FOREST GROWERS RESEARCH

GE Murphy & Associates
Forest Engineering Research and Consulting

PO Box 1127
Rotorua 3040
Ph.: + 64 7 921 1883
Fax: + 64 7 921 1020
Email: forestgrowersresearch@fgr.nz
Web: www.fgr.nz

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In-forest debarking: a review of the literature

Glen Murphy

Research Provider:
GE Murphy & Associates Ltd
Rotorua, New Zealand

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EXECUTIVE SUMMARY

Debarking of logs remains an essential task within the value chain of all timber processing industries as wood needs to be debarked before it can be processed into further products. The question is "where should the debarking task take place" and "how should it be done".

This literature review focusses on debarking early in the supply chain – either at stump, or on the log landing (in-forest debarking, or IFD), or at nearby satellite yards. Where possible, attention was given to debarking New Zealand's two most important plantation species; namely, radiata pine and Douglas-fir.

In-forest debarking was found to have a wide range of advantages and disadvantages that impact from forest establishment through to delivery of logs to domestic mills, or to shipside for export markets. IFD impacts, positively and negatively, both supply chain costs and revenues. Debarking is likely to reduce harvesting productivity by at least 10%.

Bark accounts for 11% to 13% of the over-bark volume on standing radiata pine or Douglas-fir trees. Handling of logs in the felling, extraction and processing activities has been found to unintentionally remove up to 80% of the bark of radiata pine and up to 65% of Douglas-fir. The extent of bark removal has been found to depend on season, harvesting system, and harvesting equipment.

The review identified that there were a wide range of technologies that had been proposed or developed for intentionally removing bark from trees, logs and woodchips. These ranged from chemical, biological and mechanical debarking of standing trees, to manual, semi-manual and mechanised debarking of stems, logs and woodchips. The technologies include the use of mobile systems suited for IFD and stationary systems suited for operation in satellite yards or mills.

Debarking standards required by processing mills (saw, veneer, roundwood, pulp, etc.) and phytosanitary treatment for international markets limit residual bark content to 2% or less. Some pulping operations specify as little as 0.5%. IFD systems will have to meet this goal. Otherwise additional debarking may be needed further down the supply chain.

IFD of eucalypts using harvester/processor heads is well established around the world. Focus is now shifting to developing these types of IFD systems for conifers. Trials with modified harvester/processor heads have been carried out in New Zealand, Europe and Chile. To date none of the trials have consistently achieved a residual bark target of 2%.

With some debarking systems greater bark removal can be achieved but at the expense of increased debarking time and cost, and reduced revenues due to wood fibre losses and wood damage.

Automated approaches for controlling debarking efficiency and wood fibre losses are reported in the literature. These may have application in-forest or at satellite yards. Multi-machine systems may also be required to meet the 2% residual bark content target.

Recent modelling of forest-to-mill/port supply chains has shown IFD to be economically viable. Further development of equipment and systems is needed, however. The literature review identified methods and equipment that could be applicable to that further development.

INTRODUCTION

New Zealand is a large producer of forest products. For the year ending September 2019, 36.5 million cubic metres (m^3) of roundwood was removed from plantation forests. Thirty-nine percent (13.8 million m^3) was used by domestic markets and 61% of all roundwood produced was exported as logs (22.7 million m^3).

Logs that are utilised by domestic manufacturers are mainly unpruned saw logs for construction timber, plus pruned logs for producing high-value solid wood products for the joinery, millwork and furniture industries, veneer logs for plywood and laminated veneer lumber (LVL) and pulpwood. The New Zealand sawmilling industry used 8.68 million tonnes of plantation forest saw logs in the year ended December 2017 (Ministry of Primary Industries). More than 3.67 million tonnes of pulpwood were used by pulp mills and reconstituted board mills (medium density fibreboard and particle board) in the year ended December 2017. Logs are also used as raw material to roundwood plants which produce and preservative-treat posts, piles for houses etc., and poles for agricultural and horticultural uses, for construction and for use as transmission poles.

New Zealand forest products exports were worth around NZ$6.93 billion in 2019, reflecting the importance of the sector to the national economy (NZFOA 2019). In terms of demand for forest products, there has been a fundamental shift in overseas market share for New Zealand's forest products in recent years. In 2019, China represented 53% of New Zealand's total forest product exports by value ($3.558 billion), compared to just 4% in 1992, and 79% by export log volume (17.99 million m^3).

Harvesting operations in New Zealand face some big challenges now and into the future; including labour shortages, rising costs reducing competitive advantage, increasing barriers to long term sustainability, and poor profitability of small forest holdings. In 2017 Forest Growers Research Ltd (FGR) developed a successful proposal for Primary Growth Partnership (PGP) funding to address these challenges with a goal of developing a new forestry value chain. One approach is to restructure the value chain by moving the log debarking “link” to an earlier point in the chain.

Bark is usually removed from logs at some point along the forest to wood-processor supply chain for a number of reasons; grit and sand in bark can damage sawing equipment (Harkin and Rowe 1971), it hinders the ability of sawmill scanning technologies to perform their functions accurately, it causes safety, fire and disposal problems, it increases mill cleaning and maintenance time, it reduces the ingress of chemicals in preservative treated logs, it contributes no fibrous material but adds dirt and other contaminants to wood pulping processes, and it can be a phytosanitary risk harbouring insects under the bark.

In-forest debarking of trees, prior to processing, is expected to have several advantages.

- Better log making decisions are expected due to better visibility of the log attributes.
- 4% to 5% more wood could be transported per truck load with debarked logs than bark-on logs (benefit to log processor).
- Offcuts would be clean of bark allowing possible further processing into saleable chip or other products.

- The China market accepts debarked logs[1] however as a risk reduction treatment only, not as a phytosanitary treatment. IFD would reduce the amount of chemical fumigation with methyl bromide required at NZ ports.

The New Zealand forest estate comprises mainly radiata pine (*Pinus radiata*, 90%), and Douglas-fir (*Pseudotsuga menziesii*, 6%). Other softwoods (2%) and hardwoods (2%), including eucalypts, make up the remainder (NZFOA 2019).

Waratah NZ Ltd and Satco Ltd have each developed debarking processor heads for eucalyptus species. Debarking eucalypt stems prior to processing is successful and is achieved by the rollers rotating the stem as it goes through the head, stripping off the fibrous stringy bark. Eucalypt bark comes off easily if logs are fresh. The process for debarking eucalyptus is not transferable to radiata pine without extensive modification to the head and the length measuring system.

Debarking radiata pine stems prior to processing is currently possible; however, it is slow and takes many passes to remove most of the bark. Southstar Equipment Ltd trialled debarking radiata pine in New Zealand and Chile with only limited success using their standard processing head.

Figure 1. SATCO Eucalyptus Debarker working in a NZ eucalypt plantation (https://www.youtube.com/watch?v=zRo5ic15Zfo)

This report focuses on literature that relates to IFD of stems and logs; with emphasis on methods and technology that might be applied in the debarking of conifer species, particularly radiata pine and Douglas fir, using a debarking harvester/processor head. The report purposefully covers a broader range of topics and technologies since these may lead to novel ideas for a suitable IFD system.

[1] Export phytosanitary requirements specify that no more than 2% of a parcel of logs, or 5% of any individual log, by volume can have bark attached.

Objectives

The research presented in this report focused on reviewing IFD systems that might be suitable for New Zealand. The main objectives of this study were to provide:

- Information about bark and bark characteristics for conifers, with emphasis on radiata pine and Douglas fir.
- Information on debarking standards for domestic and export logs.
- Information on technologies for removing bark in-forest or at in-forest processing yards.
- Reports on recent experience with debarking conifers using harvester/processor heads.
- Estimates of the economics of debarking at various points in the supply chain.

LITERATURE REVIEW

Bark and bark characteristics

Bark plays important roles for the growth and survival of living trees. It is made up of two types of tissues: inner bark and outer bark. The role of the inner bark is to transport sugars around the plant for growth. The role of the outer bark is one of protection.

Bark makes up 5 to 30% of the over-bark volume and weight of trees (Meyer 1946; Miles and Smith 2009). The proportion of the stem that is bark varies with species, site quality, age, tree size, and location-on-the-stem. Miles and Smith (2009) reported that bark makes up 12% of the over-bark volume of radiata pine in its natural habitat in California. Similarly, in New Zealand, bark accounts for 12 to 13% of over-bark volume and 7 to 8% of over-bark green weight for mature radiata pine boles prior to felling and log handling (Murphy and Cown 2015).

Radiata pine bark volume percent (Figure 2) varies

- with location in a stem: decreasing exponentially from the base of the stem [~22%] to the merchantable wood limit [~8%]
- with tree size: small trees [17%] accounting for almost double the proportion of over-bark volume than large trees [9%]; and
- with site: a small decrease in bark volume with mean average temperature decrease was noted; equivalent to about one quarter of a percent of over-bark volume per degree decrease in mean average temperature. Bark volume, therefore, tends to decrease with elevation and from north to south in New Zealand.

Bark makes up 15 to 18% of the over-bark volume of Douglas-fir in North America (Maguire and Hann 1990; Miles and Smith 2009). This is somewhat higher than the 11% reported for Douglas-fir in Kaingaroa Forest in New Zealand but has been shown to be provenance and site-dependent (McConnon *et al.* 2003). Like radiata pine, Douglas-fir bark volume percentage varies with height in the tree (Figure 3).

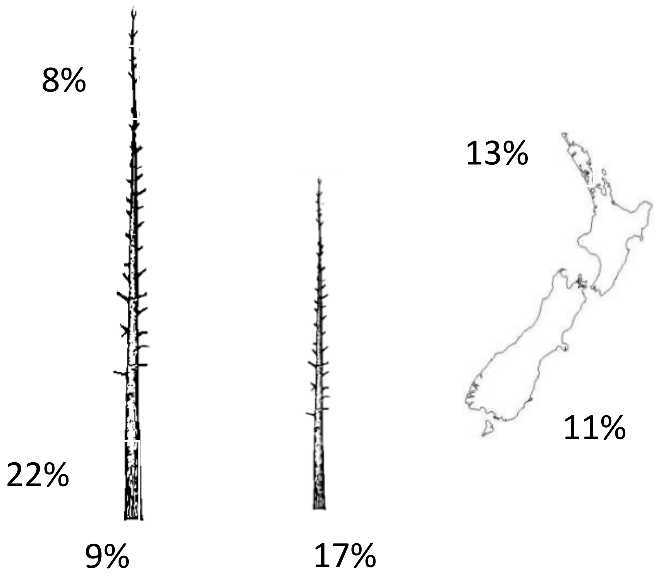


Figure 2. Radiata pine bark, as a percentage of over-bark volume in standing trees, varies with height in a tree, with tree size, and with site conditions. Source: Murphy and Cown (2015)

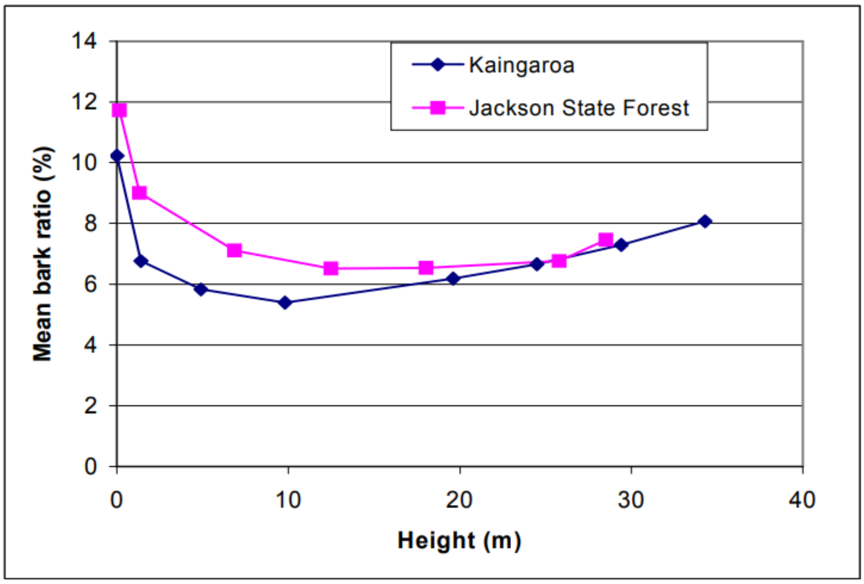


Figure 3. Douglas-fir bark ratio[2], and by implication bark volume percentage, varies with height in a tree and with provenance; Jackson State Forest is in northern California. Source: McConnon et al. 2003.

Tree and log handling activities (felling, extracting, delimbing, bucking, storing, loading, transporting, and unloading), excluding intentional debarking, result in some bark being lost. The type of harvesting system used affects the amount of bark lost. This will be covered in more detail shortly.

