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Biomass recovery operations in New Zealand: a review of the literature

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TABLE OF CONTENTS

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EXECUTIVE SUMMARY

Plantation forests in New Zealand generate a considerable amount of woody residues at the time of harvesting. These residues comprise branches, tree tops, and offcuts from log manufacturing on the landing, but also lower value merchantable material left in the cutover that is not economic to extract. Harvest residues can impede harvesting, processing and forest re-establishment operations and, if mobilised during a storm, can affect the downstream environment. Conversely, converting residues into woody biomass products create new market opportunities.

The current FGR harvesting and logistics programme focusses on automation of forest operations, including developing more effective, efficient and safe methods of processing on the log landing. As these processes focus on maximising value recovery from the forest resource, such systems cannot be successful without efficient residue management systems to support them. Concurrently, increasing concerns about environmental risk, and the role of renewable forestry resources in mitigating climate change, has resulted in increased interest in efficient and cost-effective biomass recovery operations.

There is a lack of information about the technologies used to recover harvest residues, the types of merchantable products produced, and who uses these products in New Zealand. This report introduces forest biomass operations and reviews previous literature that has studied biomass harvesting systems, both in New Zealand and overseas. Biomass recovery technologies and systems, their efficiency and costs, as well as variables affecting the supply chain have been summarised. Examples of forest biomass end-users and markets in New Zealand currently being operated in New Zealand are also provided.

INTRODUCTION

New Zealand has a temperate to subtropical climate which yields fast growing and productive forests. The forest estate comprises mainly radiata pine (Pinus radiata, 90%), and 6% Douglas-fir, Pseudotsuga menziesii (NZFOA 2016). There was a planting boom in the mid-1990s when large-scale afforestation occurred (between 50,000 and almost 100,000 hectares of new planting per annum). These plantings are being harvested from now till around 2025 when tree age is approximately 28 years (Hall 2013). While estimates of harvest residues vary with factors such as stand condition and harvest system, on average approximately 15% of the total harvested volume is left as residue. With a current harvest level of approximately 30 million cubic metres (m^3) per year, this is approximately 4.5 million m^3 of harvest residues generated each year. With these large quantities of residues left on site, there is both under-utilised material of value and the potential to cause environmental problems, both significant issues. In New Zealand, there is a growing interest to deal with forest harvesting residues efficiently and cost-effectively.

The use of renewable energy from biomass, from all sources including forest biomass, is increasing (Lal *et al.* 2011). To meet this demand there have been significant developments in terms of both dedicated machines and systems to recover biomass from forest operations. Already many studies have evaluated productivity and harvesting cost of forest biomass supply systems (Ghaffariyan *et al.* 2012). There is still a considerable regional variability in the productivity and cost of operations, which depend on factors such as the location where the operation occurs and the supply chain that has been applied (Ralevic *et al.* 2010). There is also national variability in biomass supply systems as countries develop their own strategy to mitigate emissions of atmospheric greenhouse gases (GHG), and fulfil country-specific energy demands.

New Zealand has pledged to reduce its GHG emissions to 30 percent below 2005 levels by 2030 (Fernandez and Daigneault 2016). The purpose of New Zealand's energy policies is to provide energy that is competitive, safe, sustainable, and moving towards being carbon neutral (Hall *et al.* 2009). Half of New Zealand's consumer energy depends on fossil fuels, especially oil, and is therefore sensitive to changes in oil prices (Jack and Hall 2009). According to the government's report 62 Petajoule (PJ) of energy was supplied from woody biomass in New Zealand in 2017. This accounts for 7% of total primary energy supply of 932 PJ (MBIE 2018).

In New Zealand forest operations, the dominant harvesting method is the tree length method, which typically handles the tree at the landing or central processing yard. Generally, this large scale clear-cutting creates a significant amount of residue (Figure 1) such as branches, tree-tops, and offcuts by being pushed to the landing edge or concentrated large piles (Visser *et al.* 2018). In many areas of New Zealand, treating these residues is problematic because they can damage young trees and streams, provide insect breeding grounds, cause serious fire hazards, and can be regarded as unsightly and wasteful to the public (Hall 1994). There are costs associated with risk reduction and residue clean up (Hall 1998b).

Figure 1. Discarded harvest residues at a yarder landing (Visser *et al.* 2009)

To align with the FGR programme, this report focusses on literature that relates to residues from conventional plantation harvesting operations providing saw logs and pulpwood. In particular the management of residues that impede current harvesting operations such as processing and log storage on landings and at roadside, and future site preparation for planting regardless of where log processing occurs (Visser *et al.* 2009). However, the authors recognise biomass can also come from short-rotation plantations and crops grown specifically for energy and wood harvested for use as fuel for heat or electricity generation from purpose-grown plantations or from native forests (Ghaffariyan *et al.* 2012).

