log volumes.

Skidder productivity was determined by dividing the mean load volume (m^3) for each cycle by the corresponding cycle time excluding delays. Mean load size (2.35 m^3) was calculated by dividing the sum of the merchantable volume of the studied trees by the number of skidder cycles.

Chipper productivity was determined by dividing the load weight (t) of each truck by the chipper operating time (delay free hours) required to load it.

Linear regression was used to model the relationship between machine productivity and merchantable tree volume for the harvester, feller-buncher and roadside processor. Trees identified as outliers were removed from the analysis. Goodness of fit measures were R^2_{adj}, mean absolute percent error (MAPE) and root mean square error (RMSE). Regression models and individual variables were statistically significant. Where regression models contained more than one variable, the maximum variable inflation factor value was 5.

If the dependent variable was log transformed, the model was corrected for bias using the approach of Snowdon (1991) and goodness of fit measures were calculated using back-transformed values.

Results

Harvest machine productivity

Conventional harvest

Conventional harvest site machine productivity results are shown in Table 4.

Table 4. Productivity models, goodness of fit values, sample size and mean productivity, load size and distance for machines on the Conventional harvest site

Machine	Model	Mean productivity	Sample size	Mean load size	Mean distance (m)
Harvester	$HProd = 74.24 \times MerchVol^{0.626}$ R^2_{adj} = 75%, MAPE = 13%, RMSE = 11.6	113 m^3/PMH$_0$	100	-	-
Forwarder (Logs)	$FProd = 9.23 - 0.065 \times Dist + 2.7 \times Wt$ R^2_{adj} = 92%, MAPE = 7.6%, RMSE = 5.2	64.4 t/PMH$_0$	42	25.6	213
Forwarder (Residue)	$FProd = 4.6 + 1.93 \times Wt$ R^2_{adj} = 60%	13.1 t/PMH$_0$	23	4.5 t	167

Where:

HProd is the harvester productivity (m^3/PMH$_0$)

MerchVol is the merchantable volume of the tree (m^3)

FProd is the forwarder productivity

Dist is half the sum of the travel empty and loaded distances (m)

Wt is the load weight

Fuel-adapted harvest

Fuel-adapted harvest site machine productivity results are shown in Table 5.

Table 5. Productivity models, goodness of fit values, sample size and mean productivity, load size and distance for machines on the Fuel-adapted harvest site

Machine	Model	Mean productivity	Sample size	Mean load size (t)	Mean distance (m)
Harvester	$HProd = 42.97 \times MerchVol^{0.649}$ R^2_{adj} = 69%, MAPE = 15%, RMSE = 22.5	76 m^3/PMH_0	100	-	-
Forwarder (Logs)	$FProd = 23.44 - 0.079 \times Dist + 2.36 \times Wt$ R^2_{adj} = 86%, MAPE = 7.9%, RMSE = 5.8	64 t/PMH_0	42	23.7	195
Forwarder (Residue)	$FProd = 10.96 - 0.0334 \times Dist + 2.9 \times Wt$ R^2_{adj} = 70%	22.1 t/PMH_0	24	5.5	155

Where:

HarvProd is the harvester productivity (m^3/PMH_0)

MerchVol is the merchantable volume of the tree (m^3)

ForwProd is the forwarder productivity

Dist is half the sum of the travel empty and loaded distances (m)

Wt is the load weight

The low mean productivity for the harvester resulted from the harvester operator collecting LR into piles, increasing the cycle times (see Summary). The mean productivity was also calculated using the mean Stacking and Brushing time for the Lake Muir fuel-adapted harvest study (Strandgard and Mitchell 2019): 105 m^3/PMH_0.

Whole tree to roadside harvest

Whole tree to roadside harvest site machine productivity results are shown in Table 6.

Table 6. Productivity models, goodness of fit values, sample size and mean productivity, load size and distance for machines on the whole tree to roadside harvest site

Machine	Model	Mean productivity	Sample size
Feller-buncher	$FBProd = 115.16 \times 1.39^{MerchVol}$ R^2_{adj} = 35%, MAPE = 23%, RMSE = 76.4	263 m^3/PMH_0	101*
Skidder	$SkidProd = 73.69 - 0.1611 \times Dist$ R^2_{adj} = 56%, MAPE = 14.7%, RMSE = 9.2	52 m^3/PMH_0	44
Roadside processor^	$RPProd = 75.3 \times MerchVol^{0.6}$ R^2_{adj} = 36%, MAPE = 27%, RMSE = 37.4	117 m^3/PMH_0	107*

* The number of trees processed by the roadside processor was greater than the number felled by the feller-buncher because some trees split during felling and were processed as separate trees.

^ The model was developed using a value of 2% of total time for Brushing/Clearing based on previous studies as the value in the current trial (~12%) resulted from delays supplying trees with a single skidder.

Where:

FBProd is the feller-buncher productivity (m^3/PMH_0)

MerchVol is the merchantable volume of the tree (m^3)

SkidProd is the skidder productivity (m^3/PMH_0)

Dist is half the sum of the Travel unloaded and Travel loaded distances (m) (Mean value = 133m)

RPProd is the roadside processor productivity (m^3/PMH_0)

Balanced system productivity and cost

Conventional harvest

Shift-level balancing of the Conventional harvest system required addition of a forwarder to match the harvester productivity. Although the forwarder did not load trucks during the Conventional harvest, several hours of truck loading were allowed for in the system balancing.

Fuel-adapted harvest

No additional machines were added to the balanced Fuel-adapted harvest system.

Whole tree to roadside harvest

A grapple skidder and a loader were added to the Whole tree to roadside harvest system to balance the system. Loader productivity was set to 100 m^3/PMH_0 based on Ghaffariyan et al. (2012).

Shift level productivity and cost to harvest and extract logs and extract LR to roadside are shown in Table 7.

