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TITLE:

Productivity and Cost of Harvesting a Stemwood Biomass Product from Integrated Cut-to-Length Harvest Operations in Australian *Pinus radiata* Plantations.

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HIGHLIGHTS

- Study of the productivity and cost impact of producing a woody biomass product.
- We compared two scenarios – harvesting with and without the biomass product.
- An additional 23 GMt/ha (5% of the total yield) of woody biomass was produced.
- Harvesting productivity and costs were the same for each scenario.
- Forwarder extraction was 14% less productive, increasing costs by ~4.9%.

ABSTRACT

Significant quantities of woody biomass from the tops of trees and larger woody 'waste' pieces that fall outside existing sawlog and pulpwood specifications are left onsite post final harvest in Australian radiata *Pinus radiata* (D. Don) (radiata pine) plantations. Woody biomass is a potential product for pulp making or energy generation. Commercial use of woody biomass from radiata pine plantations would add extra value to the Australian plantation estate through improved resource utilisation, and potentially reduced post-harvesting silvicultural costs. This study investigated the productivity and cost impact of the harvest and extraction to roadside of woody biomass in an integrated harvest operation in a typical Australian two machine (harvester/processor and forwarder), cut-to-length, clearfall operation in a mature, thinned radiata pine plantation.

The harvest operation yielded 23 GMt/ha (5% of the total yield) of woody biomass (known as 'fibreplus'), 443 GMt/ha of sawlogs and 28 GMt/ha of pulpwood. The mean quantity of biomass left on site was 128 GMt/ha, mainly consisting of branches and needles, sufficient to minimise nutrient loss and protect the soil from erosion. Woodchips derived from the fibreplus product were suitable for kraft pulp making, (when blended in small amounts with clean de-barked roundwood woodchips), and for energy generation.

The method trialed with the fibreplus product being produced did not impact harvesting and processing productivity and costs, but extraction was 14% less productive. Through analysis of the productivities of each phase and development of a cost model the harvest and extraction of the fibreplus product was estimated to increase total unit costs by ~4.9%.

KEYWORDS

Forestry; Logging; Biomass harvesting; Forest operations; Wood

1 INTRODUCTION

Woody biomass is a potential product for the Australian wood products market for pulp making or energy generation. Wynsma *et al.* [1] define woody biomass as 'the by-product of management, restoration, and hazardous fuel reduction treatments, including trees and woody plants (ie. branches, tops, needles, leaves and other woody parts, grown in a forest, woodland or rangeland environment)'. This definition includes the aboveground biomass (AGB) of the tree not utilised in commercial harvesting operations. Two Australian studies in *Pinus radiata* (D. Don.) (radiata pine) plantations in New South Wales (NSW) estimated that approximately 20.5% [2] and 16.8% [3] of total AGB by weight was potentially available woody biomass that was not extracted as commercial sawlog or pulpwood, nor was part of the stump. Turner [4] estimated that the woody biomass component of the AGB of the trees was up to 9% of the total recoverable volume from radiata pine plantations in Victoria. Commercial use of at least a proportion of this woody biomass would add extra value to the plantation estate through improved utilisation of the resource, and potentially reducing post-harvesting silvicultural management costs. However, development of a new woody biomass market adds another log product grade and assortment to harvest operations. This will impact on the productivity and cost of harvesting and, more particularly, of extraction [5-7] and needs to be evaluated in the context of the overall management and planning of the log supply chain.

There are four methods used for the harvesting of woody biomass:

- The use of specialised machines;
- post-harvest operations following conventional harvesting;
- pre-harvest operations prior to conventional harvesting, and;

- integrated one-pass conventional operations harvesting roundwood and biomass products simultaneously [8, 9].

A number of studies have shown that the last method was most economical when woody biomass was produced simultaneously with other higher value forest products in integrated, one-pass harvest systems, particularly when considering the post-harvest silvicultural management costs incurred from leaving the biomass behind and other forest management benefits that could accrue from their utilisation [10-13]. However, the research also indicated costs were highly variable depending on the harvesting system used, site conditions, the amount of woody biomass produced, the type and value of higher value products produced, primary extraction distance, transport distance and storage [12, 14-17].