Season, environmental factors, and species also affect bark loss (Grobbelaar and Manyuchi 2000). Bark is more easily knocked off stems, logs, and wood chips in spring, when the sap is rising, than at other times of the year (Wilcox *et al.* 1954; Berlyn 1966; Moore and McMahon 1986; Neville 1997;

[2] Bark ratio (BR) is double bark thickness divided by over-bark diameter. Bark volume % equals $(2*BR - BR^2)*100$

Murphy and Acuna 2016). Woollons and Powell (1984) reported 50 to 60% more bark arriving on logs on a daily basis to a large radiata pine mill (>600,000 tonnes of wood per year) in New Zealand during winter months than summer months. Murphy and Pilkerton (2011a) found that there was a substantial (up to five times) increase in bark loss during late spring and early summer compared with the winter season for mechanically delimbed and bucked Douglas-fir and ponderosa pine (*Pinus ponderosa*) (Figure 4). They also found that Douglas-fir incurred almost twice the bark loss compared with the loss from ponderosa pine.

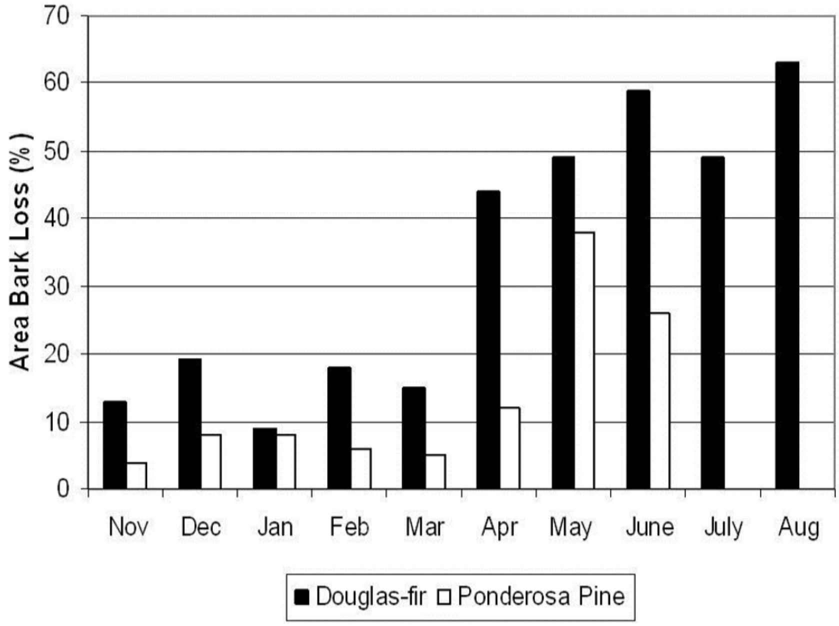


Figure 4. Percent bark loss, as a function of stem surface area, for Douglas-fir and ponderosa pine stems by month in Oregon. Source: Murphy and Pilkerton (2011).

Harder *et al.* (1978) found for the 42 species they studied in the USA that the bonding strength of the wood with the bark (BWBS) increased dramatically during the dormant season and the chance of bark being abraded was much reduced during this time period. They reported that BWBS differed between hardwoods (8 to 24 kg cm^{-2}) and conifers (5 to 10 kg cm^{-2}) during both the dormant and growing seasons in North America. Douglas-fir was found to have lower BWBS, and hence would be easier to debark, than ponderosa pine for both dormant and growing seasons (Table 1).

Table 1. Effect of season and species on bark/wood adhesion (BWBS) for samples gathered at breast height on a stem. Source: Harder *et al.* (1978), Moore and McMahon (1986)

Species	Bark/Wood Adhesion (kg cm^{-2})	
	Growing Season	**Dormant Season**
Douglas-fir	3.4	8.0
Ponderosa Pine	5.0	9.6
Radiata Pine (mid-rotation)	2.1 to 3.0	NA

Harder *et al*. (1978) did not include radiata pine in their sample of species. Moore and McMahon (1986), however, reported BWBS's for 14-year-old radiata pine in Australia of 2.1 kg cm^{-2} for Spring and 3.0 kg cm^{-2} for Summer seasons. BWBS is known to increase with tree age and when trees are growing under stress (e.g. competition, drought, and damage) (Wingate-Hill and MacArthur 1991a). BWBS parallel to the grain has also been found to be greater than BWBS perpendicular to the grain (Moore 1987 *ex* Wingate-Hill and MacArthur 1991a: Tsoumis 1992). Murphy and Pilkerton (2011a) noted that freshly felled and delimbed Douglas-fir stems were more likely to lose bark than stems which had been left for a few weeks after felling during the “sap-rise” season. Others have also found that bark adhesion increases as stems dry out after felling (Duchesne & Nylander 1996, Kubler 1990).

Advantages and disadvantages of in-forest debarking

The following advantages are noted for IFD (Murphy *et al.* 2017):

- Volume of wood on weight-limited trucks can be increased if bark is removed. This can lead to reductions in transport costs (Miranda *et al.* 2002) and the number of trucks on the road that are required to transport a given volume of wood.
- Fresh wood is about 50% water by weight. Removing bark increases drying rates and water loss (Defo & Brunette 2006; Visser *et al.* 2014; Murphy *et al.* 2019a). If truck payloads are weight limited, reducing the amount of water in a log increases the solid wood volume that can be carried.
- Bark takes up storage space. Removing bark improves solid wood volume storage in mill yards for the same storage footprint.
- Assuming that debarking is an acceptable risk reduction treatment for export logs and that debarking can be carried out to an acceptable standard in-forest, fumigation costs can be reduced or eliminated. Safety issues associated with handling toxic chemicals for fumigation can also be reduced or eliminated.
- Solid wood volume storage at ports is improved. This also leads to reduced space for equivalent volumes and reduced distances wood is carried from stack to berth and potentially reduced handling costs.
- If more accurate under-bark measurements can be gathered on harvesting/processing machines, there is an opportunity to revert to volume-based payment systems for harvesting and transport, thereby eliminating the need for weight scaling systems with associated costs.
- Loose bark at ports is considered to be a marine contaminant and a source of dust pollution (Williams 2002, McKenzie and Cairns 2019). Eliminating bark before logs arrive at the port would reduce this environmental impact.
- If bark is removed in the forest and left on site as part of the nutrient pool there is potential to reduce fertiliser costs.
- Below deck log export cargo is fumigated on-route to the customer. Above deck cargo has to be fumigated or debarked prior to loading. Fumigation is only carried out at a few ports in New Zealand. Where debarking is allowed as an alternative to fumigation, the need for ships to travel to a fumigation port to pick up above deck cargo is eliminated with IFD, saving on port fees and shipping fees.
- Collection, transport and disposal costs for bark waste in ports and mills are eliminated, but potential revenue from bark sales is lost.

The following disadvantages are noted for IFD (Murphy *et al.* 2017):

- Either an additional machine (and cost) is required for debarking in forest or productivity is reduced and cost increased for a harvester/processor that also must debark logs. Harvesting system cost increases ranging from 0% (Strandgard *et al.* 2015) to 17% (Magagnotti *et al.* 2011) have been reported for systems that include IFD.

- If wood is sold to customers on a weight basis after it has been allowed to dry, additional solid wood (m^3) must be delivered to customers, to replace the bark removed and water that is lost.
- Forwarder loading time and log extraction costs may be increased due to handling slippery logs for cut-to-length systems.
- Truck loading time and transport costs may be increased due to handling slippery logs and attaching an extra tie-down per packet of logs.
- Handling time and costs at mills and ports may be increased due to handling slippery logs.
- Site preparation costs, due to clumps of bark left around landings, may increase from debarking carried out on landings.
- Larger landings, with consequent increased construction costs and negative environmental impacts, may be required to accommodate storage of logs for additional drying days.
- Larger landings may be required to accommodate on-landing debarking for tree length harvesting systems.
- Value losses due to sap stain may be increased because of a greater amount of bark being purposefully removed (Murphy *et al.* 2019b). It should be stressed that current harvesting systems already result in significant bark loss and that the value loss referred to here is the incremental value loss that would occur from IFD.
- Increased value losses in tree length systems due to contamination from dirt and grit getting onto the wood surface.
- Reduced revenues from bark sales, if bark is left in the cutover or on landings.

Safety issues associated with in-forest debarking

Mechanised IFD in New Zealand operations is likely to involve large equipment and large logs with inherent safety risks. Although not specifically referred to in the approved code of practice for safety and health in forest operations, IFD could be expected to meet the safety requirements for operation of mobile machines and work on landings (ACOP 2012).

Brown (2016), as part of a New Zealand Forest Growers Levy Trust funded project on IFD, reviewed the safety implications of handling logs in the supply chain once they have been debarked. The following is largely extracted from his report.

Changing the form or condition of the log in the forest by removing the bark introduces different safety concerns in the handling, storage and transport of the logs that will need to be properly understood and addressed with planning, training and safety systems.

A key difference between logs with bark on and debarked logs is the coefficient of friction on the log surfaces and how that is affected when the logs are wet. Due to the rough irregular surface created by bark on a pine log the coefficient of friction between the logs and any solid surfaces they rest on are relatively high and relatively unaffected when the logs are wet. With the bark removed the logs become much smoother and thus have a much lower coefficient of friction that is significantly further reduced by a small amount of water on the surface.

There have been several trials conducted around these coefficients of friction of logs as it relates to load securement in transport and these have become the underpinning knowledge for load securement standards in North America, Australia, and New Zealand. Though the trees across these regions are quite different, the effective coefficient of friction is similar. For logs with bark on the static coefficient of friction tends to be between 0.7 and 0.8 (i.e. a force equivalent to 70% to 80% of the weight of the log is required to get the log sliding) and the dynamic coefficient of friction drops to about 0.5 (i.e., once the log is sliding it requires an applied force equivalent to about half the weight of the log to keep in moving). For logs with bark removed the static coefficient of friction typically drops to between 0.5 and 0.6, with denser (harder) woods tending to have a lower coefficient when they are dry and as low as 0.3 if they are wet (under rainy conditions). The dynamic coefficient of friction for dry debarked logs is typically between 0.3 and 0.4 and as low as 0.2 for wet logs. This reduction in the coefficient of friction, particularly under wet conditions will have important safety implications for the handling, storage and transport of the logs in the supply chain.

Recent incidences of debarked logs slipping out of the forks of loading and unloading machines in New Zealand mills give rise to safety concerns over handling of debarked logs. Preliminary reviews of equipment options, however, indicate that handling and storage issues are likely to be relatively minor and primarily will be addressed through operator training and some minor consideration in equipment selection.

For loading and unloading of debarked and wet logs, it will be preferable to use handling equipment that has projecting metal edges, to overcome a lack of friction, and is able to squeeze bundles of logs tightly. A bypass grapple, for example, includes such features.

In the training solutions it will be important to ensure operators understand how slippery the debarked logs are and how significant the reduction in friction will be when the logs are wet. Under known wet conditions it will be advisable to handle the logs in smaller bundles when loading and unloading to reduce risk of log slippage. Similarly, under wet conditions consideration will need to be given to pile technique in storage to ensure piles are even, level and well supported to compensate for the difference in friction.

Compared with handling and storage issues, transport is the biggest safety concern, due to the slipperiness of debarked logs. Hence special attention must be given to effective securing of such logs on trucks to avoid load loss.

A 2004 TERNZ study makes a specific recommendation related to debarked logs with a dynamic coefficient of friction below 0.4. Their recommendation was to have one additional tie-down on each bunk (Baas *et al.* 2004). Similarly, the 2012 Log Transport Safety Council, Log Load Securing Requirements require one additional load tie-down per packet when transporting debarked logs.

Figure 5. Example of a rear guard on a log trailer and front guard behind the truck cab to contain the load and block any log slippage.

An alternative to the increased number of load tie down devices, would be to introduce headboards and/or tail boards to the trailer to contain the load and block any log slippage. (Figure 5). This is not a particularly efficient solution as the extra weight significantly reduces payload and, by constraining the loading space, can make log loading more difficult and time consuming.

Brown (2016) comments that a portion of bark free logs already exists in most supply chains and operators have developed practices to accommodate these.

Harvesting system and equipment impacts on bark loss

Understanding what factors affect bark loss and removal will assist participants in the supply chain to manage such issues as value loss associated with skidding and processing wounds (Ohman 1970; Uzonovic *et al.* 1999), storage capacity at mills and ports, transport costs (Figure 6) and bioenergy/bioproducts supply (Murphy and Pilkerton 2011b), and phytosanitary risk (FAO 2011). Of particular relevance to this literature review, it will also assist with harvesting equipment and system design (Hartsough *et al.* 2000). Harvesting equipment results in unintentional bark removal. The amount of bark removed from logs on trucks loads delivered to a port facility on the same day varies from almost total bark removal to almost none (Figure 6).

Figure 6. Variation in bark removal from truck loads delivered to the same customer on the same day. Almost all bark had been removed from logs on the left (red arrows point to a few patches of remaining bark. Very little bark had been removed from logs on the right.

More than four decades ago, Harris and Nash (1973) reported bark losses after felling and extraction to a landing in New Zealand of approximately 10% for radiata pine. This is substantially lower than bark losses found in more recent studies by Murphy and Acuna (2016) for Australia (~40%) and New Zealand (~65%). Differences between these countries and between these time periods can be largely attributed to the harvesting systems used and, possibly, the change in average piece size being harvested.