Table 7. Shift level productivity and cost for each harvest system and LR extraction to roadside

Harvest system	Logs		Logging residue
	Productivity(m^3/shift)	Cost (AUD/ m^3)	extraction cost (AUD/ m^3)
Conventional	791	7.1	17.4
Fuel adapted	451	8.6	10.6
Whole tree to roadside	884	11	0

Chipper and excavator

As the chipper and excavator operated as a single unit, they were assumed to have the same productivity ($43t/PMH_0$). Using the chip MC value supplied by WAPRES, the oven dry productivity was $38ODt/PMH_0$. The combined cost for the chipper and excavator was determined to be AUD8.2/t.

Summary

The balanced Conventional harvest system had the lowest cost to harvest, extract and load logs on trucks. However, the forwarder extracting LR on the Conventional site had the lowest productivity and highest cost per m^3 and extracted the least quantity of LR.

The balanced Fuel-adapted harvest system was considerably less productive than the Conventional site harvest system to harvest, extract and load logs on trucks, however, costs did not increase by the same proportion as the balanced system had only two machines compared with three for the balanced Conventional harvest system. The low productivity of the Fuel adapted harvest system resulted from the harvester felling trees to the side of the harvester as the trees were too large to safely fell forward of the harvester. The LR was then gathered into piles using the harvester increasing cycle time duration. When the harvester cycle times were adjusted using the mean stack and brush times from the Lake Muir fuel-adapted harvest trial (Strandgard and Mitchell 2019), the harvester productivity was much closer to that for the Conventional harvest system. However, this adjustment does not take into account reductions in harvester and forwarder productivity when operating in a fuel-adapted harvest system noted in the Lake Muir trial and other published studies (see Section 1). Strandgard and Mitchell (2019) suggested that these reductions in productivity were partly related to inexperience in fuel-adapted harvesting, though Swedish studies suggest that there is typically a reduction in both harvester and forwarder productivity when conducting a fuel-adapted harvest. Strandgard and Mitchell (2019) noted that two factors reduced the harvester productivity: greater moving/positioning time and greater felling time. The moving/positioning time increase was related to selecting trees in front rather than to the side of the harvester which is likely to reduce with experience, while the felling time included dragging the tree across to the side of the harvester, which is likely to remain the same over time as it is an inherent part of the operation in fuel-adapted harvesting. In the same study, the reduced forwarder productivity extracting logs in the fuel-adapted harvest system was related to poor product separation requiring the operator to sort logs either in the field or at the landing. As product separation is limited by the space available when logs are stacked in line with the direction of machine travel, some level of reduction in forwarder productivity is likely to remain, even with increased operator experience.

Forwarder productivity extracting LR in the current trial was lower and extraction costs were higher than that for the fuel-adapted harvest trial reported by Strandgard and Mitchell (2019) because the mean load weights in that trial were greater than those in the current trial. This may have been caused by denser LR or larger volumes of LR per load in the trial by Strandgard and Mitchell (2019), though these factors were not measured.

The Whole tree to roadside harvest system was the most productive of the three tested system to harvest, extract and load logs on trucks and had the lowest cost to extract LR to roadside. However, its log production costs were considerably higher than those for the other two harvest systems due to the larger number of machines in the balanced system. This type of harvest system gains the most advantage over harvester/forwarder harvest systems when handling small trees as the feller-buncher and skidders can handle multiple trees. In a trial in plantation eucalypts, the balanced whole tree to roadside harvest system was considerably cheaper than the harvester/forwarder harvest system (Strandgard et al. 2019).

The quantity of LR removed per unit area can influence the delivered costs. Cutshall (2012) found that delivered costs declined considerably (35%) as tons per acre increased from 20 to 50 tons though the mechanism for this cost reduction was not detailed in the study.

4. Cost benefit analysis of each method

The cost per hectare to harvest and deliver logs and LR to roadside for each harvest system was calculated from cost data presented in Section 3 and the retained LR and total standing volume data presented in Section 7 (Table 8).

Table 8. Log harvest and extraction cost per hectare, LR extraction costs per hectare and total log and LR harvest and extraction cost per hectare.

Harvest system	Harvest + extraction cost (AUD/ha)	LR extraction cost (AUD/ha)	Total cost to harvest and extract logs and LR to roadside (AUD/ha)
Conventional	5538	974	6512
Fuel adapted	6708	774	7482
Whole tree	8580	0	8580

The Conventional harvest system was the cheapest system in terms of total cost per hectare to harvest and extract logs and LR to roadside. The Fuel-adapted harvest system had a lower cost to extract LR to roadside than the Conventional harvest system but this had little impact on the overall cost per hectare for harvesting and extracting logs and LR to roadside as LR extraction costs were less than 20% of the log harvest and extraction cost. Similarly, the Whole tree to roadside harvest system had the highest overall log and LR harvest and extraction costs even with a zero cost to extract LR to roadside. The other disadvantage of the Whole tree to roadside harvest system was that it required five machines to achieve a balanced system compared with three machines for the Conventional harvest system, which would have increased the costs to transfer machines between sites and require recruitment and retention of a greater number of operators. Use of grapple skidders may also have displaced the leaf litter layer over a substantial proportion of the site along with its considerable reservoir of nutrients and organic matter (Section 13). Whole tree to roadside harvest systems can be cost-competitive with harvester/forwarder harvest system on sites with smaller tree sizes where the multi-tree handling capabilities of the feller-buncher and grapple skidders increase their productivity (Strandgard et al. 2019).