Recent research in the production of woody biomass has focused on assessing the economic feasibility of harvesting in a range of stand conditions, using a variety of machines and/or machine combinations, to achieve various silvicultural objectives including, removal and/or thinning of small-diameter trees to restore a forest’s natural ‘balanced’ state and reduce fire hazard [18, 19]; to improve and protect forest health [20]; to utilise otherwise non-commercial stands with poor growth and form [21]; or to add value through greater utilisation of the resource [22-24]. These studies were not all integrated commercial harvesting operations. Those that were have generally focused on small tree harvesting and woody biomass utilisation using traditional harvesting equipment [8, 13, 18, 19, 25, 26] and/or purpose built equipment [27-31].

The advent of potential new markets for woody biomass has highlighted a lack of detail on the methods, potential productivity and cost impacts of harvest systems designed to remove woody biomass [25, 32], particularly in an Australian context. Work has been done in New

Zealand radiata pine plantations similar to those in Australia to investigate and identify the most cost-effective collection and delivery systems for woody biomass for energy generation [22-24, 33-36]. However, in contrast to typical Australian CTL harvesting operations, woody residues in New Zealand are concentrated around roadside landings or central processing yards following whole-tree ground-based or skyline/cable extraction, rather than spread out over the harvest site. In addition, where it occurs, woody biomass is generally collected as part of a separate operation and not as part of an integrated CTL harvest operation.

Australian plantation managers have expressed interest in the potential for harvesting stemwood biomass in radiata pine plantations using existing conventional harvest machines as part of an integrated harvest operation. This stemwood biomass would be roughly delimbed by the harvester during processing and extracted to roadside by a conventional forwarder, along with other log products, for later comminution to woodchips for pulp making or for energy generation. Similar production methods for harvesting woody biomass are the most common options used elsewhere in the world [17] and have been proven to be effective. For example, the predominant method used in Finland and Sweden has been to forward residues to roadside from final fellings for comminution [14, 37, 38].

The economics as well as the integrated management of the logistics activities to deliver the right quantity of in-specification materials in a timely manner, without detrimental environmental impacts, will be vital to the success of the new woody biomass product [39, 40]. To this end this study sought to investigate the:

- Productivity and cost impact of harvesting and extracting to roadside an additional stemwood biomass product integrated within an existing harvest operation producing sawlogs and pulpwood.

- Quantity and quality of stemwood biomass removed.
- Quantity of retained biomass on site following stemwood biomass removal.

2 METHODS

2.1 Study Design

The site was located in a Forestry Corporation of New South Wales (FCNSW) *Pinus radiata* plantation approximately 50 km north-east of Tumut, New South Wales (NSW), Australia. The site was in a homogenous stand with the same silvicultural treatment history and site conditions - trees of good form and quality, and flat terrain with no obstacles or rock present. The stand was twice thinned and 34 years old at the time of clearfall.

The study area consisted of two 2 ha sites (the ‘Control Site’ and the ‘Fibreplus Site’) and two 100 tree plots (~0.5 ha) (the ‘Control Plot’ and the ‘Fibreplus Plot’). The 2 ha sites and the 100 tree plots were harvested to existing sawlog and pulpwood product specifications using a CTL harvesting system (harvester and forwarder) to harvest, process, extract, and stack log products at roadside or load directly onto a truck. In addition, the Fibreplus Site and Plot produced a stemwood biomass product, known locally as ‘fibreplus’. Fibreplus consisted of the stemwood portion from the tops of trees and the larger ‘waste’ pieces cut from the stem that fall outside existing sawlog and pulpwood specifications (Figure 1).

[Insert Figure 1]

2.2 Harvesting and Extraction Equipment and Working Methods

The harvester was a 2004 model Timbco 475 tracked purpose-built harvester with a Rosin 997 harvesting head and a Dasa4 on-board computer (OBC) and optimiser. It had done ~9 000 hours of work.

The forwarder was a 2001 model Timbco 820D 8-wheel clambunk skidder base with a ~28 GMt capacity forwarder bunk. It had done ~19 000 hours of work.

The operation was a partial ‘hot-deck’ operation with the forwarder used to load trucks. Forwarding of the harvested log products was conducted by roadside log product assortment in the following order: long 6.1 m sawlogs, short 3.7 and 4.9 m sawlogs, pulpwood loads only in the Control study areas and, pulpwood and fibreplus products extracted as mixed loads in the Fibreplus study areas, respectively. To collect the mixed pulpwood and fibreplus loads the forwarder first collected pulpwood to create a ‘bunk floor’ or ‘basket’, then collected fibreplus to ‘top-up’ the load.

2.3 Field Data Collection

A pre-harvest inventory of both 100 tree plots was undertaken to establish the size of each tree, the tree size distribution, the mean tree diameter breast height over-bark (DBHOB), tree height, stand basal area (BA), stocking and merchantable volume of each plot. Trees in each plot were numbered with white paint so as to be visible at least two tree lengths away (~60 m).