The predominant harvesting system used in the Murphy and Acuna (2016) Australian studies was the cut-to-length (CTL system), whereas the predominant system used in their New Zealand studies was tree-length extraction and mechanized processing. The CTL system resulted in about 30% less bark removal, in absolute terms, than tree-length extraction and mechanized processing. There was no significant difference between Australia and New Zealand in bark removal for CTL systems. In the 1970's the predominant harvesting system used in New Zealand was tree-length extraction with a skidder or tractor, and manual delimbing and bucking with a chainsaw. Murphy and Acuna (2016) showed that this harvesting system (49%) resulted in an average bark removal that was 20% lower than found for tree-length extraction and mechanized delimbing and bucking (69%). Forty-nine percent is much higher than the figure reported by Harris and Nash (1973), however. The authors hypothesized that the difference may have been due to the change in average tree size in the intervening period. The current rotation age in New Zealand is 25 to 30 years. In the 1970's it was 35 to 45 years and average tree sizes being harvested were close to double what they are today. The larger trees had thicker bark which may have been less prone to bark loss during extraction.

Murphy and Acuna (2016) found that there were differences, not only between CTL and tree-length harvesting systems, but also between different processing methods for tree-length systems. Mechanized delimbing and bucking (69%) resulted in more bark removal than manual delimbing and bucking (47%), while bark removal from static delimbing and manual bucking (58%) lay between the two of these methods. Other researchers have found that mechanized delimbing and bucking resulted in more bark removal (13% to 39%) than manual delimbing and bucking (1% to 8% for two Corsican pine (*Pinus nigra*) sites in Great Britain (Lee and Gibbs 1996). Similarly, Murphy and Logan (2016) found that mechanized delimbing and bucking resulted in more bark removal (75%) than static delimbing and manual bucking (48%) for a radiata pine site in New Zealand.

A comparison of bark removal from activities prior to mechanized processing and post-mechanized processing in New Zealand showed that about three-quarters of the bark removal occurred during the felling and tree-length extraction activities and about a quarter during the delimbing and bucking activities (Murphy and Acuna 2016). Field visits to forest landings, central processing yards, and ports by the first author has shown that bark continues to be knocked off the stems and logs each time they are handled. The greater the number of times a log is handled the greater the bark loss.

The design of the mechanized processor head has been shown to affect the amount of bark loss. Granlund and Hallonborg (2001) report that bark loss by five harvesters, all fitted with rubber rollers, ranged from 0 to 5% in Sweden. Lee and Gibbs (1996) found at two Corsican pine study sites (Thetford and Inverness) in Great Britain that there was less bark loss on logs that had been mechanically delimbed and processed with rubber rollers (29% and 6%) than with spiked rollers (39% and 8%). Uzonovic *et al.* (1999) reported bark losses ranging between 7% and 35% for Corsican pine logs that had been mechanically delimbed and processed with rubber feed rollers and chains.

Anecdotal comments from processor operators in New Zealand indicated that the number of delimbing knives on a processor head also affected the amount of bark removed, the greater the number of knives, the greater the bark removal. Comparisons by Murphy and Acuna (2016) of two 4-knife processor heads with a 2-knife processor head, all fitted with spiked rollers, showed unexpectedly, however, that the 2-knife processor head resulted in more bark removal, not less, for one of the 4-knife processor heads but not the other. There were no significant differences between the 4-knife processor heads.

Comments from New Zealand processor operators indicate that location on the stem affects bark removal. It is believed that bark is more persistent on large butt logs with thick bark. It is also believed that although bark is thinner at the top of the tree and more likely to be abraded during processing, delimbing knives can have less contact with the bark at this location on the stem and remove less bark. Murphy and Pilkerton (2011a) reported that the location on the stem may have affected the amount of bark loss on ponderosa pine, with greater bark being removed towards the top of the stem, but there was no trend with location on the stem for Douglas-fir. Murphy and Logan (2016) found that location on the stem made no difference in radiata pine when stems were statically delimbed and manually bucked with a chainsaw, but location did effect bark loss when stems were mechanically delimbed and processed; there being greater bark removal towards the top of the stem. All but one of six studies by Murphy and Acuna (2016) showed that there was no significant difference in bark removal with location on the stem for radiata pine. The one study that did show a significant difference ran counter to the findings of Murphy and Logan (2016) in that bark removal on the upper portion of the stem was less, not more, than the lower or middle portions of the stem.

Technologies for removing bark in-forest or at satellite yards

Debarking location

Debarking can be carried out at the stump, at roadside/landings, at satellite yards, or in mill yards. The most appropriate location depends on such things as available technology, environmental constraints, energy sources, bark utilization or disposal, log characteristics, management objectives, phytosanitary requirements, and economics. Grobbelaar and Manyuchi (2000) list several advantages and disadvantages for debarking at each of these locations. These are shown below for debarking at the stump and at satellite yards or mill yards.

<u>Debarking at the stump</u>

- Mill debris, and associated bark transport and disposal costs, are minimised.
- Nutrient rich bark remains on site and minimises the cost and need of additional fertiliser.
- Managed bark disposal can assist in weed control and protection of the soil against erosion and loss.
- Bark removal is easier soon after felling.
- Debarking equipment may be limited in its ability to handle large logs.
- The accumulation of bark and debris in-field can potentially increase the fire hazard.
- Bark disposal practices can influence the re-establishment of the site after clearfelling.
- The accumulation of bark and debris in-field can potentially create favourable conditions for harmful insects or fungi.

<u>Debarking at the roadside or landing</u>

- Wingate-Hill and MacArthur (1991a) state that it is difficult to see any merit associated with either debarking at the roadside or at the landing from an environmental and economic viewpoint, since debarking at these locations often requires large landings and creates bark disposal problems.
- Stokes and Watson (1990) comment, however, that roadside flail delimbing, debarking and chipping allows the economical production of clear and acceptable chips in slash pine (*Pinus elliottii*) plantations in southern USA. Roadside debarking is an acceptance practice around the world. Ghaffariyan *et al.* (2013) and McEwan *et al.* (2017), for example, respectively describe CTL operations in radiata pine in Australia and tree length operations in Eucalypts in Chile where roadside debarking is carried out using chain flail debarker-chipper systems.
- Debarking stems after tree length extraction to roadside or landings for processing is likely to lead to logs with less grit and sand embedded in the wood and possibly reduced sapstain risk.

Debarking at satellite yards or mill yards

- Debarking logs in a wood yard shortly after felling can be physically and economically advantageous.
- Stationary debarking equipment requires a large capital investment.
- Where there is a market for bark, sales can offset some of the handling, transportation costs and fertilizer costs.
- Debarking in a central location can potentially reduce the debarking cost if volumes to be debarked are large enough.
- Various debarking aids or accessories (e.g. scanners, standby debarkers, water sprays) can be installed at the yard to enhance debarking efficiency and quality.

Chemical and biological debarking

In the 1940's and 1950's considerable effort was put into investigating application of chemicals into standing hardwood and conifer trees in North America to facilitate debarking after the trees had been felled (Berntsen 1954; Gammage and Furnival 1957). In 1959 a US patent for chemical debarking of trees was awarded (Ryznar 1959). The patent included recommendations on mixing an animal repellent and a highly visible dye with the treatment chemical due to its high toxicity. A wide range of chemicals were evaluated, including herbicides such as 2,4-D, and 2,4,5-T. Sodium arsenite, boronarsenate salts, and methanearsenate salts, all arsenic related compounds, were found to be the most effective in facilitating bark removal. A literature review on chemical debarking was published by Schutt (1960).

The recommended practice was to girdle the tree by completely removing bark around its circumference (Figure 7), apply the chemical onto the sapwood, then wait 4 to 12 months until the trees had died and bark was looser. Greatest success was obtained if the trees were girdled and chemical applied during the few months of sap-rise.

Figure 7. Sodium arsenite-treated girdle on western hemlock. Source: Berntsen (1954).

Although interest in chemical debarking continued into the 1960's in Australia (Truman 1969 *ex* Krilov 1980) and 1970's in USA (Miller 1975) it has not seen wide-spread use. Disadvantages associated with the use of chemicals for debarking include:

- Preparation of the stem and application of the chemical is labour intensive
- Bark is not always completely removed
- The most effective chemicals are highly toxic
- It can be damaging to the residual stand; some chemicals can be transferred via root grafting to living trees in the area
- It is only effective when the sap is flowing
- Stem breakage increased when the stems were harvested
- Tops breaking out during felling were a safety risk for tree fellers and machine operators
- Killing trees four to twelve months before felling resulted in a loss of growth, which could be significant for fast growing species.

Behrendt and Blanchette (1997) have shown that application of a white rot fungus (*Phlebiopsis gigantea*) to red pine (*Pinus resinosa*) logs can facilitate bark removal. They showed that the ease of bark removal increased with time after inoculating the logs with it; after 32 days bark "peeled off with some resistance in a few pieces" or "peeled off with little to no resistance in one piece". Other advantages found from applying the fungus were that it reduced the pitch content of wood (important for pulping processes) and inhibited detrimental blue stain fungi.

Manual debarking

Manual debarking is very labour intensive (Grobbelaar and Manyuchi 2000) and is preferred over mechanised debarking where labour costs are low. Advantages of manual debarking include: low capital cost, low environmental impact, good debarking quality, and no substantial fibre loss. Equipment used can include hatchets, axes, debarking spuds (Figure 8), and chainsaw mounted debarkers (Figure 9).

Figure 8. Removing pine bark with a debarking spud allows a less strenuous working posture than using a hatchet or axe.

Figure 9. Removing bark with a chainsaw-mounted debarking attachment. The attachment is fitted with two planer blades on a rotating cylinder.

Studies carried out in Brutian pine (*Pinus brutia*) forests in Turkey have shown that debarking with a chainsaw mounted debarker is three to five times more productive than debarking with an axe (3.35 m^3/hour vs. 0.63 m^3/hour) up to the point where bark thickness is 25 mm (Eker *et al.* 2011; Gülci *et al.* 2017). Beyond 25 mm bark thickness debarking with an axe has higher productivity.

Compression debarking

Wood pulping processes require that bark is removed from woodchips. A goal of achieving no more than 3% residual bark is sometimes expressed (Arola and Erickson 1972). Bark can be removed from chips post chipping or from the logs prior to chipping (Sharp 1989).

Compression debarking of wood chips is a method whereby a continuous single-layer flow of bark-on wood chips passes between two rotating steel rolls that have a nip spacing much smaller than the thickness of the wood chips. The compression and shear forces on the wood chips break the wood bark bonds. The chips adhere to the surface of the rolls and are removed with roll scrapers.

Arola and Ericksen (1972) investigated the effect of several natural and machine variables on bark removal. Natural variables included species, season of cut, pre-sized versus random mix, and fresh versus storage prior to chipping. Machine variables investigated included the nip pressure in the chip compression zone, the nip spacing, and the location of baffles beneath the rolls. Two hardwoods (Aspen and Hard Maple) and two conifers (Jack Pine [*Pinus banksiana*] and Loblolly Pine [*Pinus taeda*]) were tested.

Conclusions from the study were as follows:

- Single-pass compression debarking of wood chips failed to meet the goal of 3 percent residual bark. Additional processing of the wood chips would be required.
- Hardwoods (41% to 70%) had lower bark removal than conifers (57% to 80%)
- Bark removal was higher in the growing season (70% to 80%) than in the dormant season (41% to 57%)

- Jack Pine roundwood stored for 9 months had lower bark removal (58%) than fresh roundwood (72%).
- Bark removal decreased and wood recovery increased with increases in nip spacing.
- Bark removal increased and wood recovery decreased with increases in nip pressure.

Hillstrom (1974) followed up the work of Arola and Ericksen (1972) by investigating the effect of “drubbing” and screening, after compression debarking of wood chips, on bark removal. “Drubbing” is the process whereby chips are further subjected to some form of mechanical attrition. This was achieved by passing the chips through a cylindrical tumbler with internal impact hammers that beat the bark chip mass as the drum revolves. Two western US hardwood species (Red Alder and Big Leaf Maple) and two conifer species (Douglas-fir and Western Hemlock [*Tsuga heterophylla*]) were included in the tests. Bark removal achieved was 60% for Douglas-fir and 74% for Western Hemlock.

Wingate-Hill and MacArthur (1991b) describe an apparatus for compression debarking of logs in their US patent (No 5,022,446). The apparatus involves the application of substantial pressure to the bark of a log, to break the bond between the bark and the wood, and leave a tube of bark surrounding, but not separated from, the wood. The tube of bark is then cut into strips by a knife, which is typically mounted on a roller downstream from the pressure applying rollers, although the cutting of the bark may occur before, during or after the application of pressure to the bark. Fig. 4 of the patent (Figure 10 below) shows a log passing through two sets of three rollers (30, 31, 32 and 40, 41, 42). Each set of rollers maintains a significant radial pressure on the log as it is being transported through the debarking equipment. The effect of this pressure by the rollers is to compress the bark, causing expansion of the bark when the pressure is released, and separation of the bark from the wood. When the log is pressed against the roller (40), the bark is cut into at least one strip by the cutting edge (44) on the outer surface of this roller.