As noted in Section 3, harvest costs for the Fuel-adapted harvest system were inflated due to the harvester operator using the harvester to stack the LR. However, the Fuel-adapted harvest system also reduces forwarder productivity (Strandgard and Mitchell 2019), which did not occur in the current study as the logs were stacked in the same layout as in the Conventional harvest system. In the Strandgard and Mitchell (2019) study the cost to harvest and extract logs to roadside for the Fuel-adapted harvest system was approximately 15% higher than that for the Conventional harvest system, compared with a cost increase of approximately 21% for the current study. A 15% cost difference in the current study would only have reduced total log and LR harvest and extraction costs by approximately $350/ha.

The Conventional harvest system extracted less LR per hectare than the Fuel-adapted harvest system and had a higher extraction cost per tonne. Further research could be conducted into modifying the Conventional harvesting system approach to reduce LR extraction costs and increase the proportion of LR recovered. One approach would be use of modified forwarder bunks as the load sizes were approximately one quarter of the forwarder's weight capacity.

5. Interviews with FPC officers concerning additional costs that will most likely be incurred in order to bring the site to a condition capable of effective re-planting (like for like analysis that includes costs of heaping, burning, chopper rolling, Bracke plough etc

Interviews were conducted by Brad Barr with FPC officers (Graeme Hobson, Joeri Mak, and Brad Noonan) to determine alternative site preparation approaches for the study sites and the cost per hectare of each site preparation activity. This information was used in the next section.

6. The best economic outcome for site harvest to replant phase for the site types investigated.

The total cost per hectare of log and LR harvest and extraction costs, LR chipping and transport costs, LR chip sale returns and site preparation costs for each of the trial harvest systems compared with that for the current practice (Control) is shown in Table 9. Harvest costs are shown as the additional cost for each treatment compared with the Control harvest system costs. The Conventional harvest system costs (harvester/forwarder for log harvest followed by forwarder extraction of LR to roadside) were the lowest for the tested systems. The additional machines required to obtain a balanced harvest system resulted in considerably greater costs for the Whole tree to roadside system compared with those for the other harvest systems. However, the LR was not extracted for the Whole tree to roadside system in the current trial. Based on the LR chipping, transport and sale figures for the other harvest systems (Table 9), collection of LR from the Whole tree to roadside site would have reduced total costs by several thousand dollars per hectare. Costs for the Fuel-adapted harvest system were inflated because the harvester operator was unable to safely fell the large trees at the study site forward of the harvester.

For the current study, given the same costs and other assumptions, the breakeven LR sale price (equal total costs for the Control and Conventional harvest systems) for the chipped LR for the Conventional harvest system was $30/ODt.

Table 9. Study site cost (AUD/ha) of harvest (additional cost compared with Control harvest system), LR extraction and chipping, site preparation activities and the total LR extraction and site preparation cost for each harvest system. (Costs shown as negative values)

Harvest system	Harvest cost ($/ha)*	Logging residue costs and returns ($/ha)				Site preparation costs ($/ha)				Total cost ($/ha)
		LR extraction	Chipping cost	Transport cost	LR sale	Rough heap	Burning	Light CR	Line mound	
Control	0	0	0	0	0	-800	-120	-280	-260	-1460
Conventional	0	-974	-205	-399	2197			-280	-260	79
Fuel Adapted	-1170	-774	-263	-514	2826			-280	-260	-435
Whole Tree	-3042	0	0	0	0			-280	-260	-3582

* Additional cost compared with Control harvest system cost

Assumptions

LR extraction based on green MC (43% MC)

Chipping and transport costs were based on truck load weights recorded in the study for each trial harvest system converted to tonnes per hectare

Chip secondary transport cost: $0.16 tonne km for 100km transport distance.

LR sale price: $100 ODt

The results for the Fuel adapted study at Lake Muir (Strandgard and Mitchell 2019) were reanalysed assuming the LR chipping, transport and sale unit costs were the same as for the current study and the same site preparation processes were carried out as for the current study (Table 10). This allowed a comparison between the current study site which had a large mean tree size (>2m^3 merchantable volume) and the Lake Muir site which had a smaller mean tree size (1.2m^3 merchantable volume). For the Lake Muir study, the Fuel-adapted harvest system had the lowest cost for the tested harvest systems. In the Lake Muir study the harvester operator was able to fell each tree forward of the harvester leaving the LR and logs piled separately.

For the Lake Muir study, given the same costs and other assumptions, the breakeven LR sale price (equal total costs for the Control and Fuel-adapted harvest systems) for the chipped LR for the Fuel-adapted harvest system was $21/ODt.

Table 10. Lake Muir study site (Strandgard and Mitchell 2019) cost (AUD/ha) of harvest (additional cost compared with Control harvest system), LR extraction and chipping, site preparation activities and the total LR extraction and site preparation cost for each harvest system. (Costs shown as negative values)

Harvest system	Harvest cost ($/ha)*	Harvest residue costs and returns ($/ha)				Site preparation costs ($/ha)				Total cost ($/ha)
		LR extraction	Chipping cost	Transport cost	LR sale	Rough heap	Burning	Light CR	Line mound	
Control	0	0	0	0	0	-800	-120	-280	-260	-1460
Conventional	0	-559	-205	-272	1390			-280	-260	-186
Fuel Adapted	-135	-545	-271	-359	1830			-280	-260	-20

* Additional cost compared with Control harvest system cost

These costs need to be considered in conjunction with the losses of nutrients and organic matter (and potentially tree growth) from LR removal particularly from burning (Section 13).

Alternative site preparation approaches could be investigated in further studies, including removing the chopper-rolling from the LR extraction sites and using heavy chopper-rolling and spot mounding instead of heaping and burning when LR is retained.

7. Identify remaining site debris as a total volume and percentage of the stands Total Standing Volume (TSV)

The LR remaining on each study site at the end of the study was sampled by selecting ten plot locations at random from fifty possible plot locations arranged in a grid across each study site. Each grid was aligned at an angle to the planting rows to avoid bias in LR accumulation associated with the direction of movement of harvesting machines. On each of the ten plots, a 1m x 1m square was placed on the ground and all the LR within the square was removed and weighed. On several plots on each site, the LR was divided into stem wood, large branches (>30mm), small branches (<30mm), twigs and needles, cones and bark and each component was weighed separately.