For each 2 ha site, the DBHOB and height of 42 trees was measured at random to estimate the mean tree size and tree size distribution, mean tree DBHOB and height, and mean stand BA, stocking and merchantable volume. A count of all trees on each site was also made.

For the harvesting and processing phase, the time needed to harvest each 100 tree plot (including delays) was recorded along with a video recording of the harvesting and processing of each tree. The time spent undertaking each harvest work element (Table 1) for each tree cycle was recorded using the video recording and the TimerPro® software [41].

[Insert Table 1]

For each 2 ha site, instantaneous observations were taken every minute over 120 minute periods to record the harvest work element (Table 1) being conducted and the number of trees felled and number of logs processed from each tree.

For the extraction phase, the time needed to extract each load of logs (including delays) was recorded along with a video recording of the forwarding of each load of logs from each site and plot. The time spent undertaking each forwarding work element (Table 2) was recorded for each load cycle using the video recording and the TimerPro® software [41].

[Insert Table 2]

Distance travelled during work elements ‘Travel Empty’ and ‘Travel Loaded’ was recorded using distance markers located ~20 m apart. Distance travelled during work elements ‘Moving During Loading’ and ‘Moving During Unloading’ was estimated by counting the forwarder’s wheel rotations - 1 wheel rotation equalled ~4 m. The log product assortment and number of logs in each grapple load being loaded and unloaded was recorded as well as whether logs were unloaded to roadside log stack or truck.

Log products extracted from each site and plot were stacked at roadside in their respective log product assortments and segregated from log products produced elsewhere. Net weight of each truck load was recorded from the customer weighbridge(s).

The fibreplus product was chipped at roadside in the Fibreplus Plot and Site separately and the quantity of woodchips produced weighed at the customer’s weighbridge.

The amount of retained biomass on the Fibreplus Site was estimated 4 months post-harvest. Thirty-six, 1 x 1 m plots were sampled on a 20 x 25 m grid aligned at 45 degrees to the extraction tracks to reduce bias. All pine biomass (branches and woody debris, fine branches and needles) within each plot, was collected and weighed. Plot weights were grouped into two strata (high or low forwarder traffic) because areas of high forwarder traffic had less retained biomass. Mean, standard deviation and probable limits of error (PLE) [42] of the amount of retained biomass for both strata and over the whole site were calculated.

2.4 Data Analysis

Mean tree DBHOB, mean tree volume, mean tree BA and mean tree height, for the trees on each plot were compared using t-tests (α=0.05).

Yields by product type from each plot and site were determined as follows:

- Sawlogs – Total delivered weight by log product assortment for each site and plot.
- Pulpwood - Total delivered pulpwood weight for each site and plot.
- Fibreplus - Total delivered woodchip weight for each Fibreplus Site and Plot.

For each plot the total weight by product type was converted to cubic metres using standard weight to volume conversion ratios by product and compared to the aggregated volume measurement of each log from the harvester's OBC stm file to check the degree of agreement between each measurement method. Aggregate volume for each tree (recorded by the harvester's OBC) was used to calculate the mean tree size. These metrics were used in the analysis and comparison of machine productivity for each of the Control and Fibreplus scenarios.

Time data for each work element and yield data collected in the sites and plots for each machine were analysed to:

- Compare the productivity, and related components of productivity – work elements, distances travelled, speed, volume cut and extracted, of each machine by work phase and scenario;

- Develop and compare productivity models relating independent variables (e.g. tree size, load volume, extraction distance) to the productivity of each machine by work phase and scenario.

For each work phase, productivity was compared based on individual work cycles, as well as an overall productivity comparison. Productivity was determined by dividing volume of product produced by cycle time, excluding delays > 10 centi-minutes (PMH_0). Delays < 10 centi-minutes, (~6 seconds), were included in the work element in which they occurred.

For the harvesting phase, mean times for each work element recorded for every tree in the two plots were compared using t-tests (α=0.05).

Harvester productivity is highly dependent on tree size [43]. To remove the effect of tree size, each plot's harvester productivity model was compared using the 'Chow test' (or extra sum of squares F-test); and a multiple regression using an indicator (dummy) variable to test for coincidence [44].