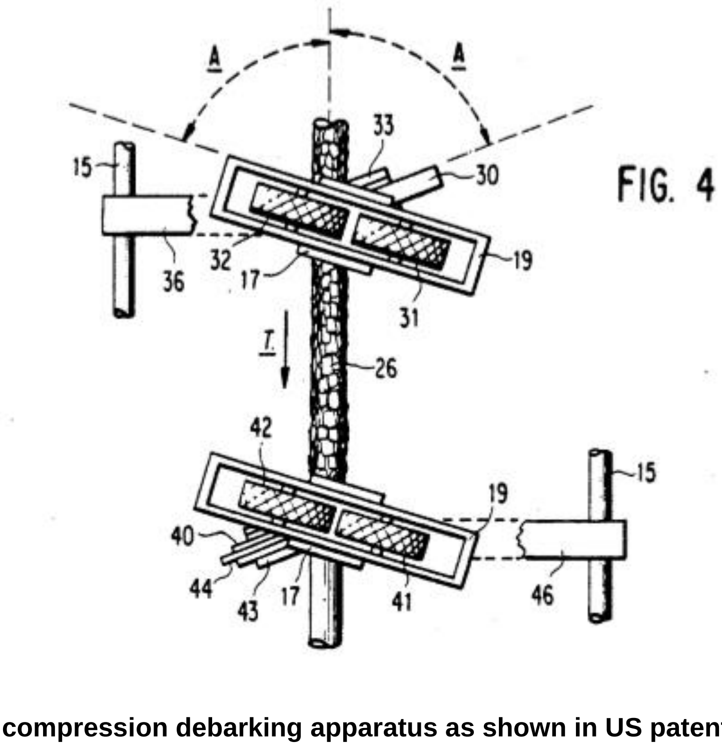


Figure 10. Log compression debarking apparatus as shown in US patent 5,022,446.

An earlier US patent (2,576,967) also utilised an apparatus for compression debarking of logs (Pauley and McCanna 1951). In this apparatus the log was held in a set of chucks and rotated while a carriage on tracks travels along the length of the log. The debarking head, mounted on an adjustable arm attached to the carriage, contains a small blunt tool which is pressed against the log with considerable force, sufficient to break the bark/wood bond. The debarking head is adapted to ride over the irregularities in the bark and, due to its small size, it subjects the hollows and depressions to the same pressure treatment as cylindrical logs. The patent does not provide detail on how the bark is removed once the bark/wood bond has been broken.

Drum debarking

Drum debarkers are usually large, expensive stationary installations more suited for application in satellite yards than in-forest, and for use with pulp logs rather than higher value saw logs or veneer logs (Figure 11). They operate either on a batch processing or a continuous process. As the drum revolves, the logs tumble against other logs and sometimes against baffles inside the drum. The bark/wood bonds are broken by the force from logs hitting each other and the bark is knocked off. The amount of bark removed is a function of the retention time inside the drum, drum rotational speed, and filling degree etc. Wood loss is also linearly dependent on retention time and is influenced by rotation speed

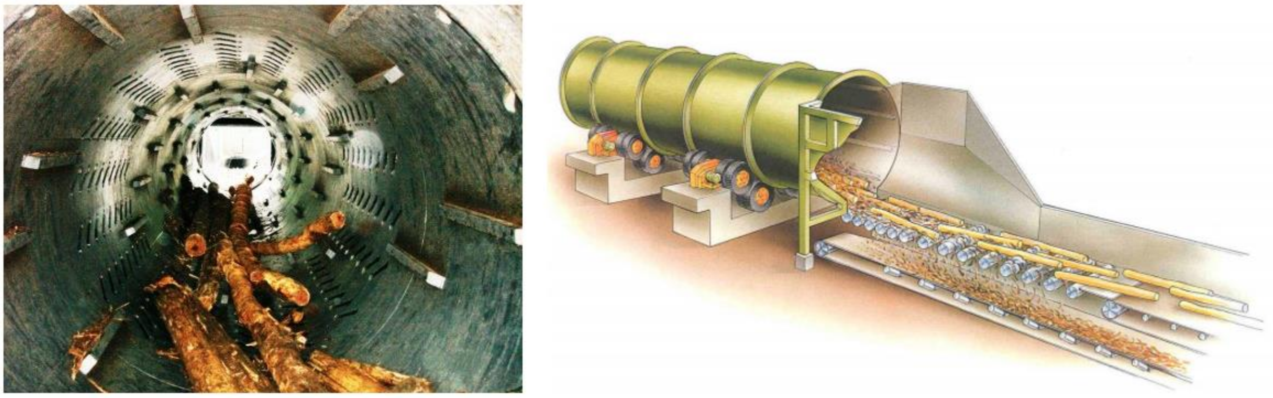


Figure 11. Two examples of drum debarking systems. In the system on the left, bark that is removed falls through slots in the drum. In the system on the right, bark is separated from the logs after the logs exit the drum.

An advantage of drum debarking is that they can handle a wide variety of piece sizes more efficiently than sequential, one-log-at-a-time, debarking systems (Wingate-Hill and MacArthur 1991a). Disadvantages include high capital cost, loss of wood fibre and breakage of small diameter timber. Debarking efficiency can also be reduced due to the cushioning effect of retained bark in the drum (Grobellaar and Manyuchi 2000). Baroth (2005) reports on several methods for reducing breakage and fibre loss and improving the efficiency of the debarking process.

Cradle and trough debarkers operate on a similar principle to drum debarkers. They utilise a continuous or batch debarking process and logs tumble against each other, knocking off the bark. Bark falls through the base of the container. Where they differ from drum debarkers is that the cradle or trough does not rotate. A system inside the unit agitates and rotates the logs (Figure 12). Trough debarkers usually have a smaller holding container with a gentler rotation of logs compared with large drum debarkers.

Productivity of a Swedish mobile trough debarker, removing 80% of bark from pine and spruce, was found to be 45 m^3 per delay free hour. Increasing the bark removal to 95% reduced the productivity by half (Dehlen *et al.* 1982 *ex* Wingate-Hill *et al.* 1991a).

Trough and cradle debarkers are less expensive than drum debarking, can be portable and used in-forest, and have low fibre loss.

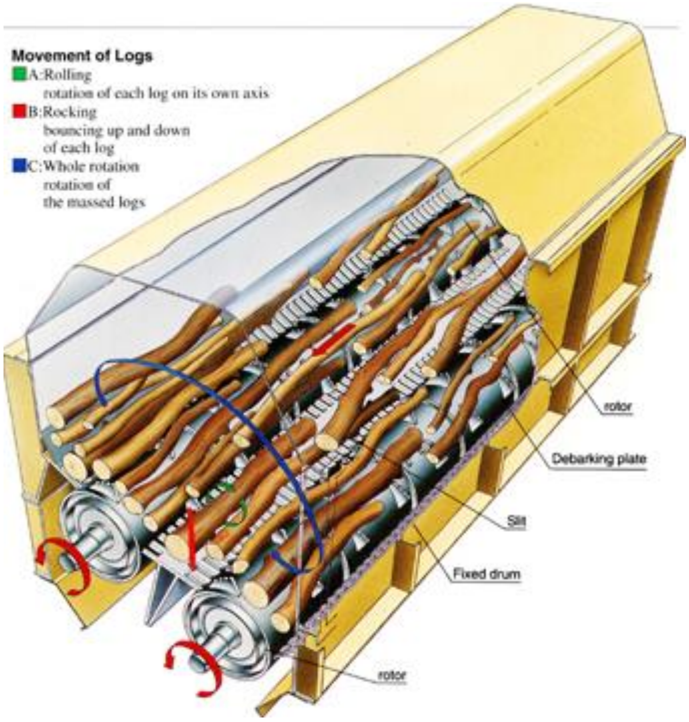
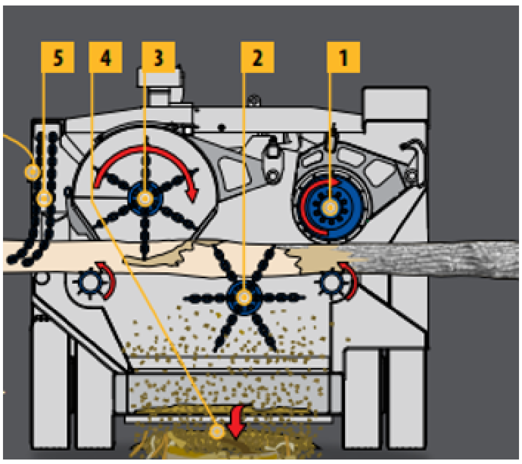


Figure 12. Example of a trough debarking system. Bark is removed through logs rolling against, and falling onto, each other and onto debarking plates inside the trough. Source: Fuji Kogyo Debarkers.

Chain-flail debarking

The basic chain-flail debarker involves hydraulic rollers feeding logs between two contra-rotating shafts with chains flailing the bark and branches from the logs (Figure 13).



1. Direct drive upper roll feeds the log through the debarker
2. Fixed lower chain flail removes bark from the underside of the stems
3. Floating upper chain flail removes the remainder of the bark from the top and sides of the stem
4. Bark and limbs fall down into a bark pusher which removes them from the debarker
5. Chain curtains sweep the remaining debris from the stem

Figure 13. Mobile chain-flail debarking system. Source: Peterson Pacific Corp.

Chain-flail delimbing and debarking machines were used in New Zealand as early as the mid-1970's (Terlesk and Walker 1982). Delimbing was the main objective for use of the machines in small tree size (0.16 to 0.21 m^3) ponderosa pine stems. Delimbing of multiple stems at a time was carried out at the stump by a Vulcan chain-flail delimber mounted on a rubber-tyred skidder. Productivity for the delimber was 22 m^3 per delay-free machine hour. No assessment of bark removal was made.

White (1990) evaluated chain-flail delimbing of small diameter (up to 300 mm) Tasmanian blue gum (*Eucalyptus globulus*), Maritime pine (*Pinus pinaster*), and radiata pine logs in Western Australia. The general performance of the chain-flail debarker was considered to be "excellent". Damage to the logs, however, was assessed as minor for Maritime pine, and moderate for both Tasmanian blue gum and radiata pine.

Thompson and Sturos (1991) compared the debarking efficiency of two types of chain-flail debarking equipment in Northern US hardwoods. One type was a mobile machine that delimbed and debarked stems at the stump. The other type was a portable machine (Peterson Pacific 4800) that delimbed and debarked stems extracted to a landing. The portable flail consistently produced chips with less bark than the mobile flail; 4.6% and 9.2% bark, respectively. The authors noted that the speed at which material was fed though the portable flail affected the amount of interaction between the trees and the chains. Faster feed speeds resulted in less debarking and vice versa. Faster shaft rotational speeds resulted in better debarking but greater damage to the stems. Productivity was higher for the mobile chain-flail unit than the portable chain-flail unit; 33.8 and 50.8 tons per scheduled hour, respectively.

McEwan *et al.* (2017) evaluated the productivity and work quality of chain-flail delimbing and debarking in a *Eucalyptus globulus* stand in Chile. Machine productivity averaged 59 m^3 per scheduled machine hour. Debarking quality was rated good for 58% of the stems, medium for 29%, and poor for 13%. Residual bark content was estimated to be less than 1% for the good and medium debarking quality classes. Tree form had no effect on debarking quality.

Grobbelar and Manyuchi (2000) list the following advantages and disadvantages of chain-flail debarking:

- Log or tree-form is not critical
- It is not as sensitive to piece size as some debarking systems since it can handle multiple stems at a time.
- Chain wear is a significant cost
- Log surface damage and fibre loss can be prohibitive in certain markets.
- After debarking the rougher outside surface of the timber is more susceptible to picking up dirt.

Ring debarkers

Ring debarkers have cutting tool arms attached to a rotating ring providing a scraping action over the surface of the log so that bark is sheared at the cambium layer (Figure 14). Feed rates of 90 to 100 m per minute are achievable in industrial operations. Ring debarkers are high capital cost items and are usually located in stationary positions in mill yards or satellite yard.