Total standing volume (TSV) of 780 m^3/ha was estimated from the total recovered volume per hectare supplied by FPC (710m^3/ha) with an adjustment of 10% to give TSV and from StanForD pri file data for approximately 50 trees in the study area.

Quantities of LR retained, extracted and chipped, total LR and retained LR as a percentage of TSV are shown in Table 11. LR retained, extracted and total LR GMt figures were based on an MC of 43%. Chipped LR figures were obtained from the truck weight data and were based on an MC of 12%.

Table 11. Quantity of LR (Green Metric tonne (GMt)/ha and Oven Dry tonne (ODt)/ha) extracted (sum of LR forwarder load weights), LR retained, total LR and retained LR as a percentage of TSV. Extracted and retained LR values are also shown as a percentage of the total LR (in brackets).

Harvest system	LR retained		LR extracted		Total LR		Chipped LR		Retained LR as % of TSV	
	GMt/ha	ODt/ha	GMt/ha	ODt/ha	GMt/ha	ODt/ha	GMt/ha	ODt/ha	GMt/ha	ODt/ha
Conventional	29 (34%)	16.5	56 (66%)	31.9	85	48.4	25	22	3.7	2.1
Fuel-adapted	24 (25%)	13.7	73 (75%)	41.6	97	55.3	32	28	3.1	1.8
Whole tree to roadside	20	11.4	-	-	-	-	-	-	2.6	1.5

The LR plot data on each study site were compared using a one-way ANOVA ($p = 0.05$) which showed that there was no significant difference between the quantities of LR retained on each site. This reflected the high variability of LR quantities across each trial site.

Total LR quantities reported in the fuel-adapted harvest trial by Strandgard and Mitchell (2019) are shown in Table 12. Total LR quantities in that study were similar to the total LR quantities in the current study. LR recovery on the fuel-adapted site in their study (68%) was similar to that in the current study whereas that on the LR conventional site was considerably less (42%).

Table 12. Retained, recovered and total LR (green and oven dry (OD) tonnes per hectare). Retained and recovered LR are also shown as a percentage of the total LR. (Strandgard and Mitchell 2019).

Harvest system	LR retained (green/OD) (%)	LR extracted (green/OD) (%)	Total LR (green/OD)
Conventional	61/28 (58%)	43/20 (42%)	104/48
Fuel-adapted	28/13 (32%)	58/27 (68%)	86/40

LR recovery percentages reported by Nurmi (2007) were similar for the fuel-adapted harvest site (79%) and lower, but closer, for the conventional harvest site (58%). Retained LR quantity was similar to that retained after extraction of scattered LR on a clearfelled mature *P. radiata* plantation site by a Bruks terrain chipper (Ghaffariyan et al. 2014).

8. Determine a method that reliably delivers product to highest of export biomass or domestic biomass specifications.

The intended use of the chipped LR from the current study was for direct combustion, which is the major use of forest biofuels worldwide. Other potential biofuel uses include conversion to pellets, gasification and pyrolysis. All of these alternatives require a lower feedstock MC than boilers (~10%) which cannot be achieved by natural drying, though delivering feedstock with a low MC will reduce the requirement for artificial drying. Pellet production requires a small particle size (several millimetres across) that is achieved by grinding at the pellet mill (Lehtikangas 1999) whereas pyrolysis and gasification can accept chips of the size produced in the current study (Lim et al. 2008, Campbell et al. 2018). Pellet dies can also be rapidly worn by forest biomass sand contamination (de Wet et al. 2016). The suitability of the feedstock for these alternative uses would require further studies as there are numerous attributes of both the feedstock and the further processing that affect the cost and efficiency of the process and quality of the outputs.

In addition to use of LR as biofuel, Iwakiri et al. (2017) reported that *Pinus taeda* LR (branches, tree tops, stumps and roots) could be used in a 50/50 mix with pine woodchips to manufacture particleboard with equivalent properties to particleboard made from 100% pine woodchips. The potential for addition of chipped and screened LR such as produced in the current study to produce particleboard would need to be tested.

Solid biofuel quality standard

The international standard for solid biofuels is ISO 17225-1. The industrial biofuel component of the ISO standard was under development at time of writing. The non-industrial component (boilers <500kW) will be used in this section to illustrate woodchip biofuel quality requirements.

The main quality criteria for chipped LR are moisture content (MC), particle-size distribution and ash content.

1. Moisture content is the key variable used to describe chipped LR quality as it determines its net calorific value as energy is used to boil off moisture contained in biofuels during combustion. Chipped LR purchasers may vary payment rates with MC to reflect its energy content (Erber et al. 2012).

   In general, larger boilers are more tolerant of high and variable chip MC than small boilers, though the preference is for consistent MC to avoid changes to boiler settings (Kofman 2006). Boiler efficiency can be considerably increased through use of lower moisture content LR (Prasertsan and Krukanont 2003).

2. Specifications for particle size distribution can vary between purchasers. These specifications set minimum proportions within desired size classes and maximum proportions for oversize chips, fines and bark. Smaller boilers typically require smaller chips while feed mechanisms on larger boilers are more tolerant of oversize chips (Kofman 2006). The ISO standard for particle size covers woodchips and hog fuel. The classes are specified in terms of the maximum chip size from 16mm to 300mm. At least sixty percent of the chips must be between 3.15mm and the specified maximum chip size. Limits are also placed on the percentage of oversize chips and fines. Bark content is not part of the ISO standard specification for biofuel woodchips, though it is covered in effect through limits on ash production, as bark is a major source of ash.