In order to better isolate the impact of integrating the fibreplus product into the harvest operation from that of other variables (or differences) between the two plots that may have affected the harvester's productivity, malformed or unusual trees were removed from the datasets, leaving only 'normal trees' (those trees which were not edge trees, trees with double leaders or trees with broken tops, or trees that had been identified as having unusual processing times). There were 48 'normal trees' on the Control Plot and 55 on the Fibreplus Plot.

Regression models were fitted to data from 'normal trees' from each plot. The independent variable was processed tree volume measured by the harvester and the dependent variable was productivity. Total cycle time was determined using mean time values for work elements relatively unaffected by tree size (travel, moving/positioning, stacking/bunching and brushing/clearing) and actual felling and processing times for each tree. Model forms with various transformations of the variables were compared for goodness of fit using mean bias, root mean square error (RMSE), R^2 and spread of residuals. Models were validated using witness samples and calculated confidence intervals for each coefficient.

The extraction phase analysis compared the mean times for each work element, and the distances and speed travelled by the forwarder by scenario (Control and Fibreplus Areas) using t-tests (α=0.05). Extraction Distance for each forwarder load was calculated using the method outlined in Tiernan *et al.* [45].

The volume of each non-fibreplus forwarder load was estimated by calculating the mean log volume by log product assortment and multiplying by the number of logs counted in each forwarder load. The volume of fibreplus product in each mixed fibreplus/pulpwood forwarder load was determined by calculating the mean forwarder grapple volume from the total volume of fibreplus extracted divided by the total number of fibreplus grapple loads and multiplying it by the number of fibreplus grapple loads in each mixed forwarder load. Volumes of pulpwood and fibreplus in each mixed load from the Fibreplus Site and Plot were aggregated to estimate the total volume in each mixed forwarder load.

Regression analysis was carried out for forwarder productivity on each study site using load volume and extraction distance as independent variables. An analysis of variance (ANOVA) was performed to test the significance of log product assortment on forwarder productivity. Mean forwarder productivity across all log products was also compared between each study area using a t test (α=0.05).

2.5 Machine Cost Calculations

The cost impact of integrating the fibreplus product into the harvest operation was estimated by modelling the harvester and forwarder running costs using the method described by Miyata [46]. Assumptions used in the costing model are shown in Table 3. The costing model excludes any allowance for a contractor margin. It is likely that operational constraints and/or costs may become apparent that are difficult to foresee or quantify and actual costs may vary from the model on a case by case basis.

Machines were assumed to be operated year round. Utilisation rates were recorded by a Multidat machine data logger over a period of 6 months following the harvest of the study areas. The higher utilisation rate for the forwarder resulted from it being used to extract logs and load trucks.

A sensitivity analysis was performed to examine the cost impact of reducing the productivity of both the harvester and forwarder uniformly by 10%, and by 25%.

[Insert Table 3]

3 RESULTS

3.1 Plot Pre-harvest Inventory

Mean DBHOB, mean BA and mean tree volumes were significantly different between plots, whereas mean tree heights were the same. The plots had similar stockings (sph). The Control Plot had a slightly greater number of larger DBHOB trees, and therefore had greater total BA and total merchantable tree volume per hectare. Both plots were closely matched in terms of the range of tree sizes harvested and provided a reasonable basis for the comparison of harvest productivity.

Plot and site pre-harvest inventory results are shown in Table 4.

[Insert Table 4]

3.2 Yields

Product yields measured by customer weighbridges from each Plot and Site are shown in Table 5. Harvester OBC estimates of total merchantable yield from each plot were within +/- 5% of these yields.

[Insert Table 5]

3.3 Harvesting Phase

Mean work element times were not statistically different between the study areas (Table 6).

[Insert Table 6]

Mean harvester productivity for the Control plot was 93 GMt/PMH_0 and for the Fibreplus plot was 94 GMt/PMH_0.

The harvester productivity models developed for each plot that gave the best fit to the data were natural log functions of the following form:

Productivity = $\beta_0 = \beta_1$ * In (Processed Volume)

Model coefficients and goodness of fit statistics are in Table 7.

[Insert Table 7]

Other assignable causes of variation in the harvester's productivity for 'normal trees', other than tree size, were not apparent from field observations, nor from the data collected. Witness samples and model coefficient confidence intervals showed that the models were valid. No significant difference was found between the two plot productivity models for either test of coincidence showing there was no difference in harvester productivity between the plots over the range of tree sizes harvested (Figure 2).

[Insert Figure 2]

3.4 Forwarding Extraction Phase

Mean times for each work element were not statistically different between the study areas, with the exception of 'Travel Empty' (Table 8). Mean cycle time per forwarder load was not significantly different between study areas.