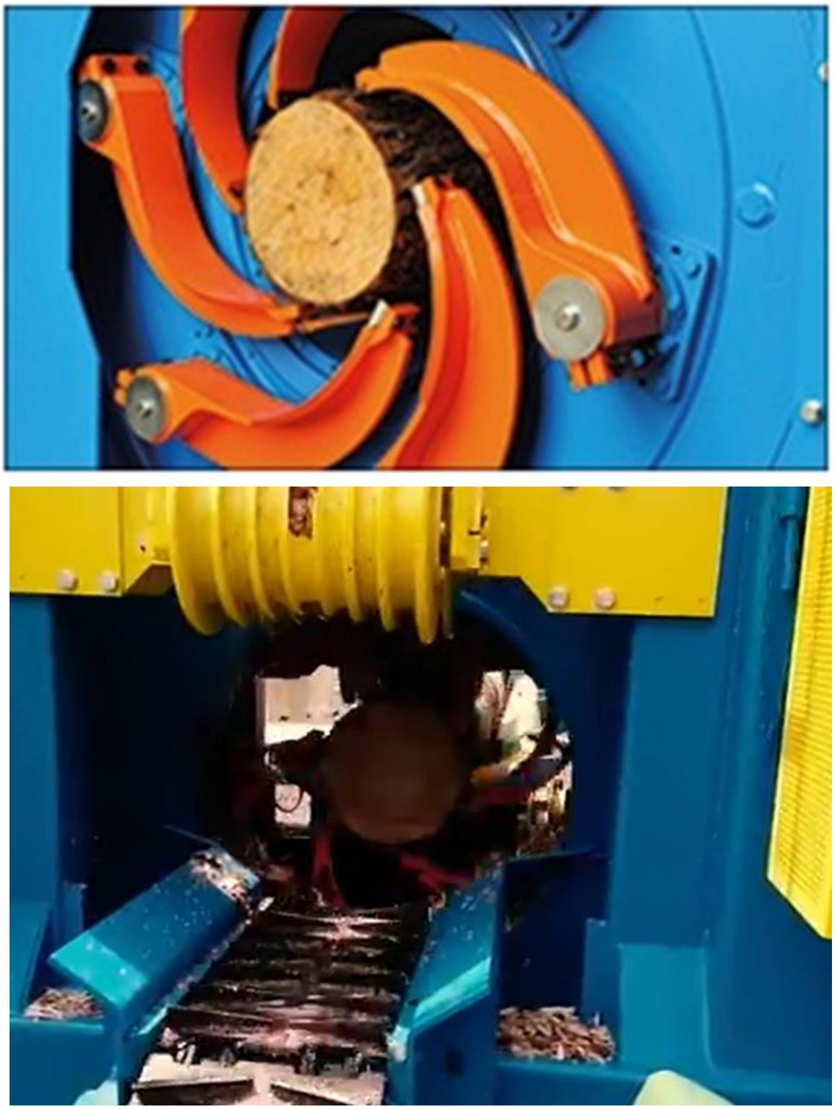


Figure 14. Exposed view of the debarking knives on a ring debarker with knives (top), and log passing through debarking knives which were rotating around the log (bottom).

Grobbelaar and Manyuchi (2000) describe two mobile ring debarkers that were used in pulpwood operations in South Africa in the 1980's and 1990's; a Valon Kone 16E and a Demuth. Both debarkers were PTO-driven from farm tractors and mounted on a two-wheel chassis. The VK16E ring debarker was fitted with two cutting and two abrading tools on the vertical PTO-driven rotor. These were small machines with high manual labour input requirements; 4 to 5 men to load, unload and operate the machines. The Demuth had a Loglift crane mounted on the tractor's cab (Figure 15). Productivity rates of about 8 m^3 per productive machine hour were reported for both machines.

McEwan *et al.* (2011) looked at factors affecting the debarking productivity of four mechanised debarking systems in *Acacia mearnsii* stands in South Africa. Tree size was small in the stands harvested by all four systems: 0.09 to 0.15 m^3. The four debarking systems were a Demuth ring debarker, a Hyena debarking head, a Hypro PTO-driven debarker, and a Maskiner SP 591 LX harvesting head. Unfortunately, the debarking efficiency (% of bark removed) was not recorded. Productivity of all systems was positively affected by tree size, positively affected by tree form (better form, higher productivity), and negatively affected by bark-to-wood bond strength (BWBS). The Hypro debarker was affected the most by BWBS.

Figure 15. Demuth DDM 420 ring debarker. (Source: 2012 YouTube video https://www.youtube.com/watch?v=f5zvPjDly04)

Rosser-head debarking

Rosser-head debarkers consist of a framework for rotating a log and a carriage-mounted debarking head rotating with its axis parallel to the longitudinal axis of the log (Figure 16).

Wingate-Hill *et al.* (1991a) found that the single-log debarking mechanism makes it very sensitive to piece size; throughput ranged from 4.6 to 51.5 m^3 per productive machine hour for log sizes of 0.1 m^3 and 1.07 m^3, respectively. Debarking quality and productivity are very dependent on log quality; poor debarking quality, low productivity and high fibre loss may be achieved with rough logs.

Figure 16. Rosser-head debarker installed in a mill yard. Source: Fulghum Industries Inc.

These type of debarkers are usually installed in sawmills and veneer mills, although portable versions have been developed that could be used for debarking in the forest (Figure 17). Cost of this unit was about $36,500 delivered to New Zealand. It has a 6hp motor to rotate and advance the log, and an 11hp motor to debark the log. Logs up to 6m in length can be debarked with this unit.

Figure 17. Portable Canadian Rosser-head style debarker

Raymond (1989) compared wood fibre loss from Rosser-head debarkers and ring debarkers in a softwood application in Canada. Results showed that wood fibre loss was eight times higher for the Rosser-head debarkers (9.5%) than for the ring debarkers (1.1%).

Western Juniper (*Juniperus occidentalis*) is a species characterised by large and numerous limbs, rot, bark seams, spiral grain, and stringy, fibrous bark. Debarking it prior to chipping, so that "clean" chips can be produced, can be a challenge. Leavengood and Swan (1997) compared debarking of Western Juniper with three types of debarker: ring debarkers, a Rosser-head debarker and a chain flail debarker. In "poor quality" logs, the Rosser-head debarker removed more bark than the ring-debarkers but took considerably more time (~ 5 minutes per 8.4 m log). Fibre loss was similar for both the Rosser-head and ring debarkers. In "better than average" logs, a ring debarker was able to achieve 2-3 % bark content and wood loss was "not excessive". Bark content from logs debarked with the chain flail debarker was estimated to be 2%.

Hydraulic and compressed air debarking

Swift (1949) was awarded a patent for hydraulic debarking of logs using high velocity jets of water. The log is passed through a ring of movable and stationary nozzles. The full surface of the log can be debarked without rotating the log. Krilov (1983 *ex* Grobbelaar and Manyuchi 2000) successfully tested hydraulic debarking of different eucalypt bark types known for difficult debarking. The debarking quality was generally superior to that of any other equipment and log form is not critical. Water consumption was between 0.12 and 0.68 litres per second per meter of log length. High initial machine and running costs, water filtration requirements, wet bark disposal, and large water consumption requirements are some of the drawbacks of this method. Filtration and recirculation can reduce water consumption by 80%. A hydraulic debarker has been operating at Oji Fibre Solutions (NZ) Ltd's Kinleith Mill, for over 40 years (Raymond pers. comm.). Hydraulic debarking is unlikely to have application in-forest but may be applicable at satellite log yards.

An experimental pneumatic debarker was developed in Russia in the 1960's (Plotnikov and Polozov 1966). The debarker separated bark from the log and ground it into particles using a mixture of compressed air and bark particles, the particles (with an average diameter of 2mm) being accelerated to ultrasonic velocity. The debarker had specially constructed nozzles, placed on the periphery of two-ring shaped frames, so that the air jets cover the whole surface of the advancing log. Bark particles knocked from the log are collected, screened, and then re-used. The debarker was extensively tested on conifer and hardwood logs and was found to be especially suitable for irregularly shaped logs and those with many knots. The optimum composition of the debarking mixture was 99.6% air with 0.4% bark particles by volume. The optimum pressure at the outlet of the nozzles was 0.8 to 1.0 MPa.

Harvesting/processor debarking heads

Harvester heads in general make use of the compression principle to loosen the bark and delimbing knives help remove the bark. Information on debarking results using harvester/processor debarker heads has been presented in the section *Harvesting system and equipment impacts on bark loss* (page 11). Additional information on recent trials with debarking heads in conifer stands is also presented in this report under "*Recent trials with debarking using harvesting/processor heads"* (page 28).

Debarking eucalypts (Eucalyptus spp.) with harvester/processor heads is now well-established (Figure 18). Debarking heads have been used in New Zealand for more than 25 years (Gadd and Sowerby 1995). A quick web-search will also find examples of debarking heads being used in eucalypt plantations in South America, South Africa, and Australia.

Figure 18. Eucalyptus debarking head being used in a Brazilian plantation.

Eucalypt debarking heads do a very good job and remove most of the bark. Strandgard *et al.* (2019) reported bark content of 0.1% or less for debarking at stump or at landing with harvester/ processor heads in Western Australia. Video clips on YouTube of debarking heads show that some bark can remain, mostly on the first half metre (or less) of the stem and towards the top of the stem where the stem diameter is smaller and the bark is thinner.

van der Merwe *et al.* (2015) found that spending more time trying to remove as much eucalypt bark as possible can lead to greater fibre losses. Wood fibre losses were found to be almost double for 5-pass debarking methods versus 3-pass debarking methods; 1.70% versus 1.06%, respectively.

Standing tree debarking

In 1949 a patent was awarded for the design of a machine for debarking and delimbing either standing trees or felled tree trunks (Figure 19) (Emery and Shuff 1949). The design also included the ability to cut felled stems into logs (effectively a rudimentary design for a modern-day processor head). The inner portion of the unit rotated so that the debarking and delimbing knives followed a helical path up the stem. It is difficult to see in the design how the unit was placed around the tree or felled stem.

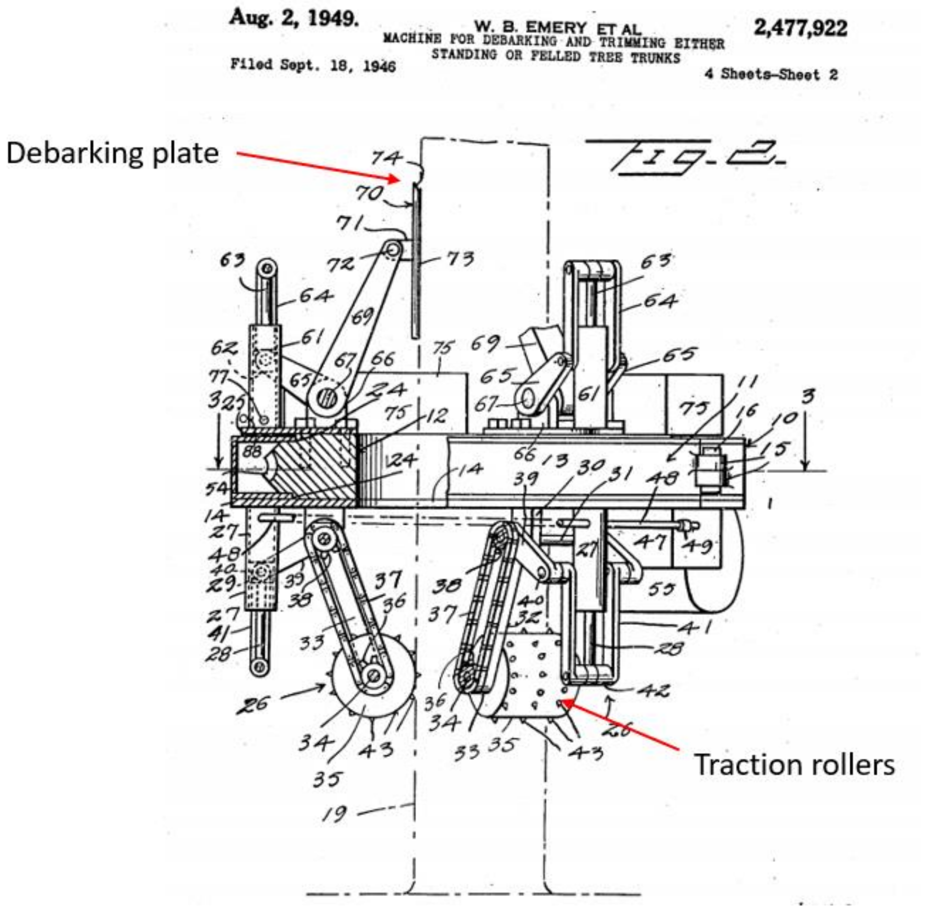


Figure 19. Early design for a harvesting processor head that included debarking, delimbing and bucking capability for either standing trees or felled stems.

In 1972 a patent was awarded for a standing tree debarking and delimbing apparatus (McColl 1972) which was part of a multi-stem felling, delimbing, debarking, chipping, and chip cartage system for small pulpwood trees (Figure 20). The debarking/delimbing apparatus was mounted on a rotating plate that moved around the tree stem. Debarking blades were used to remove the bark.