Objectives

The research presented in this report focused on reviewing the forest biomass operations in New Zealand. The main objectives of this study were to provide:

- Information about the current forest biomass technologies and operations.
- Estimates of productivity and cost of commonly used forest biomass systems that have been studied.
- Examples of existing forest biomass end-users or markets.

LITERATURE REVIEW

Biomass supply chains, productivity, and costs

New Zealand operations

Hall (1995) investigated several methods of recovering forest residues generated from conventional harvesting operations. The total cost for the systems was in the range of NZ$24.00 to NZ$70.00 per m^3. The materials were delivered to a chip utilisation plant, more than 110 kilometres away from the site.

Hall (1997) also studied the total cost of processing and transporting residue from yarder landings to a mill for burning as a fuel. The residue was moved to a nearby landing to be processed, reloaded, and delivered to the mill. Long transporting distance with 110km from the landing to the mill resulted in transportation costs accounted for nearly half of the total system cost. It was found that the total cost could be reduced from NZ$39.65/tonne to NZ$34.00/tonne by modifying the system (e.g., a better payload of the truck and capacity of the grinder).

Another previous study evaluated a system that comminuted the piles of logging residue surrounding a landing after ground-based harvesting was completed and delivered it to a mill as hog fuel (Hall 1998a). Two loaders fed the logging residues into a machine that produced hog fuel, then it was loaded and delivered using trucks to a mill within 5km. Total cost in 1998 for comminuting and transporting was NZ$17.50/tonne with an acceptable quality of hog fuel. The low cost of this system was due to the short transport distance, however, if distances were longer, the total costs were estimated to increase to NZ$23.85/tonne for a 50km transport distance.

One later study compared systems from dumping or burning the residues to utilising residues as either hog fuel or high value products (Hall 2000). Based on the result, total costs for discarding and burning residues were NZ$7.58/tonne and NZ$11.88/tonne, respectively. On the other hand, utilizing and selling the residues created revenues. Unfortunately, the transition from residue to hog fuel was difficult to offset the total system cost (NZ$4.16/tonne) with the low market prices for hog fuel (NZ$10/tonne). The conversion to higher value products such as chips for pulp or pulpwood for panel production could have sufficiently offset the high total cost (NZ$21.70/tonne) by the higher revenues. This study verified that the residue recovery systems were more economically and environmentally efficient than the other systems such as dumping or burning due to changes in the utilisation value of the residue.

A similar study conducted in 2001 evaluated different residue delivery systems to a plant (Hall *et al.* 2001). These systems included; harvesting, processing, chipping, storing, and transporting. The total cost of residue recovery systems at the landing ranged from NZ$22.03/tonne dry matter (DM) to NZ$36.60/tonne DM. The costs of other systems that collected residues from the cutover ranged from NZ$29.61/tonne DM to NZ$78.93/tonne DM. The study concluded that this difference resulted from different site characteristics and other variables and that the simpler the system, the lower total cost of the system could be guaranteed.

In a more recent study in 2009, integrated biomass recovery operations were investigated to give information about productivity and cost of systems (Visser *et al.* 2009). The first operation described an excavator retrieving residues, while another excavator fed them into a grinder to provide hog fuel. Chip vans then transported the hog fuel to the plant. In the second operation, a truck equipped with a large bin hauled the residue to a landing area where chipping was done by mobile chipper. Then chip vans delivered the chips to the end user. In a third operation, unlike the other two operations, the residue was bundled and transported to the plant directly. The bundled residue was then chipped with a stationary chipper. Total costs of the three operations were estimated at NZ$33.90/tonne, NZ$34.50/tonne, and NZ$44.40/tonne, respectively. Even though the stationary chipper operated efficiently in the third operation, the cost of bundling residue was higher than that of the first two operations due to the high cost of bundling and the limitations of the bundler machine.

European operations

The European Union aims to produce 20 percent of its total energy as renewable resources by 2020 (Eliasson *et al*. 2017). Generally, forest biomass supply chains have been created in Sweden and Finland such as roadside comminution, terminal comminution, or comminution at the processing plant, (Routa *et al*. 2013). About 70 percent of Finland's and 90 percent of Sweden's logging residues are chipped by roadside comminution, which is widely used (Figure 2). Terminal comminution involves hauling residues to the terminal for comminution, and storing, mixing, and transporting them to the plant by truck, train, or barge as needed. Comminution at the plant allows chipper and chip truck to operate independently. In these countries, comminution on the cutover has been limited because of logistical difficulties and high cost.