3. One of the important factors in determining the quality of LR for use in producing bioenergy is the production of ash during combustion, which can reduce boiler efficiency and increase required maintenance (Deboni et al. 2019). Bark and needle content and LR contamination with soil, particularly containing sand, have been found to be major sources of ash production in forest biomass boilers (Werkelin et al. 2005; Rodríguez et al. 2021). Soil and sand contamination have been found to be responsible for the majority of Si, Al and Fe in LR (Werkelin et al. 2005). As well as contributing to ash production, soil and sand contamination can increase wear on biomass processing equipment (Lacey et al. 2018).

   As ash is largely a function of non-woody components of LR, minimising ash requires maximising woody components and/or minimising non-woody components. Bark proportion increases as branch diameter decreases (Ximenes et al. 2012).

Method to produce high quality biomass

1. Moisture content

   Natural drying of LR prior to chipping is the simplest, low-cost means of increasing the quality of the LR chips. Drying of LR at the trial site over summer considerably reduced its MC from a mean value of 43% for fresh LR to a mean MC of 12-16% for the delivered LR chips. Although the rate of drying was not measured at the trial site, based on a previous study (Strandgard et al. 2020), the majority of the moisture loss was likely to have occurred in the first two weeks after felling/processing of the trees. However, the same study noted that a rainfall event during storage of the LR rewetted it by approximately 10%. Unpublished *P. radiata* LR drying data suggested that the rate of LR drying is less when stored in seasons other than summer. Further research is required to develop *P. radiata* LR drying models for all seasons.

   Reducing LR MC through infield or roadside storage can also considerably reduce its transport costs, particularly when trucks have unutilised volume when reaching their weight limit transporting green LR chips (Strandgard et al. 2021).

2. Particle size distribution

   As mentioned above, particle size distributions vary according to the customer specifications. Quality is defined by the degree to which specifications are met or exceeded.

   Particle size distribution is influenced by the characteristics of the resource and the chipper. A comparison of biofuel chip sources in Italy found that conifer LR produced the poorest quality chips with a high proportion of fines (~13%) and a high proportion of bark and twigs (~19%) (Spinelli et al. 2011). Nati et al. (2010) found that chipping pine logs produced a higher proportion of acceptable chips and lower proportion of fines compared with chipping pine tops and branches. The high proportion of small branches and needles in the conifer LR (Spinelli et al. 2011) was likely to have caused the high proportions of fines, bark and twigs, particularly as bark proportion increases with decreasing branch diameter.

   The trial LR chips were screened at the receiving facility prior to testing for particle size distribution, which was likely to have resulted in the very low proportions of bark and fines compared with those reported by Spinelli et al. (2011) (Table 13). Kuptz et al. (2019) found that unscreened coniferous residue chips from six locations in Germany failed to meet the ISO standards for particle size distribution and ash content. Screening allowed chips from all locations in this study to meet the ISO standards. In particular, fines were reduced from over

15% to 3-4% or less in all cases. This suggested that the fines had a large proportion of bark and needles resulting in the excessive ash content. Screening of *P. radiata* LR is likely to be essential to meet customer quality requirements.

Particle size distribution can also be affected by chipper settings and knife sharpness (Spinelli et al 2005). Contaminated LR may require more frequent knife changes (Spinelli et al. 2014).

Table 13. Logging residue chip size distribution, bark percentage and moisture content for the study site and the customer specifications.

	> 50.8mm	50.8mm - 3.2mm	<3.2mm	TOTAL %	BARK (%)	MOISTURE (%)
Trial results	4.61	95.00	0.39	100.00	3.4	11.98%
Specification	<5%	>90%	<5%		<8%	

3. Ash content

As noted above, ash content for LR chips is strongly correlated with the proportion of bark and needles. Contamination with sand and soil can also be a major source of ash content (Smith et al. 2012). Therefore, improved particle size distribution quality through reducing fines will also reduce ash content. Screening of LR chips was noted in the previous section as an effective means to reduce fines and ash content. Forwarder operators could also potentially improve LR quality by prioritising collection of larger, woody sections and ignore individual small LR pieces. This approach may also increase the forwarder productivity extracting LR. Further research would be needed to confirm these potential outcomes.

Soil and sand contamination can be reduced by not driving machines over the LR and by leaving the bottom layer of the stacked LR onsite as it is likely to be the most contaminated. In Scandinavia, LR may be stacked on logs to reduce the soil contamination and increase the proportion of LR recovered from a site. However, the majority of the LR on these sites consists of tree tops, which can be more readily stacked.

9. Determine/estimate cost of lowest specification biomass product

The lowest specification biomass product is dependent on customer specifications which can vary over time. As noted in the previous section, the quality constraints are dependent on the intended use for the LR. In the current study, the LR chips supplied met the WAPRES chip specifications after screening.

Green LR can be acceptable for large boilers where it can be mixed with drier chips prior to use and/or dried onsite using waste boiler heat. Supply of green LR removes the need to return machinery to the site but loses the potential transport cost savings from transporting dry LR chips.

As noted in the previous section, chip size is more critical for smaller boilers as large chips can bridge over and block their feed mechanisms. The proportion of fines is strongly related to the proportions of ash and other contaminants. High ash levels can lead to increased boiler maintenance and high proportions of abrasive substances can increase wear of LR processing equipment. As such, screening of LR prior to use is likely to be desirable for most LR chip uses. Sale of unscreened LR chips may substantially reduce their price as the purchaser would need to screen the chips and dispose of the fines which can make up a substantial proportion of the LR chips (>15%), depending on their source and level of contamination.