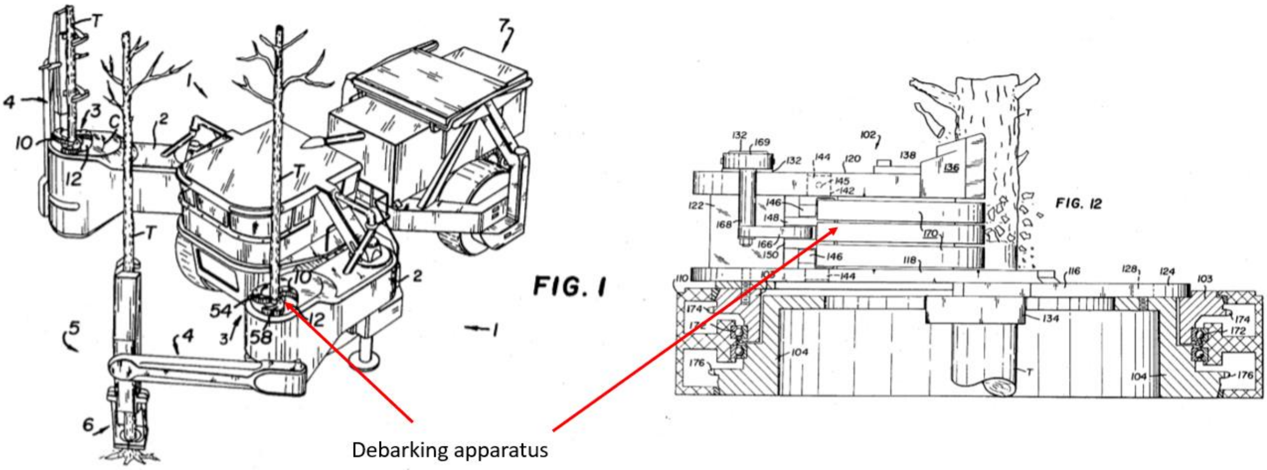


Figure 20. Multi-stem standing tree debarking, delimbing, felling and chipping machine (left) fitted with a debarking apparatus (right).

Additional patents that may be of interest

Andersson (1952) was awarded a patent for a machine for removing bark from logs. The machine combines a bark cutting tool, a friction shearing tool to break the bark/wood bonds, and a bark planing tool to peel off the bark. The bark cutting and friction shearing tools rotate around the log in a spiral fashion as the log passes through the machine (Figure 21).

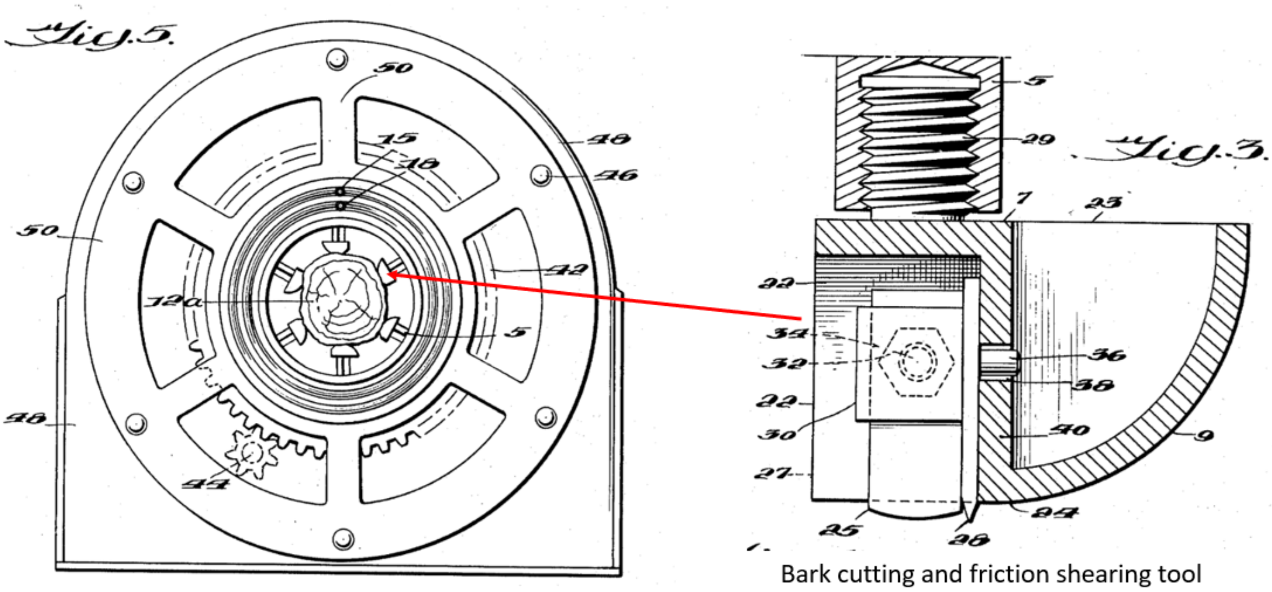


Figure 21. Machine for removing bark from logs (left) and bark cutting (28 on drawing) and friction shearing (25 on drawing) tool (right).

Hosmer (1957) was awarded a patent for a bark removing apparatus with impacting hammers. One part of the apparatus used wedge-shaped blades to insert slots, running longitudinally with stem, through the bark to the wood. Since BWBS is lower perpendicular to the wood grain than parallel with the grain the bond between the bark and the wood is more easily broken and the bark is loosened around the stem. The wedge-shaped blades are later followed by impact hammers which knock the bark from the stem (Figure 22).

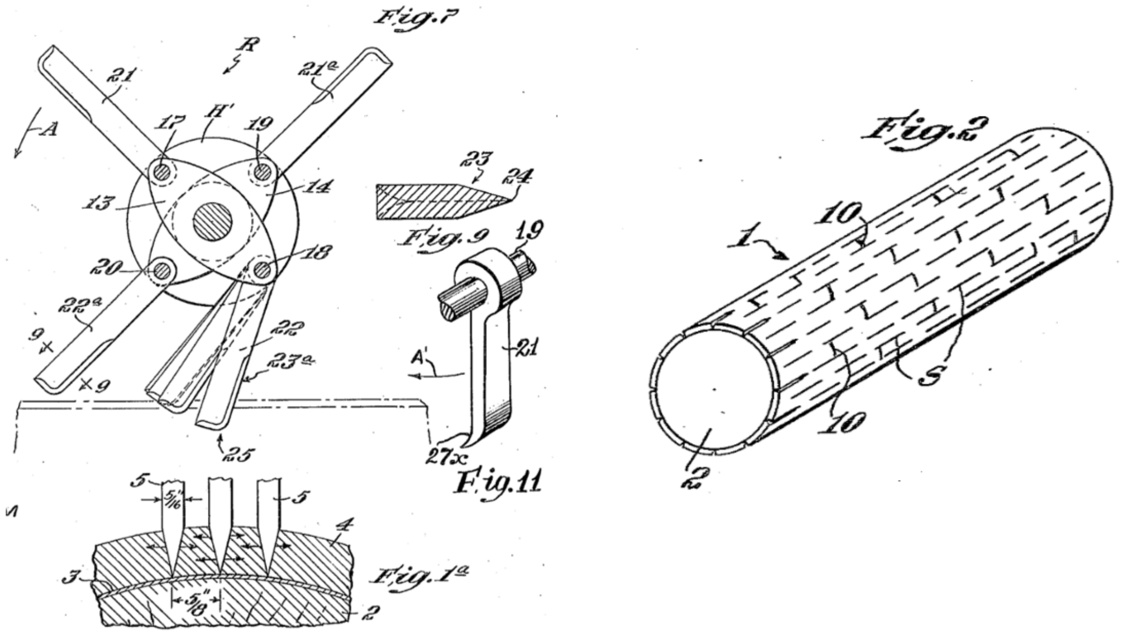


Figure 22. Apparatus for removing bark from logs. Wedge-shape knives (Fig. 1a in the patent) create slots in the bark (Fig. 2 in the patent) which help break the bark/wood bonds. Impact hammers (Fig. 7 in the patent) knock the loosened bark from the stem.

Oldenburg (1976) was awarded a patent for a debarking assembly for tree harvesters. The assembly comprised a linked wrap-around system with debarking blades attached (Figure 23).

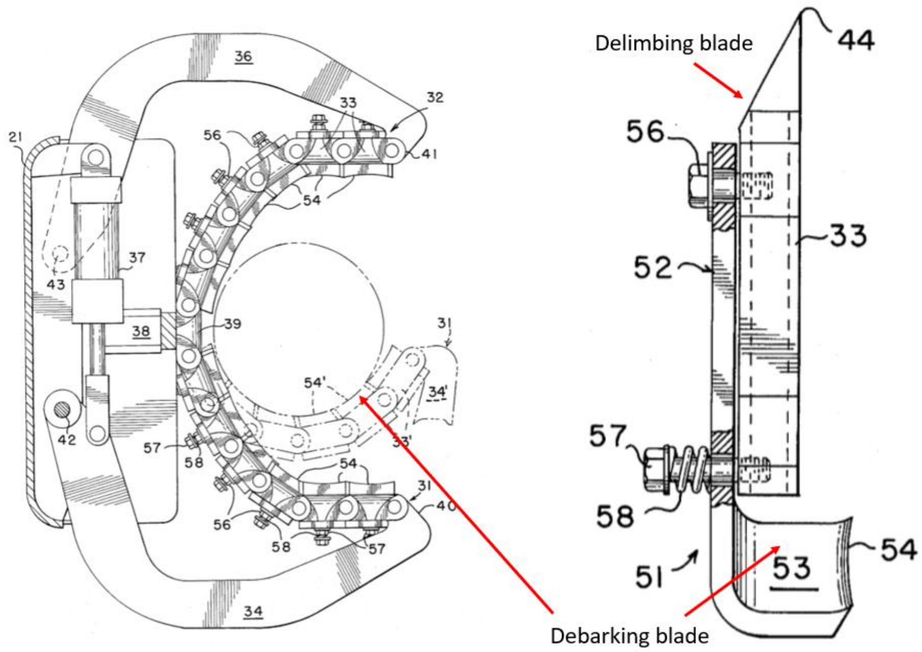


Figure 23. Assembly for removing bark from logs. Debarking blades were attached to linked wrap-around system.

Trials with debarking using harvester/processor heads

Radiata pine debarking trials – New Zealand 2014

A series of trials were carried out in radiata pine stands in late spring/early summer of 2014 by Forme Consulting Group Ltd. on behalf of the Stakeholders in Methyl Bromide Reduction, STIMBR (McReedy *et al.* 2015). The goal of the trials was to determine if log processor heads could debark radiata pine logs to phytosanitary standards (maximum of 5% bark on any individual log and 2% on any batch of logs).

Four processor heads produced by New Zealand manufacturers were measured: felling and delimbing at the felling face, delimbing at a landing, and debarking only. Modifications to machines trialled by the processor head manufacturers were mainly limited to altering the feed rollers used and modifying the knife and arm pressures.

Debarking costs ranged from under \$10 per JAS m^3 to over \$25 per JAS m^3, varying with average tree size and operator skill (Figure 24).

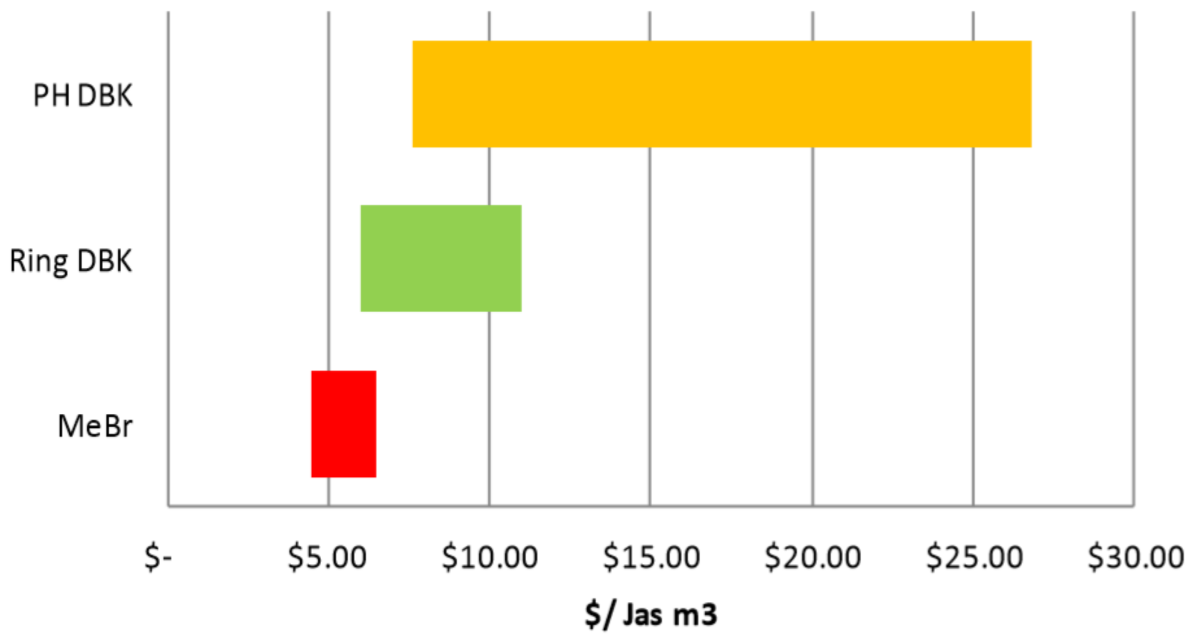


Figure 24. Cost comparison between three phytosanitary treatment solutions; processor head debarking (PH DBK), ring debarking (Ring DBK) and methyl bromide fumigation (MeBr). Source: McReedy *et al.* (2015)

The costs of processor head debarking compared unfavourably with the costs of more well-established phytosanitary treatments; namely, methyl bromide fumigation and ring-debarking at a port or satellite yard. Since the process of debarking with log processors in this study was new to the processor head operators, operating techniques were not fully developed. Productivity was, therefore, expected to increase and costs per unit volume to decrease over time. The critical factor that affected the estimated cost of debarking was the number of passes required to fully debark a stem to the required phytosanitary standard (5.45 passes). This compares poorly with an average of 1.06 passes for satisfactory felling and delimbing, and 1.13 passes for delimbing only.