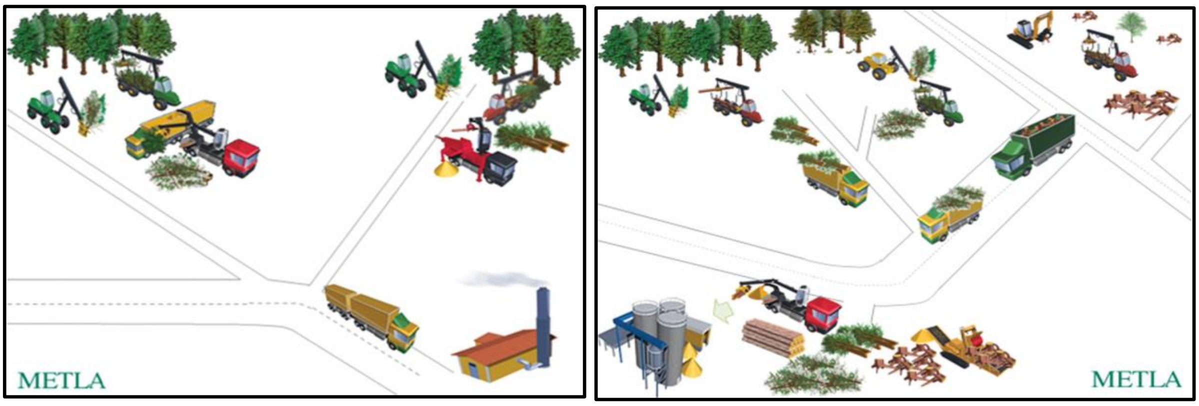

Figure 2. Forest fuel supply chain based on comminution at the landing (*left*) and power plant (*right*) (Johanna Routa *et al.* 2013).

Kanzian *et al.* (2009) investigated costs of flows of biomass material from forest to plant direct or via terminal for conversion. The study showed that if trucks were available to access the harvesting area, transporting to the plant and chipping fuelwood directly was the cheapest supply chain with the cost of €5.60-6.60/m^3. Forest biomass scattered on the cutover, should be gathered from a large number of stands (Hakkila 2003).

Cut-to-length (CTL) harvesting methods are predominant harvesting systems whereby a harvester and forwarder are used and constitute about 95 percent of harvesting in Ireland

(Jiroušek *et al*. 2007). Murphy *et al*. (2014) examined supply chains that produce biomass from Sitka Spruce plantations in Ireland. In this supply chain, trees were felled, processed, and cut into the various products, such as saw logs, pulpwood, pallet wood and stake wood, by the harvester then a forwarder hauled the products to the roadside. Woody biomass that had been laid down for at least one summer to lower the moisture content was comminuted at the roadside with the chips sent to the end user.

Tobias and Velazquez-Marti (2007) compared two systems in Norway spruce stands affected by a bark beetle infestation. The first system was that of a forwarder-mounted chipper that chipped scattered trees that were felled by chainsaws in the stand. In a second system, a forwarder hauled and piled trees along the road, then the trees were fed into a truck-mounted chipper. Total costs for the systems were €4.74/m^3 for chipping in the stand and €5.63/m^3 for chipping at the roadside, respectively. The authors found that both options were cost-effective systems that could produce wood chips from unmerchantable trees.

In the southern European country of Spain, Tolosana *et al.* (2014) conducted a biomass recovery operation with a mechanised CTL system in a conifer plantation. Once the harvester felled and processed stems, logging residues were extracted and bunched by a forwarder and bulldozer. A shredder crushed bunched logging residues. Two factors were tested: the method of bunching the biomass and the size of the top diameter cut by the harvester head. The authors found that producing larger top diameter and bunching the biomass with the bulldozer showed the most cost-effective result.

In a different region of Spain, a whole-tree chipping operation was performed in coppice natural stands of Oak, Quercus Pyrenaica (Laina *et al.* 2013). This operation felled and bunched stems with a feller-buncher, hauled the whole trees to the landing with a forwarder (Figure 3), and comminuted the material at the landing by a truck-mounted drum chipper. Total cost for producing chips was €65.30/ODT, and chips contained 40% moisture.

Figure 3. Whole-tree extraction by forwarder in coppice forest (Laina *et al.* 2013)

A comparison of two harvesting systems for the production of forest biomass from thinning Norway Spruce (Picea abies) was undertaken in northern Italy (Spinelli and Magagnotti 2010).

The first system was whole-tree harvesting (WTH), producing only whole-tree chips for energy purposes. The other system was cut-to-length (CTL) mechanical harvesting with an excavator-based harvester. Norway spruce plantations were thinned at the age of 35 years using a CTL harvesting system including an excavator with a harvester head and a farm tractor equipped with a self-loading trailer and log truck. An excavator bunched processed logs in small piles on the side of the strip road. These piles were hauled off by the tractor to a landing then, trucks transported them to the end user where sorting, storing, and chipping was completed. The CTL harvesting system was cost effective method with a total cost of €42.90 per green tonne (GT).