[Insert Table 8]

The significant difference in the 'Travel Empty' work element between the study areas was related to a significant difference between mean 'Travel Empty Distance' because the forwarder travel speed (both empty and loaded) was found to be the same between the study areas. All other distances travelled by the forwarder were the same between study areas.

Mean 'Travel Empty' speed (76.5 m/min) and 'Travel Loaded' speed (74.3 m/min) between study areas were not significantly different, which indicated the forwarder's speed was not influenced by the load weight.

3.4.1 Comparison of Productivity

Mean forwarder productivity for the Control study areas was 93 GMt/PMH_0 and for the Fibreplus study areas was 80 GMt/PMH_0.

The forwarder productivity in this study was found to be highly dependent on the volume loaded and the extraction distance, as shown by Tiernan *et al.* [45]. However, differences in load volume and extraction distance were found to reflect the log product assortment being extracted. The ANOVA indicated significant differences in productivity between each product extracted, but not between the Control and Fibreplus study areas.

Comparison of the mean forwarder productivity by extracted log product indicated the forwarder's productivity was not significantly different when extracting long or short sawlogs from the two study areas. However, there was a significant productivity difference between the pulpwood only loads in the Control study areas and the mixed fibreplus/pulpwood loads in the Fibreplus study areas (Table 9). This was caused by the significant difference between the mean forwarder load weight in the Control (18.0 GMt) compared with that in the Fibreplus study areas (12.9 GMt). There was no significant difference in the mean total cycle times between the Control (26.4 min) and the Fibreplus study areas (24.7 min).

[Insert Table 9]

3.5 Quality of Woodchip Produced from the Fibreplus Product

The fibreplus woodchips were found to contain ~3% bark and were suitable to be blended in small amounts with clean de-barked roundwood woodchip to make kraft pulp. The fibreplus derived woodchip would also be suitable for energy generation.

3.6 Cost Impact of Harvesting and Extracting Fibreplus

In order to extract the fibreplus product and maintain the productivity balance between the harvester and forwarder, the forwarder would have to work longer hours than the standard shift incurring additional labour (extra AUD7.00/hour) and repair and maintenance costs

(90% of depreciation) which would increase forwarding unit costs and hence total unit costs. The difference in the total unit costs of harvest, (AUD3.95/GMt for both areas), and extraction, (AUD2.10/GMt for the Control and AUD2.40/GMt for the Fibreplus areas), between the two study areas was relatively small at ~AUD0.30/GMt or an additional ~4.9% (AUD1.00 equalled USD0.91 and EUR0.70 at time of the study).

The sensitivity analysis showed that reducing the productivity of both the harvester and forwarder uniformly by 10%, and by 25%, led to an increase in the total unit costs for the Fibreplus study areas by 11% and 33%, respectively.

3.7 Retained Biomass on Fibreplus Site

The mean amount of retained biomass on the Fibreplus Site was 128 GMt/ha. The spatial distribution of the retained biomass was highly variable ranging from 14 GMt/ha, to 616 GMt/ha. Although the biomass fractions (stemwood, large and small branches, needles, bark and cones) were not sampled separately it was observed that much of the retained biomass consisted of large and small branches and needles, and the occasional small stemwood piece.

4 DISCUSSION

The harvester's productivity was lower than the mean productivities of similar harvesters (135.7 m^3/PMH_0 and 164 m^3/PMH_0) felling and processing trees with similar mean tree sizes [47]. In a separate study of the same harvester, Alam *et al.* [48] identified the operator's working technique to be the predominant cause of the harvester's lower productivity.

The study found that harvesting the additional fibreplus product made no significant difference to the harvester's productivity and hence did not alter harvesting costs. This was because the fibreplus was already delimbed and cross-cut as part of normal operations and the relatively small quantity of fibreplus (5% of the total yield) would have had minimal influence on the harvester's productivity. This is similar to the findings of previous studies which reported the impact of additional log products on harvester productivity to be small [5-7].