Changing the feed rollers from standard rollers to eucalypt debarking rollers was the most effective modification trialled. Adjusting knife pressure was also successful in some cases.

Debarking quality did not meet the phytosanitary standard for some of the smaller top logs where the bark was thinner and tighter and log diameter had diminished to the point where the geometry of the processor heads and knives prevented application of adequate pressure or shear force to remove the bark. Debarking quality did not meet the phytosanitary standard for some of the rougher logs (butt, mid or top) which were heavily convoluted. These can also be a challenge for ring debarkers. The authors commented that strategies would need to be developed to deal with smaller top logs and rough logs.

The authors concluded that using processor heads to debark radiata pine could be cost competitive with methyl bromide as a solution, in certain circumstances including improvements in operating technique and processor head design.

Radiata pine bark retention trial – Western Australia 2015

In spring 2015 a debarking trial was carried out on radiata pine in Western Australia (Murphy 2015). The sponsor for the trial – a sawmill with a good market for landscape bark chip – was interested in retaining, rather than removing, as much bark as possible. Eight treatments were carried out by the sponsor's harvesting contractor; four with a standard Waratah processor head along with various combinations of roller and knife pressures, and four with modified feed rollers (Moipu brand), along with various combinations of roller and knife pressures (Figure 25).

Figure 25. Moipu outer feed rollers manufactured by Moisio Oy in Central Finland. Similar rollers were included in the Australian radiata pine debarking trial.

Bark weight was determined by weighing packets of logs with the bark on for each treatment and then debarking the logs and weighing the bark from each packet separately. A ratio of bark weight to under-bark log weight was compared for each treatment. A line intersect method (Canfield 1941) was also used to compare bark retention for 344 logs.

Results showed the greatest bark retention was obtained with the standard Waratah rollers and standard Waratah pressures. Reducing the roller and knife pressures for both the standard rollers and the adapted rollers unexpectedly resulted in lower bark retention. Differences in bark retention were significantly different between Treatments 1 and Treatments 4 or 8. There was no significant difference between Treatments 4 and 8.

Two additional findings from this trial are of interest. Firstly, the ratio of Treatment 1 (bark on) to Treatment 4 (or 8) was similar (~1.10) for both the bark weight method and the line intersect method. This is of interest since the line intersect is a much easier exercise to undertake logistically – a camera and computer software are the main tools required. Secondly, the bark retention (81%) for the conventional processor head was much higher than found for the same type of heads for other radiata pine bark loss benchmarking trials carried out in Australia during spring (53%) (Murphy 2015). The cause of the difference was unknown, although it was possible that the machine operator for the bark retention trial was taking more care handling logs than was normal practice because he knew it was a trial. Results from three of the eight treatments included in the Australian bark retention trial are shown in Table 2. The same conclusions were drawn from both the bark weight method and the line-intersect method.

Table 2. Effect of Processor Head Characteristics on Bark Retention

Treatment	Bark Retention (kg Bark/tonne Solid Wood)	Statistical significance (p = 0.05)	Bark Retention (%) based on line-intersect measurement	Statistical significance (p = 0.05)
1. Conventional Waratah Rollers and Standard Roller and Knife Pressures	62	-	81	-
4. Conventional Waratah Rollers and Reduced Roller and Knife Pressures	55	1 vs 4 Sign. Diff.	72	1 vs 4 Sign. Diff.
8. Moipu Outer Rollers and Reduced Roller and Knife Pressures	57	1 vs 8 Sign. Diff. 4 vs 8 Not Sign. Diff.	73	1 vs 8 Sign. Diff. 4 vs 8 Not Sign. Diff.

Radiata pine debarking trials – New Zealand 2015

A debarking trial was carried out in spring (August 2015) in a radiata pine stand located about 15 km south of Rotorua (Murphy 2015). A 22-inch SATCO eucalypt debarking head on a Caterpillar excavator base was used by the logging contractor to delimb and shovel log stems (Figure 26).

Figure 26. Small almost fully debarked stems (left), Caterpillar excavator with SATCO head (centre), 22-inch SATCO eucalypt debarking head (right)

Twenty-three stems were felled near a roadside. The stems had their slovens removed and were then delimbed and passed to a grapple loader for stock-piling. The logging contractor noted that some stems were too big for efficient handling by the debarking head. Even though the debarking head was too small for many of the logs being handled it was the only debarking head available for the trial at the time. A short study of delimbing and debarking of about 20 stems was carried out. A video was recorded and a time study undertaken. The goal of the trial was not to see how much bark could be removed; rather it was to see how much bark was removed during “normal” operation.

Table 3 presents the results of a short time study of the operation. The average time for handling broken top pieces was 0.07 minutes per stem, “machine suitable” stems was 1.16 minutes per stem, and “too large” stems was 5.25 minutes per stem.

Table 3. Handling times for a Eucalypt debarker head in radiata pine.

Piece description	Average log handling time (minutes per stem)	Number of stems or top pieces
“Machine Suitable” stems	1.16	20
“Too Large” stems	5.25	3
Broken top pieces	0.07	3

* Times for broken top pieces are pro-rated across all stems

Overall the eucalypt debarking head did a poor job of removing bark from the stems that were too big. A significant amount of the bark was removed from the smaller stems but possibly no more than would have been removed by a conventional processing head for radiata pine. The logging contractor and the machine operator both thought that a conventional head would have done a better job of removing radiata pine bark. They believed that the amount of bark removed with the eucalypt debarking head was more a function of how many times a stem was handled (particularly with using the debarker to assist with shovel logging) than the type of head being used.

Radiata pine debarking trials – New Zealand 2017

A short trial (4 hours) was carried out in August 2017 in Tairua Forest on the Coromandel Peninsula to determine debarking productivity on a landing and quality of bark produced from a cut-to-length (CTL) harvesting system (Murphy 2017). The sponsor of the trial, a nutraceutical company, wanted to collect bark of appropriate quality for use in its processing operations. The CTL system was selected since it was expected to result in less mud and stones in the bark and the quantity of bark on the logs carried to the landing would be greater than that for the tree-length extraction system.

A John Deere 909 tracked carrier, with a 4-knife Waratah 625C harvesting/processing head, was used in the debarking trial (Figure 27). The head was designed to delimb and cut stems into logs – not to debark logs. The machine operator was very experienced in felling and processing but had no experience in debarking logs.

Logs that had been forwarded to the landing and usually found in three sections of the tree stem (bottom logs, second logs, and top logs) were used in the trial. Thirty logs of each type were debarked, and the bark collected on a tarpaulin. Logs were run back and forth through the processor head several times to remove as much bark as possible, but in a timely manner. The time to debark the logs was recorded. The logs were also assessed, using a line intersect method, before and after debarking to determine the amount (%) of bark removed. The volume of bark was also estimated.

Figure 27. John Deere 909 carrier with Waratah 625c processing head was used in the 2017 radiata pine debarking trial.

Logs delivered to the landing by the CTL operation had 15-49% of their bark removed during log handling, with a greater percentage of the bark removed from top logs (Table 4). Debarking of logs at the landing removed an additional 12-41% of bark. The amount of bark remaining on the logs ranged from 39-44%. Debarking productivity ranged between 11.5-23.7 tonnes per scheduled machine hour (SMH); depending on location of the logs on the stem. It was noted that the machine operator's productivity (in terms of number of logs handled) increased slightly as the trial progressed.

Table 4. Summary of results from radiata pine debarking trial in Tairua Forest.

Description	Bottom Logs	Second Logs	Top Logs
Log area with bark – before debarking (%)	85	61	51
Log area with bark – after debarking (%)	44	41	39
Area of bark removed (%)	41	20	12
Average log volume (tonnes)	0.65	0.36	0.19
Average time per log (delay free) (minutes)	1.23	1.09	0.74
Number of logs per SMH including delays	36.5	41.3	60.6
Debarking productivity (tonnes per SMH)	23.7	14.9	11.5
Estimated rate of bark volume produced (tonnes per SMH)	0.93	0.59	0.26

Although the sponsor of the trial was interested in the amount of bark produced for domestic consumption and not the amount of bark left on the logs, it was noted that the amount of bark remaining (~40%) would far exceed the amount of bark allowed on logs for export without methyl bromide fumigation (2% to 5%).

At the end of the log debarking trial the machine operator felled and debarked a few stems in long length form. Debarking productivity was substantially higher both in terms of the rate at which bark was removed and the quantity of bark removed per stem (Figure 28).

Figure 28. Demonstration of debarking full-length radiata pine stems.

Other debarking trials in radiata pine.

Southstar Equipment Ltd trialled debarking radiata pine in New Zealand and Chile with only limited success using their standard processing head.

Debarking trials – Germany 2017

Climate change and uprising biotic (insects, fungi, pathogens) and abiotic (fire, drought, storms, snow) threats to European forests is leading forest researchers to look for new solutions for managing these issues. One solution being considered is to adopt what was once a broadly established forestry practice – in-stand debarking.

A series of seven trials were set up within German state forests to evaluate debarking efficiency and harvest system efficiency when debarking rollers and other modifications designed for eucalyptus harvesting heads were applied on conventional harvesting heads (Heppelmann *et al.* (2019). Three harvesting heads were modified to achieve a debarking effect within the harvesting process (Figure 29).

Modifications tested in this series of trial were:

- on Setup 1 (S1) inner and outer feed rollers and measuring wheel
- on Setup 2 (S2) feed rollers
- on Setup 3 (S3) inner and outer feed rollers, measuring wheel, upper delimbing knives, top knife.

Roller types tested were:

a) conventional spike rollers
b) single-edge debarking rollers, used within S1 and S2 tests
c) diamond edge debarking rollers, used within S3 tests.

	Setup 1 (**S1**)	Setup 2 (**S2**)	Setup 3 (**S3**)
Harvester	John Deere 1270E	TimberPro 620E	Ponsse ScorpionKing
Harvesting head	John Deere H480C	Log Max 7000C	Ponsse H7

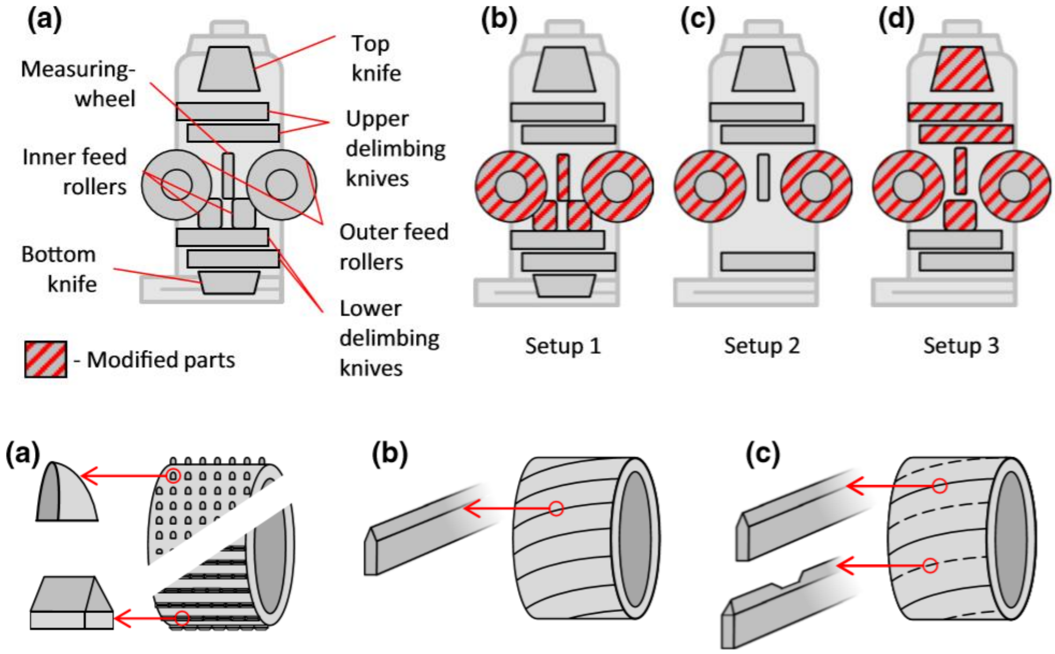


Figure 29. Harvesting machine types (top), modified parts (highlighted, middle), and roller types (bottom) tested in German forests. Source: Heppelmann *et al.* (2019).