A chipping operation was studied on flat terrain in a pine plantation in central Italy (Marchi *et al.* 2011). The study compared chipping in the cutover versus roadside chipping. Stands were clear-cut using a feller-buncher and sorted into logs, tops and branches, and small trees. In the cutover chipping operation a forwarder-mounted chipper comminuted residues directly into a tractor-trailer. A truck and trailer transported chips to a landing to load chips into chip vans, which delivered them to the plant. In the roadside chipping operation a semitrailer-mounted chipper was fed by an excavator. The chips were blown into open top chip vans so re-loading was not necessary. Roadside chipping was four times more productive than cutover chipping (90.9 GT/PMH versus 16.7 GT/PMH) and enabled total harvesting costs to be reduced by one-third (€12.30/GT versus €18.30/GT).

United States operations

In northern California, USA, Bisson *et al*. (2015) studied a centralised biomass recovery operation. In this operation, a loader loaded piles from landings and scattered residues to a dump truck. Another loader fed delivered material into the grinder, and ground material was directly loaded into a chip trailer. A tractor moved the chip trailer to a transfer site, then an additional tractor reloaded and delivered material to the power plant located 24km away from the site. The total cost of felling, processing and transporting was US$44.30 per bone dry ton (BDT) with production rate of 38.0 bone dry tons per productive machine hour (BDT/PMH).

In western Oregon and Washington a study investigated chipping systems with processed and piled residues at a centralised landing for comminution by a stationary grinder (Zamora-Cristales *et al*. 2013).Three different transportation systems were studied: a single road with turnaround located after processing site; a single road with turnaround located before processing site; and a one-way-loop road. They found the number of trucks, truck utilisation and road accessibility characteristics (such as grinder location relative to available truck turnaround, truck turn-around time and truck positioning time) were the main factors that affected the grinder's productivity. It was recommended to build truck turnouts close to the grinding site or increase the grinder landing area to allow off-road truck loading. After optimising transport, the total estimated processing and transportation costs in dollars per bone dry metric tonne (BDMt) for each option was $56.01/BDMt (60% grinder utilisation with 6 trucks); $38.45/BDMt (77% grinder utilisation with 7 trucks); and $48.34/BDMt (74% grinder utilisation with 4 trucks), respectively.

Anderson *et al.* (2012) evaluated productivity and cost for two biomass recovery systems where large chip vans were inaccessible to the site. The two systems were: (1) transporting, storing, and grinding residues at the centralised landing, then loading into chip vans and (2) grinding on the cutover then, transporting, storing, and loading at the centralised landing. Total costs of processing and loading residues were $24/BDt and $25/BDt for each system, respectively. Based on the result, if residues were scattered and there was a long-distance for in-woods grinder mobilisation, it was reasonable to use the first system. However the other system was more suited to use if residues were piled heavily on the roadside.

Kizha and Han (2015) investigated two whole-tree harvesting systems recovering residues: shovel and cable yarding. For shovel logging, a feller-buncher felled and bunched trees, a shovel loader moved them to the roadside, then they were processed by a grapple processor into log lengths. In cable yarding, once trees were felled by chainsaw, a swing yarder transported the logs to the uphill landing. A grapple processor processed the trees at the landing. Then a modified dump truck gathered the residues at both operations and transported them to a grinding site to process and deliver materials to power plants. Results of this study showed that the biomass recovery for the shovel logging, at 157 oven dry metric tonnes per hectare (ODMT/ha), was higher than that for the cable yarding (110 ODMT/ha). This was on account of better machine accessibility in shovel logging terrain.

Biomass densification systems have been studied in clear cut harvesting sites by Harrill *et al.* (2009). This system included a slash bundler, a loader, hook-lift trucks, a grinder, and chip vans. The hook-life trucks delivered bundles and loaded containers to a centralised landing where the bundles were ground into hog fuel. A total production of this system was 280.7 BDT over 70.2 hours. Due to the poor system balance, a total system cost was US$60.98/BDT which is high.

More recently an integrated harvesting system in stand conversion clear cut operations in northern California was evaluated (Harrill and Han 2012). Douglas-fir (Pseudotsuga menziesii) trees were processed into saw logs while whole trees of tanoak (Lithocarpus densiflorus), and sub-merchantable materials (small-diameter trees, tops and limbs) were fed directly into a chipper to produce biomass for energy production. Bunches of trees were transported to a centralised processing site by log trucks. Once a disk chipper produced chips, a front-end loader loaded the chips into chip trailers that transported the chips to the power plant. The total system production rate was 35.26 BDT/PMH, determined by the individual process with the lowest production rate (i.e., hauling chips). The costs of the integrated system were US$ 29.87/BDT for biomass and US$4.26/BDT for saw logs. Since this integrated system comprised various machinery and provided different types of products, system balance should be considered carefully, and this could result in increased productivity and decrease the cost of the system.