The productivity of the forwarder was comparable to the mean productivity of a forwarder (80.9 m^3/PMH_0) working in a radiata pine plantation under similar conditions [49]. The study found that the forwarder's productivity when extracting all products including fibreplus was 14% less than without fibreplus, though the difference was not significant. This is substantially greater than the 3-7% drop in forwarder productivity resulting from an additional log product assortment reported in other studies [5, 7]. However, the additional log products assortments in these studies were created through changes in log assortment specifications whereas in this study the additional log product was a former waste product piled at low density on the extraction tracks, therefore its collection increased the overall extraction task both in terms of volume extracted and forwarder distance travelled. The 14% productivity difference resulted from a significant drop in productivity (23%) when forwarding mixed loads of fibreplus/pulpwood from the Fibreplus study areas compared with forwarding pulpwood only loads from the Control study areas. There were no significant differences in the productivity of forwarding long or short sawlogs between the two study areas. As sawlog loads made up a substantial portion of the total number of loads forwarded in each of the study areas, the impact of the less productive mixed fibreplus/pulpwood loads on the overall forwarder productivity was reduced.

The reduction in the productivity of the forwarder when forwarding mixed fibreplus/pulpwood loads resulted from these loads having significantly lower mean load volumes compared with pulpwood only loads due to the lower bulk density of the fibreplus product. The decrease in volume loaded for the mixed fibreplus/pulpwood loads required the forwarder to complete additional loads in the Fibreplus study areas to extract all the products (51 loads compared to 47). Although additional product was extracted in the Fibreplus study areas, the extra loads increased the overall extraction time more than the extra yield could make up for, leading to the decline in forwarder productivity.

Modifications to the forwarder’s bunk by using temporary ‘roll-on/roll-off’ cages, additional or extended stanchions to increase the forwarder’s maximum volume carrying capacity would allow collection of more fibreplus product per load thus reducing unit costs [38]. Use of an asymmetric grapple [50] may also increase forwarding performance due to improved loading and unloading productivity. However, these changes are unlikely to substantially reduce overall harvest and extraction costs when extracting the fibreplus product. For example, increasing the productivity of extracting the fibreplus product by 10%, would decrease total unit harvesting and extraction costs by ~AUD0.04/GMt, or less than 1%. Future research should continue trialling different machines, machine combinations, new technologies and work techniques to extract stemwood biomass.

The cost model indicated that the additional cost for harvesting and extracting fibreplus was solely related to the extraction phase. Part of this additional cost resulted from the forwarder needing to work an extended shift to match the harvester’s production and load trucks in the current partial hot-deck operation. Alternatively the harvester could slow production (by slowing productivity or reducing its utilisation rate) to maintain system balance or the operation could be changed to a cold deck operation. Slowing production would increase the total unit cost of harvesting with fibreplus more than calculated in the study as the harvester is the more expensive of the two machines per scheduled machine hour (SMH). A cold-deck operation uses a dedicated loader to load trucks which would allow the forwarder to use all its productive time to extract log products to roadside and reduce its cost per SMH.

The impact of harvesting and extracting fibreplus on the total unit costs is quite modest (~4.9%). However, changes to the variables underpinning the cost model could have a sizable impact on the results. The sensitivity analysis indicated an accelerating cost increase as the productivity of harvest and extraction decreases. Stands with different silvicultural histories or characteristics from those of the current study may yield different product proportions which could result in different machine productivity and cost outcomes. Replication of this research in different stands would be required to gain a full appreciation of the productivity and cost implications of harvesting and extracting fibreplus.

The finding that woodchips derived from the fibreplus product could be used as feedstock in the kraft pulp making process when blended in small amounts with clean de-barked roundwood woodchip (as well as for energy generation) was significant because it would provide a much broader market for this product. The use of this product for higher value-added processes like pulp making will change the circumstances under which it becomes an economically viable product to harvest and extract.

A substantial quantity of pine biomass including branches, woody debris, and needles, was retained on the Fibreplus Site post-harvest. The amount of retained biomass was similar to that reported in studies from elsewhere in Australia and New Zealand (104-160 GMt/ha assuming 50% moisture content) [51-54] following removal of stemwood material greater than ~10 cm diameter. The retained biomass in the current study was higher than that reported by Ghaffariyan *et al.* [28] for an Australian *Pinus radiata* plantation in South-west Victoria (32-55 GMt/ha) where a stemwood biomass product had been removed post-harvest by a Bruk's chipper. Branching on the Bruks chipper study site was noticeably lighter than that for the current study site which may explain the difference in the quantities of retained biomass. Results from Ximenes *et al.* [3] indicated a mean quantity of 61 GMt/ha, (with a range of 28-105 GMt/ha), of retained biomass following the harvest of a number of twice thinned radiata pine plantation sites in NSW, where a stemwood biomass product was not recovered.