10. Develop a harvest methodology to inform harvest contractors.

The results from the two harvest trials conducted in Western Australia to test integrated harvesting approaches to extract logs and LR (Lake Muir and Margaret River) suggested that different harvest systems should be applied to harvest and extract logs and LR based on the stand mean tree size. The split between the two suggested harvest systems is not prescriptive and will depend on the characteristics of the stand (e.g. tree size distribution), site (e.g. slope and obstacles) and harvester (e.g. power/weight/head size)

1. Stands with a mean tree size >2m^3 merchantable volume

For stands with a large mean tree size, Conventional harvesting with a harvester/forwarder harvest system followed by LR extraction to roadside by forwarder was found to be the most cost-effective approach as it was unsafe to fell large trees forward of the harvester as is done for fuel-adapted harvesting.

2. Stands with a mean tree size <2m^3 merchantable volume

For stands with a smaller mean tree size, the fuel-adapted harvest system was found to be the most cost-effective harvest system. Fuel-adapted harvesting involves felling trees to the front of the harvester and processing them to the side of the harvester. This approach leaves the logs and LR in separate piles alongside the forwarder path with the log piles aligned with the direction of harvester travel (Figure 2). Multiple trees are processed onto each log and LR pile. The number of trees processed at each pile will depend on tree size and stand density. In the Lake Muir trial, six to seven trees were processed at each pile.

Figure 2. Layout of log and LR piles at the Lake Muir fuel-adapted harvest site

For both harvest systems, the productivity of the forwarder extracting LR to roadside may be improved by increasing the volume of the forwarder bunk by increasing the stanchion height and/or the bed length to increase the weight of LR extracted in each forwarder load. In the Australian LR extraction trials, approximately 50% of the rated load weight capacity was used whereas in Europe, larger load beds have increased load weights to 75% of the forwarder capacity. The technique of commencing to load the forwarder from the rear can also increase load size as the operator's view of the load is maintained throughout loading (Figure 3).

Figure 3. Loading LR onto a forwarder commencing at the rear (Laitila et al. 2013).

11. Consideration/Discussion on applicability of the studied harvest and site preparation techniques to Karri forest silviculture.

Karri (*E. diversicolor*) harvesting operations in the south-west of Western Australia produce a considerable quantity of logging residue (LR) largely in the form of crown material and bark left onsite. To allow site preparation (ripping or scarification of compacted areas) and replanting to occur the LR needs to be removed from the site, which is currently done by burning (Bradshaw 2015). Prior to burning, the LR may have to heaped and moved from the coupe perimeter to reduce damage to surrounding forest and the risk of fire escaping incurring additional cost. Fire damage to retained stems may also occur. Smoke from burning residue can taint grapes in nearby vineyards (Bradshaw 2015) and also cause a nuisance to residents of nearby towns (Raison and Squire 2008). Burning LR also removes a proportion of the site's nutrient stocks. Constraints on when burning can be conducted may result in a lengthy period between harvesting and LR burning increasing the bushfire risk, though some nutrients and fine material may transfer from the LR to the soil during storage (O'Connell 1997).

The approach used in the current study where LR was extracted to roadside using a forwarder or where whole trees were skidded to roadside and then processed may represent a viable alternative to burning LR in Karri silviculture. The size of Karri crowns may also allow them to be bunched and skidded to roadside. Retained LR could then be chopper-rolled followed by cultivation where required. The roadside LR would then be chipped directly into trucks. The chips could be used for bioenergy production, or, where the wood content was sufficiently high, as a source of chips for pulp or particle board production. The potential advantages of mechanical LR removal include revenue from chips, reducing site preparation costs, eliminating agricultural crop tainting and nuisance from smoke, and increasing flexibility of site preparation and replanting timing, which are currently constrained by suitable conditions for burning. The potential costs and benefits of current practice compared with LR extraction would need to be tested in a research trial.

12. LR chipping Time and Motion study and costs

This deliverable was combined with Deliverable 3 “Time and motion studies on three alternative methods for collecting and processing harvest residue”

13. Review of residue left on site and the implications for soil nutrition issues

Background

The Code of Practice for Timber Plantations in Western Australia (Forest Industries Federation (WA) Inc 2014), in common with those of other Australian states, refers to the requirement to sustainably manage plantations in the State, but does not provide further detail. Site nutrition is an important factor in sustaining long term site productivity and the potential for decline in the productivity of future rotations resulting from removal of nutrients and organic matter through whole tree harvesting, burning or LR removal was noted in the CSIRO review of the Western Australian Code of Practice (Smethurst et al. 2012).

Predicting the impact on site productivity of removing a proportion of the LR from harvested areas is complicated by interacting factors including relative nutrient stocks in LR components, soil and leaf litter, differences in availability of nutrients within soil, the proportion of nutrients contained in harvested stem wood, whether bark is retained or removed, rotation length and species. Table 14 shows the percentages of macro-nutrients in trees, soil (0 – 75 cm) and leaf litter for a 30 y.o. *P. radiata* plantation in south-west Victoria established on relatively infertile sandy soil (Hopmans and Elms 2009).

Table 14. Percentages of macro-nutrients in trees, leaf litter and soil (0 – 75 cm depth) (Hopmans and Elms 2009).

	Macro-nutrient					
Component	N	S	P	K	Ca	Mg
Trees (%)	10	10	9	13	8	6
Litter (%)	30	31	16	5	21	12
Soil (%)	60	59	75	82	71	82

The soil is the major nutrient reservoir in a *P. radiata* plantation (Hopmans and Elms 2009), though defining the size of this reservoir is complicated by difficulties in determining the volume of soil explored by the tree roots and the availability of the nutrients detected in the soil through chemical analysis (Turner and Lambert 2011).