Saunders *et al.* (2012) studied an integrated harvesting system in a mixed oak-hickory forest. Based on the study result, a total cost for producing wood chip from the stump to the truck was US$22.8/green ton. In this study, trees were felled and left along skid path by a feller buncher then, they were manually delimbed by a chainsaw. A skidder extracted these bundles to the landing site. Delivered small-diameter trees, branches, and tops were comminuted by a chipper and directly loaded into chip van. Although, additional costs such as product transportation and road construction were not added in this study, the integrated harvesting system showed potential for operating in hard wood forest.

Baker *et al*. (2010) investigated integrated harvesting systems with a small chipper to produce biomass in clear cuts and thinnings in the southern United States. The equipment included: feller-bunchers, grapple skidders, trailer-mounted loaders, a mobile loader, a track-mounted excavator with processor head, and a chipper. The feller-buncher felled and bunched trees then, the grapple skidder extracted the trees to the roadside. These trees were loaded and processed using the loader and processor. The limbs, tops, and merchantable trees were chipped using chipper. A result showed that adding the small chipper to conventional harvesting system was less impacted on the clear cuts than in thinnings due to small tree size and limited operating space in the thinning site.

Spinelli and Visser (2009) used literature related to in-field wood chipping operations to estimate delays of different machines and different operating conditions. They found an average chipper utilisation rate of 73.8 percent. Almost two-thirds of delays reported (16.6%) were caused by organizational-type delays related to truck interference, waiting for the biomass, and refuelling.

In a biomass recovery system in pine plantations in the south-eastern USA, two set-out trucking operations were found to increase transportation efficiency by reducing truck delay time (Jernigan *et al*. 2013). In a thinning operation, trees were felled by a feller-buncher, hauled by a skidder, and delimbed by a delimber on a loader. Residues were fed in to a chipper by the loader. In a clear cut operation, a feller-buncher felled trees, and two skidders hauled the trees. Two pull-through delimbers used by the loaders processed trees, then residues were fed into a chipper by a loader. According to the results, a total cost for thinning operation was $18.38/tonne in thinning operations, whereas in clear cut operation, the total cost of the system was $17.81/tonne. Both systems were feasible and cost-effective for biomass recovery operation unless conventional log operations affected the system.

Australian operations

In Australia, biomass harvesting for energy has currently begun to develop compared to New Zealand (Ghaffariyan *et al*. 2017). Ghaffariyan *et al.* (2011a) applied a bundling operation under two treatments in clearfelled Eucalyptus plantations. In the first treatment an excavator accumulated residues into rows then a bundler started bundling. In the second treatment, the bundler made bundles with scattered slash from the cutover area. It was suggested that better bundling costs could have been obtained by applying this system at the whole tree landing site where substantial amount of slash was generated.

In Western Australia, whole-tree chipping was studied to produce biomass material in low quality Eucalyptus plantations (Ghaffariyan *et al*. 2011b). Trees were felled and bunched on the ground, then a grapple skidder hauled them to the roadside. Processed chips produced by a mobile chipper from whole trees were directly fed into the trailers and transported to the pelletizing plant. Poor quality and small size of the trees (diameter at breast height of 14 cm) resulted in low productivity (63.9 GT/ha) and high harvesting cost of the biomass recovery system in this study. Better results will be obtained from harvesting plantations near power plants to reduce travel costs or to use systems optimized for small trees.

Variables affecting biomass recovery operations

The overall productivity and delivered cost of biomass recovery operations is influenced by stand and site conditions including tree size, tree age, and stand density (Mederski 2006; Ghaffariyan *et al.* 2011b; Spinelli *et al.* 2011). Bisson *et al.* (2015) concluded that the type of material (whole tree or slash) that is handled and its location scattered within the harvest unit affected the operation. Spinelli and Hartsough (2001) and Mola-Yudego *et al.* (2015) found a similar result that piece size had significant effect on productivity of chipping operation.

Factors associated with machinery also affect the overall productivity and costs of the system. These factors include type of machinery, machine composition, operator's skill, and capacity of machine (Hall 1995, Hall 1997; Hall and Evanson 2007b). Along with the machinery factor, it has been pointed out that the importance of the amount of residue at landing and the size of the residue (Hall and Evanson 2007b; Visser *et al.* 2009). These factors have an effect on machine utilisation if the residue is not enough accumulated and type of machine if the proper machine is not utilized for processing. In processing, a total delivered cost and production rate are affected by moisture contents of residue (Hall 1995; Hall *et al.* 2001). In the previous study, Hall (1997) concluded that the shorter the transport distance from landing to an end-use facility, the lower the total delivered cost.