Smethurst & Nambiar [54] found that radiata pine fine branches and needles contain substantially more nutrients than other AGB components. The high proportion of this material retained on site post-harvest suggests that the method trialled for integrated harvest of woody biomass would ensure sites were not denuded of nutrients and that soil would be protected by a slash bed, therefore maintaining the site's sustainability and productive capacity. Site preparation costs may also be reduced through removal of larger woody material, contributing to better conditions for deep ripping, planting and other post-harvest silvicultural works.

5 CONCLUSION

The integration of the harvest and extraction of a stemwood biomass product (fibreplus) as part of existing conventional harvest operations in Australian radiata pine plantations had no impact on the harvesting phase, but reduced the productivity of the extraction (forwarding) phase of the operation. The additional extraction costs attributable to the fibreplus product were estimated to increase the total unit costs of harvesting and extraction by ~4.9%. However, these costs are sensitive to changes in machine productivity and costs. How these results are applied in the current cost and/or pricing structures will determine if it is economically viable. The method employed will also impact on the economics and integrated management of the logistics activities of the log supply chain, and how the supply chain is planned, managed and adapted will also determine the economic viability of the product. Further research or simulations should be undertaken to determine the productivity and cost impacts in stands that yield less high value sawlog and more fibreplus product, as well as the energy generation potential of the product. From an environmental perspective it is unlikely that the proposed method will cause any detrimental environmental impacts as sufficient biomass was left on site to ensure that it was not denuded of nutrients and the soil was protected by a slash bed.

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Table 1: Work elements for harvesting and processing phase

Moving/Positioning: Starts when the wheels or tracks begin to rotate and/or the harvester's boom begins its swing towards the next tree and ends when the harvesting head clamps onto the base of the next tree or the machine starts to perform some other activity.
Felling: Starts when the harvesting head clamps onto the base of the tree, immediately prior to the felling cut, and any machine movement momentarily ceases, and ends when feed rollers are activated, or the tree is horizontal, or the first bucking cut is made to reset the harvesters length measurement, (whichever occurs first).
Processing: Starts when feed rollers are activated, or the tree is horizontal, or the first bucking cut is made to reset the harvesters length measurement, (whichever occurs first), and ends when the bucking cut on the last log is made and the log is dropped on the extraction track pile.
Stacking/Bunching: Starts when the harvester's boom commences a swing to any processed log product, (including any move to retrieve, move or 'pile' on the extraction track any processed logs) and ends when the machine starts to perform some other activity.
Brushing/Clearing: Any interruption to work elements to remove non-merchantable trees or clear processing debris/slash or undergrowth.
Travel: The time taken to turn the machine around to start a new row (or swath) of trees. Starts when the wheels or tracks began to rotate and ends when the harvesting head clamps onto the base of the next tree or the machine movement ceases to perform some other activity.
Delay: Any interruption to a work element. Delay cause is recorded.

Table 2: Work elements for the forwarder extraction phase

Travel Empty: Starts when forwarder commences travel into the harvest area from the roadside or landing area and ends with the start of the first crane movement to collect logs from the 'piles' on the extraction track.
Loading: Starts with the commencement of the first crane movement to collect logs from the 'piles' on the extraction track and ends when travel loaded back to the roadside or landing area commences.
Moving During Loading: Includes the forwarder movement along the extraction track between log piles with no crane movement during loading. Starts only when the machine begins to travel (wheels begin to rotate) along the extraction track to another log pile. This time element ends when the crane recommences movement to new log pile.
Travel Loaded: Starts when travel to the roadside or landing area with a full or completed load commences and ends when travel ceases at the unloading site (roadside or landing area).
Unloading: Starts with the commencement of the crane movement to unload logs from the forwarder's bunk and ends when the crane is parked after the last grapple load has been unloaded.
Stacking: Any time to adjust or align the logs in a stack at roadside not directly associated with forwarder unloading or truck loading.
Delay: Any interruption to a work element. Delay cause is recorded. Includes any wait for the truck when the forwarder is directly loading the truck from the forwarder's bunk.