While the concentration of nutrients in wood and bark is low, the large mass of wood and bark harvested from a plantation results in the removal of a large proportion of the macro-nutrients contained in the above ground tree biomass in a mature *P. radiata* plantation, including approximately 30-40% of the N and P and over 40% of the K, Ca and Mg (Baker and Attiwill 1985; Hopmans and Elms 2009). The composition of LR following cut to length harvesting at the stump consists of the needles, cones and branches from the tree crowns, unmerchantable stem wood and varying quantities of bark removed by feed rollers, grapples and abrasion. The majority of the remaining macro-nutrients in the trees is contained in the needles (approximately 25% to 50% of the tree macro-nutrients) (Baker and Attiwill 1985; Smethurst and Nambiar 1990b; Hopmans and Elms 2009). Most of the remaining above ground tree biomass macro-nutrients are contained in the branches.

Ximenes et al. (2012) noted that the nutrient loss implications of removing coarse woody residues (stem wood and branches >8cm in diameter) was relatively low. However, the stem wood component was relatively high in their study as the minimum small end diameter for pulp logs was

8cm compared with 0cm in the current study. This was reflected in the large proportion of stem wood in their study where >70% of the stem wood residues were over 1m in length.

Leaf litter in *P. radiata* plantations can contain a higher proportion of the total site stocks of macro-nutrients than that in the trees (Baker and Attiwill 1985; Hopmans and Elms 2009) (Table 14). However, the quantity of leaf litter can vary widely with published values ranging from approximately 19 t/ha (Baker and Attiwill 1985) to 32 t/ha (Smethurst and Nambiar 1990b) and up to 121 t/ha (Hopmans and Elms 2009), though the latter figure was likely to have resulted from a late thinning and high mortality in the studied stand. Murphy et al. (2004) reported that mean tree volume at age 21 was reduced by 8% in a New Zealand *P. radiata* plantation where the leaf litter layer had been removed and the soil lightly compacted.

On sites with low soil nutrient levels, removal of LR and leaf litter, as can occur when LR is burnt, can reduce the growth of trees in the second rotation (Farrell et al. 1986; Hopmans et al. 1993; Smith et al. 2000). However, on a similar low nutrient site Smethurst and Nambiar (1990a) found no impact of removing LR or LR and leaf litter on growth of *P. radiata* trees in the first three years. Sites with high soil nutrient levels were found to have no change in growth of second rotation trees following LR removal (Smith et al. 2000; Mendham et al. 2014). However, Mendham et al. (2014) reported that growth of the third rotation trees in a *Eucalyptus globulus* plantation on a fertile site was reduced following LR removal at the end of the second rotation.

Nilsson (2016) found that ~30% of the needles on a clearfelled coniferous forest site in Sweden were present in the LR retained onsite. Studies in in Sweden and Finland have found that leaving LR to dry infield can result in a considerable proportion of the needles in the stored LR being shed across the harvest site during storage or extraction to roadside (Nurmi 1999; Nilsson et al. 2015). The degree to which needle shedding occurs for stored *P. radiata* branches is unknown, however, the majority of the nutrients in green needles can be leached into the underlying leaf litter or soil within two months of their deposition on the forest floor (Girisha et al. 2003). Drying can also decrease transport costs (Strandgard et al. 2021) and increase the net calorific value of the LR (Moskalik & Gendek 2019). However, leaving the LR infield as opposed to stacked at roadside is likely to require the return of a machine to the site to extract the LR to roadside, incurring additional costs.

Mendham et al. (2014) found that, in addition to release of nutrients, retained LR increased *E. globulus* tree growth in the next rotation through a "mulching" effect reducing moisture loss from the soil, though this effect would be likely to be diminished in a *P. radiata* site with an intact leaf litter layer.

Replacement of the nutrients lost in wood and LR removal from the site would mainly occur through application of fertiliser, though this would need to be subjected to a cost-benefit analysis (May et al. 2009). Deposition of nutrients in rainfall can be significant over the course of a long rotation though the quantities added can vary greatly between locations and years (Turner et al. 1996). Acacias growing in a *P. radiata* plantation can add substantial quantities of nitrogen, though Turvey et al. (1983) found that growth suppression of the *P. radiata* trees resulting from the competition from the Acacia trees outweighed any benefit from increased soil nitrogen. Boiler ash is also returned to forest harvest sites to replenish site nutrients in Europe (Sarabèr and Feuerborn 2018). Its potential use in Australia would require further investigation as the ash is strongly alkaline as it contains predominantly base cations (Kuokkanen et al. 2009).

There has been little work done on the long-term impacts of removal of some or all of the LR. In a review of the effects of forest biomass harvesting on soil productivity, Thiffault et al. (2011) reported that in thinning trials, growth decline for whole tree harvesting compared with stem only harvesting only occurred for 3 to 10 years post-thinning. On Scots pine sites in southern Sweden, whole tree removal resulted in reduced height and basal area compared with stem only removal due to reduced nitrogen supply. When stem and branches were removed but needles were retained, tree growth was similar that that on stem only removal sites until year 15 then declined to be similar to that on whole tree removal sites.

In addition to retaining nutrients on site, LR is retained to prevent damage to the soil from erosion, particularly on steep slopes or compression or rutting. A study in Virginia, USA, found that implementation of Best Management Practices related to LR retention was not significantly affected by LR extraction (Barrett et al. 2016). Further research would be required to examine whether retained LR levels are sufficient to prevent unacceptable levels of erosion, compaction and rutting in Australian forest operations.

Study results

The nutrient status of the LR and of the soil and leaf litter layers and the quantity of leaf litter at the study site were not evaluated in the current study, allowing only general conclusions to be drawn about the potential impacts of nutrient export associated with LR removal from the site.