Spinelli and Hartsough (2001) and Tobias and Velazquez-Marti (2007) confirmed that different types of machines with different horse power affected productivity of chipping operations. For instance, if small sized residues are fed into a heavy-duty chipper for medium to large sized whole-tree operations which have a high fixed cost, the total cost of system will be increased. Operator skill is other important factor due to the operators often having years of experience with machine types which resulted in different total cost (Mola-Yudego *et al.* 2015).

Location of the chipping area is another key variable in the biomass recovery operation. Some studies found that lower chipping cost was obtained by chipping at a plant or terminal, but it was could not offset the costs for transporting and handling (Laitila 2008; Kanzian *et al.* 2009). Spinelli and Hartsough (2001) pointed out that chipping area had a significant effect on the chipping operation. If a large pile concentration of wood is supplied at the roadside, roadside chipping is a cost-efficient system compared to chipping at a terminal or end-user facility (Laitila and Väätäinen 2012). Ghaffariyan *et al.* (2012) also concluded that chipping at the roadside resulted in high productivity with non-merchantable trees and forest residues.

Transportation distance to plants or end-user facility is an important factor. Hudson and Hudson (2000) highlighted that transport distance substantially affected a total system cost, which also confirmed by Spinelli and Magagnotti (2010). As transportation distance for low-value products increasing, transportation cost increases which also result in an increase in total cost of the system. This would offset by densifying the residues before transportation and increasing payload of the truck (Hudson and Hudson 2000; Tolosana *et al.* 2014). Another factor that affects transportation cost was material moisture content which pointed out by Sessions *et al.* (2013).

The biomass recovery operation is an integrated harvesting system combining the conventional log harvesting operation and biomass harvesting operations, and various machines are used. Thus, system balance influences the total cost of the system due to the complex of machine combination. Harrill and Han (2012) confirmed that productivity and cost can positively change by pairing of machinery that has similar production rates. Eliasson *et al.* (2017) also concluded that a total cost of a system reduced by applying two operations, chipping and transport, into one operation phase. For instance, by reducing machine delays such as chipper waits for sufficient supply of materials at the landing to fill a bin or trailer or an insufficient number of trucks being used which results in increasing chipper delays could improve the total cost of the system.

Table 1 provides a summary of the studies with regard to system, productivity and cost.

Table 1. Summary of machinery, productivity, and cost of biomass operations: International sources

Author	Machine	Productivity	Cost
Anderson *et al.* (2012)			
Clear-cut 60 year-old Douglas-fir, MC 24.2%			
Slash forwarding	Grapple loader (Caterpillar 322B LL)	45.7 BDT/SMH	2.3 $/BDT
	End-dump tractor	6.8 BDT/SMH	9.6 $/BDT
	Grapple loader (Caterpillar 325 LL)	43.4 BDT/SMH	2.6 $/BDT
	Horizontal grinder (Peterson 7400, wheeled)	41.2 BDT/SMH	6.2 $/BDT
			Total: 23.6 $/BDT
In-wood grinding	Grapple loader (Caterpillar 322B LL)	27.3 BDT/SMH	3.8 $/BDT
	Horizontal grinder (Peterson 4710B, tracked)	26.7 BDT/SMH	9.0 $/BDT
	Dump truck	7.7 BDT/SMH	8.1 $/BDT
	Front-end loader (Caterpillar 966D)	62.9 BDT/SMH	1.6 $/BDT
			Total: 24.5 $/BDT
Baker *et al.* (2010)			
Clear-cut on pine plantations	Feller-buncher (Tigercat 724D)	-	-
	Grapple skidder (John Deere 684) * 2	-	-
	Trailer-mounted loader (Tigercat 230) *2	-	-
	Track-mounted excavator (John Deere 2054)	-	-
	Chipper (300 kW Woodsman 334)	-	-
Bisson *et al.* (2015)			
Clear-cut second growth mixed conifer	Loader with dump truck (Linkbelt 3400)	46.6 BDT/PMH	6.4 $/BDT
plantation	Dump truck (Volvo A35C, Caterpillar D300D)	26.2 BDT/PMH	6.1 $/BDT
MC = 25%	Loader with grinder (Linkbelt 3400)	38.0 BDT/PMH	6.1 $/BDT