Table 3: Cost assumptions

	Harvester	Forwarder
Operating Days Per Year	249	249
Shifts per Day	1	1
Hours per Shift	10.0	10.0
Purchase Price (AUD)	950,000	660,000
Machine Life (yrs)	5	7
Salvage Value (% of purchase price)	0%	0%
Utilisation Rate, PMH/SMH (%)	60%	80%
Repair and Maintenance (% of depreciation)	75%	75%
Interest Rate (% of average yearly investment)	9%	9%
Insurance and Tax Rate (% of average yearly investment)	6%	6%
Fuel Consumption (L/PMH)	31.0	20.0
Fuel Cost (AUD/L)	0.98	0.98
Oil & Lubricant (% of fuel cost)	50%	50%
Labour costs (AUD/SMH)	46.59	46.59
Supervision (% of Labour Costs)	10%	10%

Table 4: Results of pre-harvest inventory for the study areas

	Control		Fibreplus	
	Plot	Site	Plot	Site
Plot Area (ha)	0.5	2.0	0.5	2.0
No. of Trees (n)	100	393	101	375
Stocking (sph)	200	197	202	188
Mean Tree Volume (m^3)	2.52	2.73	2.24	2.80
Mean Tree Diameter, DBHOB (cm)	52.6	52.1	49.9	53.6
Mean Tree Height (m)	34.3	38.1	33.7	37.0
Basal Area (m^2/ha)	44.3	41.9	40.1	42.3
Merchantable Volume (m^3/ha)	504	537	452	525

Table 5: Yields (GMt and GMt/ha) by log product assortment from the two study areas

	Log Product Assortment				Total Study Yield	Yield/ha (GMt/ha)
	Sawlog		Pulp	Fibreplus		
	Long (6.1 m)	Short (3.7m or 4.9 m)				
Control Plot	211	24	20	N/A	254	509
Control Site	853	123	52		1029	514
Control Study Areas (GMt/ha)	**426**	**59**	**29**			**513**
Fibreplus Plot	192	31	14	8	244	489
Fibreplus Site	775	108	58	48	989	494
Fibreplus Study Areas (GMt/ha)	**387**	**56**	**28**	**23**		**493**

Table 6: Results of the comparison of mean time by work element per tree in the Control and Fibreplus Plots (minutes)

Work Element	Control Plot	Fibreplus Plot	Difference	95% C.I. for Difference	*P*-value
Moving/Positioning	0.20	0.22	-0.02	(-0.04, 0.01)	0.285
Felling	0.19	0.17	0.02	(-0.01, 0.04)	0.135
Processing	1.07	1.02	0.05	(-0.06, 0.16)	0.382
Stacking/Bunching *	0.01	N/A	N/A		
Brushing/Clearing	0.07	0.05	0.02	(-0.01, 0.05)	0.301
Travel	0.10	0.10	0.01	(-0.19, 0.21)	0.948
Mean Cycle Time per Tree	**1.64**	**1.55**	**0.08**	**(-0.17, 0.33)**	**0.522**
Sample Size (n)	100	101			

* The Stacking/Bunching work element did not occur in the Fibreplus Plot.

Table 7: Model coefficients and goodness of fit statistics for the harvester productivity models for each plot

	β_0	β_1	R^2	Mean Bias	Mean Average Deviation	RMSE
Control Plot	71.7	38.4	0.33	0.00	12.02	96.86
Fibreplus Plot	62.1	51.3	0.61	0.00	10.21	92.63

Table 8: Comparison of mean time by work elements for forwarded loads in the Control and Fibreplus study areas (minutes)

Work Element	Control Areas	Fibreplus Areas	Difference	95% C.I. for Difference	*P*-value
Travel Empty	2.10	1.62	0.48	(0.13, 0.84)	0.007
Loading	6.16	6.77	-0.61	(-1.64, 0.41)	0.239
Moving During Loading	1.81	2.00	-0.19	(-0.95, 0.58)	0.632
Travel Loaded	1.20	1.23	-0.03	(-0.25, 0.20)	0.830
Unloading	4.85	4.92	-0.07	(-0.37, 0.22)	0.599
Mean Cycle Time per Load	**16.50**	**16.81**	**-0.31**	**(-1.97, 1.36)**	**0.716**

Table 9: Comparison of forwarder's mean productivity (GMt/PMH$_0$) between the study areas by log product extracted (number of full loads/cycles in brackets)

Product	Control Areas	Fibreplus Areas	Difference	95% C.I. for Difference	*P*-value
Long Sawlog	112.7 (35)	108.7 (36)	4	(-2.6, 10.7)	0.229
Short Sawlog	56.5 (8)	58.1 (6)	-1.6	(-5.2, 2.0)	0.357
Pulpwood & Fibreplus/Pulpwood	41.0 (4)	31.5 (9)	9.4	(4.96, 13.9)	0.002

Figure 1: Fibreplus stack

Figure 2: Scatterplot of Processed Tree Volume vs Productivity with regressions for harvesting of 'normal trees' grouped by plot