The trials were carried out in summer and winter seasons. In total, 1720 debarked Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) logs were measured. Tree diameters (DBH) ranged between 15 and 35 cm. After felling, each tree was fed in its complete length forward and back (passes 1 and 2) through the harvesting head. Branches and bark were removed during the first pass and only bark during the second pass. Some bark removal and bucking of the delimbed stem into assortments occurred during the third pass. The number of passes was limited to three to minimise log surface damage and loss of biomass.

In general, the modifications performed well, especially in summer. Within three passes of the stem within the harvesting head, 90% and 84% bark removal were regularly achieved in pure pine and mixed conifer stands, respectively, with Setup 1. With Setup 2 and Setup 3 73% and 84% bark removal was achieved in summer, respectively. Under winter conditions, however, the debarking percentage decreased to 54% (S1) and to 35% (S2). The authors commented that further modifications to hardware (such as installing additional top and/or bottom knives) and work procedures (increasing the number of debarking passes) could lead to greater levels of bark removal.

The S1 data-base had sufficient trees to test for differences in debarked percentage between species. No significant difference was found between spruce and pine for summer debarking (both equalled 87% removal), but significant differences were found for winter debarking (pine 55% removal vs. spruce 43%). The position of logs within the tree also affected debarking efficiency; efficiency was 15% lower at the butt and 9% lower at the top of the tree compared with logs from the middle of the tree.

An assessment was also made of the impact on harvesting productivity and costs from applying debarking with a modified harvesting head as part of the harvesting process. Only pine stems harvested in summer were included in the analyses. On average, harvesting productivity was 10% lower with the debarking configuration compared to conventional operations performed in stands with similar sized stems.

Debarking standards

Ensuring that "all" bark is removed from logs in the debarking process, frequently means that some wood fibre will be removed as well. For example, Ngueho Yemele *et al.* (2013) observed that 20% of the black spruce (*Picea mariana*) bark from an industrial sawmill in Quebec, Canada, was wood fibre content. Gagnon *et al.* (2013) presented a relationship between residual bark content and wood loss as found in a study of a rotary debarker operation in a Canadian sawmill. Low levels of residual bark can be associated with high levels of fibre loss (Figure 30).

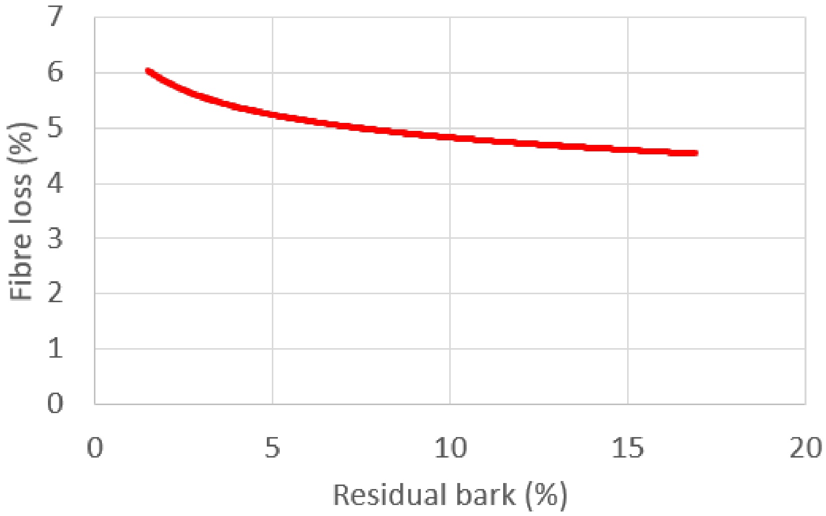


Figure 30. Relationship between fibre loss and residual bark content for a black spruce sawmill in Canada; Source: Gagnon *et al.* (2013).

Mills, therefore, often set residual bark targets that are above 0% to reduce wood fibre loss and to improve pre-treatment process efficiency. Different pulping processes have different residual bark targets, ranging from 0.2% to 2.0% (Figure 31).

Pulp type	Target bark amount, w-%	Maximum allowed, w-%
Groundwood	0.2	0.5
TMP	0.2	1.0
CTMP	0.2 – 1.0	2.0
Unbleached kraft	1 – 1.5	
Bleached SW kraft	1.0 – 2.0	
Bleached HW kraft	0.5 – 1.0	

TMP=thermomechanical pulp; CTMP=chemithermomechanical pulp; SW=softwood; HW=hardwood

Figure 31. Target and maximum residual bark standards for various pulping processes. Source: Anonymous (2015).

If chips supplied to the pulp mill, exceed the target residual bark content, bark content can be reduced by further treatments of the wood chips prior to pulping. However, pulp mills may choose to downgrade the value of the woodchips or refuse to accept them.

Wood chips, the main raw materials for most pulp and paper, MDF, and HDF panel industries, mainly come from the outer slab wood from logs debarked at sawmills, although they can come from smaller top logs from stems and shorter non-saw log pieces. Sawmills typically set a maximum bark content target of 1% in the growing season and 1.5% in winter (Gagnon *et al.* 2013). Given that residue wood from sawmills, which is converted to wood chips, accounts for less the half the volume of the saw log, it can be calculated that residual bark on debarked logs would need to be 0.3 to 0.8% of total log volume.

China, New Zealand's largest export log market, accepts debarking of logs as a phytosanitary risk reduction measure. ISPM 15 (International Standards for Phytosanitary Measures) states that long thin pieces of bark are acceptable if they are less than 3 cm wide. If they are more than 3 cm wide, the piece of bark must be less than 50 cm^2 in area (FAO 2011).

New Zealand biosecurity rules for log export require that bark amounts to no more than 5% on a single log and 2% on a batch of logs where logs are not fumigated (MPI 2020). There is no standard method to assess this bark content, however. The inspection organisation is responsible for developing a method which the Ministry for Primary Industries can accept or reject.

One organisation (un-named) relies on what was described as a "calibrated eye-ometer" approach. That is, the inspector estimates how much bark is present in a batch of logs or on a single log. To calibrate the eye, large and small end diameters along with log length are used to determine log surface area [based on seeing approximately 60% of a log] from a look-up table. Bark segments are then measured, summed and the total calculated as a percent of the log surface area. A total of 10 logs are selected as being representative of a batch of logs.

This is a semi-subjective, but cost-effective, technique for measuring bark content. It is based on bark area, not bark volume. Logs are not turned. It is unknown whether this approach results in an over or under-estimate of bark (Murphy 2015).

The debarking targets set by modern sawmills and pulp mills are more stringent than the international phytosanitary targets for some countries where bark removal is accepted as a phytosanitary treatment. This means that logs debarked in-forest should either meet the debarking standards required by domestic customers or incur the costs of additional debarking treatments further along the supply chain.

Automated debarking control

Controlling the quality of debarking, so that residual debarking standards are met, and wood fibre loss is minimised, will be difficult for a human operator without some form of assistance.

Baroth (2005) presents an equation for drum debarking that estimates the degree of bark removed (Y_{rem}) as a function of the bark to wood bond strength (BWBS), bark thickness (B), and debarking time (T).

$$Y_{rem} = e^{-2.5} \times (BWBS \times B)/T^{1.5}$$

To be able to make use of this equation the operator would need to have prior knowledge of the bark to wood bond strength (BWBS) and bark thickness (B).

Measuring debarking quality in real time would seem to be a more suitable approach. Gagnon *et al.* (2013) described a method for controlling the quality of debarking and wood fibre loss which makes use of computer vision and artificial intelligence technologies. Residual bark and wood fibre loss would be quantified in real-time and the results used to cease debarking of the current log or to adjust parameters of the debarking equipment.

The authors tested their method on a ring debarking operation in a mill and compared the results with those from an experienced human operator. Over 1800 logs were included in the test. It is unknown whether the method tested included pre-training of the detection algorithm using artificial intelligence. If not, the results could be expected to improve with time. Residual bark was higher for the vision-based system (5.1%) than for the human-controlled system (3.5%). However, wood fibre loss was lower for the vision-based system (8.1%) than for the human-controlled system (10.3%). Such an approach could be used in-forest or at a satellite yard.

Economics of debarking

In 2012, to determine the economic feasibility of debarking radiata pine, Interpine Forestry Ltd. investigated the actual cost of debarking in various scenarios and benchmarked it against the current cost of chemical fumigation. The study found that debarking costs were more expensive than chemical fumigation despite benefits gained through transport load improvements and offset against possible bark sales (Interpine Forestry Ltd., 2012, *unpublished*). In addition, the project found that, although debarking at the stump was the most economical option in most areas of New Zealand, logistical issues and phytosanitary effectiveness of the debarking process were unknown.

Murphy *et al.* (2017) described development of a spreadsheet-based economic model that allowed quantification of the potential costs and benefits of IFD, as well as break-even costs for a purpose-built pine debarker head. The model spanned from forest establishment through to delivery of logs to mills for domestic markets, or to shipside for export markets. The model was populated with data from a mix of trials carried out in New Zealand and Australia, forest industry sources, and published figures. The model contained a summary worksheet that allowed inputs for key parameters (e.g. harvesting system, harvesting season, drying days, percent of harvest volume exported) and provided summarised outputs for revenues and costs for IFD supply chains and non-IFD supply chains.

Linked to the summary worksheet were eight worksheets that included wood and bark data, harvesting economics, transport economics, port economics, waste handling costs, additional shipping costs, other costs (e.g. site preparation, weigh bridge scaling), and revenues from log and bark sales.

The model indicated that, for both Australia and New Zealand, IFD might be an economically viable alternative to debarking further along the supply chain. Potential gains in net revenue of 2.3% were calculated for the NZ base case, equivalent to $1.65 per m^3. Breakeven capital costs for a purpose-built pine debarker head that could be fitted to an excavator base were calculated and ranged from $245,000 to $480,000. Net revenue gains and breakeven prices were sensitive to several key factors. Wood fibre losses resulting from debarking were not considered in the model, but contamination from sand and grit was. The effects of value losses associated with sapstain following IFD was mentioned as deserving further investigation.

In an industry survey of log buyers, log sellers, and industry experts on the effect of sapstain on softwood log prices, carried out in Australia and New Zealand in 2018, Murphy (2019) found that log prices were reduced if sapstain severity exceeded approximately 10% for appearance grade logs and 50% for structural grade logs. To reach 10% sapstain severity levels in Australia debarked radiata pine logs take only a few days in spring and summer, but greater than 5 weeks in autumn and winter (Murphy *et al.* 2019b).

Despite sapstain affecting log prices, economic analysis of the effects of debarking, drying and anti-sapstain treatments in export supply chains determined that the preferred treatment combinations for radiata pine were to either debark at the port followed by no drying or anti-sapstain treatment, or to debark in-forest and dry logs in winter but not in spring (Murphy and Berry 2019).

SUMMARY

Debarking of logs is an essential task within the value chain of all timber processing industries. All wood industry sectors share the same common need – wood needs to be debarked before it can be processed into further products. The question is “where should the debarking task take place” and “how should it be done”.

This literature review focussed on debarking early in the supply chain - in-forest at stump or on landings (IFD), or at nearby satellite yards. Where possible we focussed on information that was relevant to debarking New Zealand’s two most important plantation species, viz. radiata pine and Douglas-fir.

IFD was found to have a wide range of advantages and disadvantages that spanned from forest establishment through to delivery of logs to mills for domestic processing, or to shipside for export markets. IFD impacts, positively and negatively on both supply chain costs and revenues. Negative harvesting productivity impacts of 10% or more are likely.

Bark accounts for 11% to 13% of the over-bark volume on standing radiata pine or Douglas-fir trees. An unintended consequence of handling of logs in the felling, extraction and processing activities is the removal of up to 80% of bark for radiata pine and up to 65% for Douglas-fir. Amount of bark removal has been found to depend on season, harvesting system, and harvesting equipment.

The review identified that there were a wide range of technologies that had been proposed or developed specifically for removing bark from trees, logs, and woodchips. These ranged from chemical, biological, and mechanical debarking of standing trees, to manual, semi-manual and mechanised debarking of logs and woodchips. The technologies include the use of both mobile systems suited for IFD and stationary systems suited for operation in satellite yards or mills.

Debarking standards required by processing mills (saw, veneer, roundwood, pulp, etc.) and phytosanitary treatment for international markets limit residual bark content to 2% or less. Some pulping operations specify as little as 0.5% residual. IFD will have to meet this goal if it is to replace debarking further down the supply chain.

IFD of eucalypts is well established around the world. Focus is now shifting to developing IFD systems for conifers, particularly Radiata pine. Trials with modified harvester/processor heads have

been carried out in New Zealand, Europe and Chile. There is also interest in Australia in trials with modified harvester/processor heads.

To date none of the trials have consistently achieved a residual bark target of 2%, so this is the focus of future work. With some debarking systems greater bark removal can be achieved but at the expense of increased debarking time (= cost) and reduced revenues from wood fibre losses and wood damage. Automated approaches for controlling debarking efficiency and wood fibre losses are reported in the literature. These may have application in-forest or at satellite yards. Multi-machine systems may also be required to meet the 2% residual bark content goal.

Recent modelling of forest-to-mill/port supply chains has shown IFD to be economically viable. Further development of equipment and systems is needed, however. This literature review has identified methods and equipment that could be applicable for that further development.

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