	Grinder (Peterson Pacific 5710C)	38.0 BDT/PMH	11.8 $/BDT
	AWD truck tractor	26.5 BDT/PMH	6.4 $/BDT
	Chip trailer	11.9 BDT/PMH	7.5 $/BDT
		Total: 38.0 BDT/PMH	Total: 44.3 $/BDT
Ghaffariyan *et al.* (2011a)			
Eucalyptus plantation			
Concentrated slash	Excavator (P200 Komatsu)	-	-
Moisture content: 33.5%	Bundler	-	-
		Total: 11.8 t/PMH	Total: 23.8 $/t
Scattered slash	Bundler	-	-
Moisture content: 17%		Total: 4.9 t/PMH	Total: 57.3 $/t
Ghaffariyan *et al.* (2011b)			
Mixed Eucalyptus plantation	Feller-buncher (Tigercat 845C)	50.1 t/PMH	-
	Grapple skidder (Tigercat 730C)	44.6 t/PMH	-
	Mobile full-tree chipper (Husky precision 2366)	51.7 t/PMH	-
	Slash bundler (John Deere 1490D)	10.6 GT/PMH	16.2 $/BDT
Harrill *et al.* (2009)	Loader (Hitachi EX200-3)	55.9 GT/PMH	3.0 $/BDT
Clear cut on second growth (60 years) of	Hook-lift truck	14.7 GT/PMH	9.3 $/BDT
redwood and Douglas-fir plantations	Grinder (Peterson Pacific 7400)	46.7 GT/PMH	18.0 $/BDT
Moisture content: 29.0%	System support	-	14.5 $/BDT
			Total: 61.0 $/BDT
Harrill and Han (2012)			
Clear cut on understocked conifer	Feller-buncher (Timbco T445D)	44.7 BDT/SMH	3.4 $/BDT
plantations	Loader (Komatsu PC300) * 2	172.6 BDT/SMH	3.3 $/BDT
Moisture content: 43.2%	Log truck * 2	36.5 BDT/SMH	4.6 $/BDT

	Loader (Komatsu PC300) * 1	242.7 BDT/SMH	2.2 $/BDT
	Swing loader (Linkbelt 3400) & Morbark disk chipper	47.2 BDT/SMH	9.9 $/BDT
	Front-end loader (Cat 962 G)	132.4 BDT/SMH	0.9 $/BDT
	Chip trailer * 2	35.3 BDT/SMH	5.5 $/BDT
			Total: 29.9 $/BDT
Hall 1998a			
Residues at hauler landings	Front end loader & Wastepro hog	-	14.85 NZ$/tonne
5km transport distance	Truck		2.65 NZ$/tonne
Moisture content: 46%			Total: 17.50 NZ$/tonne
Hall *et al.* 2001			
Pine plantation			
Site 1: large forest area with 25km	Landing residues	-	22.03-41.38 NZ$/t DM*
transport distance	Cutover residues	-	29.61-64.98 NZ$/t DM
Site 2: large forest area with 50km	Landing residues	-	32.08-46.60 NZ$/t DM
transport distance	Cutover residues	-	38.39-74.60 NZ$/t DM
Site 3: scattered forest with 75km	Landing residues	-	36.60-50.40 NZ$/t DM
transport distance	Cutover residues	-	42.34-78.93 NZ$/t DM
Hall 1995			
Collection of stem waste wood			
System 1	11 tonne excavator (Cat 311)	14 m^3/PMH	7.45 NZ$/$m^3$
Average 150 km lead distance	Self-loading crane mounted 3-axle bin semi-trailer	-	0.20 NZ$/tonne/km
	8*4 bin truck & 4-axle bin trailer	-	0.16 NZ$/tonne/km
			Total: 35.00 NZ$/$m^3$
System 2	Moxy off-highway truck (grapple mounted)	-	13.60 NZ$/$m^3$
280km lead distance	8*4 bin truck and trailer	-	0.20 NZ$/tonne/km
			Total: 70.00 NZ$/$m^3$

System 3	6-wheel drive highway truck (self-loading crane and grapple with		5.05 NZ$/m^3
115km lead distance	logging bolsters)		
	3-axle bin trailer		18.75 NZ$/m^3
			Total: 24.00 NZ$/m^3
Hall 1997			
Residues at hauler landings	Loader & truck	-	5.60 NZ$/tonne
Moisture content: 46-47%	12 tonne excavator & tub grinder 260W	-	13.15 NZ$/tonne
	Front-end loader	-	1.60 NZ$/tonne
	Bulk cartage truck	-	19.30 NZ$/tonne
			Total: 39.65 NZ$/tonne
Jernigan *et al.* (2013)			
Pine plantations			
Thinning	Loader with pull-through delimber (Timberjack 430B)	-	-
Moisture content: 52.5%	Chipper (Bandit 1850)	17 t/PMH	8.5 US$/t
			Total: 18.4 US$/t
Clear cut	Loader (Blount prentice 210D)	-	2.2 US$/t
Moisture content: 46.6%	Chipper (Bandit 1850)	17 t/PMH	6.1 US$/t
			Total: 17.8 US$/t
Laina *et al.* (2013)			
Coppice plantation	Feller-buncher (Timberjack 1070)	2.8-3.9 ODT/PMH	-
Moisture content: 69%	Forwarder (Timberjack 1410)	6.3 ODT/PMH	-
	Truck mounted drum Chipper (Pezzolato 900/1000	5.3 ODT/PMH	-
			Total: 65.3 €/ODT