Approximately 25% - 34% of the LR was left on site following LR extraction by forwarder for the Conventional and Fuel-adapted sites and of whole trees in the Whole tree to roadside site. For the Conventional and Fuel-adapted sites, further LR was retained on site in the lower contaminated layer of the roadside LR pile and from breakage during handling and chipping. The additional LR retention equated to approximately 20% - 25% of the total site LR for both sites (overall LR retention equivalent to ~50% of the total site LR). This level of retained LR quantity met the minimum LR retention requirements of the 17 North American and European jurisdictions listed in Titus et al. (2021). As noted above, none of the LR for the Whole tree to roadside study site was chipped due to contamination. Based on the results from trials cited in the previous section, the LR was likely to have contained approximately 50% to 70% of the macro-nutrients in the above ground biomass of the trees harvested from the site, the majority of which was contained in the needles. As approximately 50% of the LR was left onsite for the Conventional and Fuel-adapted treatments, the retained LR was likely to have contained 25% to 35% of the total macro-nutrients in the above ground biomass of the trees harvested from the site.

The Whole tree harvesting system used a skidder to transport the trees to roadside, which can sweep leaf litter from the skid paths (Hartsough et al. 1994). Although the extent of leaf litter sweeping was not measured during the trial, bare patches of soil were noted on the Whole tree harvesting site.

The residue was retained on site for 3 to 4 months prior to chipping. Based on the study noted above, the majority of the macro-nutrients contained in the needles was likely to have leached out into the leaf litter and soil resulting in only a small proportion of the nutrients in the LR being exported from the site as chipped LR. There is not enough information in the published literature to speculate as to what quantity of macro-nutrients was contained in the chipped material. As noted in the previous section, drying LR infield results in a more even dispersal of needles shed from LR and nutrients leached from LR across the site but is likely to require the return of a machine to the site to extract the LR to roadside, increasing costs, delaying extraction and reducing flexibility in the use of the LR. This may be viable on larger sites where the benefits of infield storage may outweigh the associated costs.

The relatively long rotations for *P. radiata* plantations mean that removal of the proportion of LR extracted in the current trial for the Conventional and Fuel-adapted sites is unlikely to have an impact on the long-term sustainability of tree growth on more fertile sites due to the large nutrient stores available in soil and leaf litter (assuming burning is not conducted in site preparation). Storing the LR on site for several months prior to chipping would result in a proportion of the nutrients it contains being left on site through leaching and physical loss of fine material (needles and small branches). However, investigation of the impact of LR removal requires long-term monitoring of subsequent tree growth on sites covering a range of soil fertilities.

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Appendix 1

Definitions of harvester time elements

Time element	Definition
Travel	Starts when tracks begin to move harvester from roadside to harvest area. Ends when boom begins to move to first tree.
Moving/positioning	Starts when tracks begin to move or when boom begins its swing towards next tree. Ends when felling commences.
Felling	Starts when head clamps onto tree. Ends when feed rollers are activated or tree is horizontal.
Processing	Starts when feed rollers are activated. Delimbing and cross-cutting of tree. Ends when felling boom begins to swing to next tree or tracks begin to move.
Brush and clear	Clearing of unmerchantable trees or processing debris/undergrowth.
Stacking	Starts when the boom commences moving to retrieve, move or 'stack' any processed logs. Ends when another element commences
Delay	Any interruption causing the harvester to cease working during a shift.

Definitions of forwarder time elements

Time element	Description
Travel Empty	Starts when forwarder commences travel into the harvest area from the landing and ends when crane commences moving to collect logs/LR.
Loading	Starts when crane commences moving to collect logs/LR and ends when another element commences. Includes adjustments to the logs/LR on the bunk.
Moving During Loading	Movement between logs/LR piles with no crane movement. Starts when wheels begin rotating and ends when crane recommences movement. Simultaneous crane and wheel movement is recorded as loading.
Travel Loaded	Starts with travel to the landing with a load and ends when wheels cease to rotate or crane commences to move at the landing.
Unloading	Starts with commencement of crane movement, grapple empty, towards the forwarder's bunk and ends when another element commences. Includes adjustments to the log/LR stack.
Moving During Unloading	Movement between log/LR stacks at the landing with no crane movement. Starts when the wheels begin to rotate and ends when the

	crane recommences movement to the forwarder bunk. Simultaneous crane and wheel movement is recorded as unloading.
Brush and clear	Clearing of non-merchantable trees/undergrowth or processing debris.
Stacking	Adjustment of logs/LR in a roadside stack not associated with unloading or loading.
Delay	Any interruption causing the forwarder to cease working during a shift.

Definitions of feller-buncher time elements

Time element	Definition
Travel	Starts when tracks begin to move harvester from roadside to harvest area. Ends when boom begins to move to first tree.
Moving/positioning	Starts when tracks begin to move or when boom begins its swing towards next tree. Ends when felling commences.
Felling	Starts when head clamps onto tree. Ends when feed rollers are activated or tree is horizontal.
Brush and clear	Clearing of unmerchantable trees or processing debris/undergrowth.
Stacking	Starts when the boom commences moving to retrieve, move or 'stack' any processed logs. Ends when another element commences
Delay	Any interruption causing the harvester to cease working during a shift.

Description of processor time elements

Time element	Definition
Travel	Time taken to turn around to start new stack or move to and from break. Starts when wheels/tracks begin to rotate. Ends when boom begins its swing towards first tree on new stack
Moving/positioning	Starts when the processor begins to move and/or swing its boom towards a felled tree and ends when the head clamps onto the tree
Swinging	Starts when head clamps onto a felled tree and ends when feed rollers are activated, or the first cut is made to reset the processor length measurement (whichever occurs first)
Processing	Starts when feed rollers are activated, or the first cut is made to reset the processor length measurement (whichever occurs first) and ends when the last log is cut and dropped on the log pile
Brushing/Clearing	Any interruption to other elements to remove unmerchantable trees or clear processing debris
Stacking/Bunching	Starts when the boom commences a swing to retrieve move or »stack« any processed logs. Ends when the boom moves to perform some other activity
Delay	Any interruption to the previous time elements. The cause of the delay (e.g. operational, personal, mechanical, or study induced)