Marchi *et al.* (2011)			
Pine plantation			
Terrain chipping	Chipper	16.7 GT/PMH	-
Moisture content: 49.3%	Chip shuttle	-	
			Total: 18.3 €/GT
Roadside chipping	Chip shuttle	-	-
Moisture content: 48.8%	Forwarder	-	-
	Chipper	90.9 GT/PMH	-
			Total: 12.3 €/GT
Saunders *et al.* (2012)			
Mixed oak-hickory plantation	Feller-buncher (Timberjack 740)	27.4 ton/PMH	1.7 US$/ton
	Grapple skidder (Timberjack 460D)	10.9 ton/PMH	2.1 US$/ton
	Knuckleboom loader (Timberjack 530)	19.3 ton/PMH	1.3 US$/ton
	Stationary chipper (Vermeer prototype)	24.1 ton/PMH	2.3 US$/ton
			Total: 7.4 US$/ton
Spinelli and Magagnotti (2010)			
Norway spruce plantation			
Moisture content: 55%			
Whole tree harvesting	Felling	3.7 t/SMH	5.8 €/t
	Extraction	3.0 t/SMH	15.3 €/t
	Loading	11.7 t/SMH	7.7 €/t
	Transport	5.8 t/SMH	11.7 €/t
	Relocation	-	0.2 €/t
			Total: 40.6 €/t
Cut-to length harvesting	Harvesting	4.4 t/SMH	24.0 €/t
	Extraction	7.7 t/SMH	7.1 €/t

	Loading	34.0 t/SMH	2.0 €/t
	Transport	8.1 t/SMH	8.4 €/t
	Relocation	-	1.3 €/t
			Total: 42.9 €/t
Tobias and Velazquez-Marti (2007)			
Norway spruce plantations	Mobile chipper mounted forwarder	-	4.7 €/m^3
	Forwarder & Chipper mounted truck	-	5.6 €/m^3
Tolosana *et al.* (2014)			
Mixed pine plantation	Harvester (Timberjack 1270 C, John Deere 1270 D)	-	-
Moisture content: 51.3%	Forwarder (Dingo 6x6, Timberjack 1410 D)	-	-
	Bulldozer (Fiat-Hitachi FD 175)	-	-
	Shredder (Hammer VB 950)	-	-
			Total: 29.7-31.5 €/GT
Visser *et al.* 2009			
Option 1	350 kW mobile tub-grinder & 20-t excavator * 2		22.80 NZ$/t
40km transport distance	Chip van	8.50 t/SMH	11.10 NZ$/t
			Total: 33.90 NZ$/t
Option 2	Bin and loader mounted off-road truck		10.30 NZ$/t
2km hauling distance to landing	Mobile chipper & excavator-based loader		13.80 NZ$/t
	Chip van	9.20 t/SMH	10.30 NZ$/t
			Total: 34.50 NZ$/t
Option 3	Truck-mounted bundler		28.40 NZ$/t
Bundling the residue	Self-loading log truck & excavator loader	9.20 t/SMH	11.70 NZ$/t
	Stationary chipper		4.20 NZ$/t
			Total: 44.40 NZ$/t

Zamora-Cristales *et al.* (2013)			
Moisture content: 41.3%			
Case 1: Douglas-fir,	Grinder (Peterson 5710C)	31.6 BDT/PMH	48.5 $/BDT
Truck interference with truck turnouts	Rear-steer-axle trailer * 2	-	31.2 $/BDT
Case 2: Douglas-fir,	Grinder (Peterson 4710B)	35.8 BDT/PMH	17.4 $/BDT
Truck interference with turnaround located before grinding site	Trailer equipped truck * 3	-	22.6 $/BDT
Case 3: Sitka spruce and western hemlock,	Grinder (Peterson 4710B)	25.9 BDT/PMH	29.7 $/BDT
Truck interference with off-road truck-loading space	Two truck * 2	-	25.8 $/BDT

Forest biomass markets and end users

New Zealand has the potential to utilise significant amounts of forest residues as a biomass. Many of forest residues are generated from harvesting operation, post-harvest, or plant as a by-product during log processing. Based on one report (Hall and Evanson 2007a), plants such as saw mills, pulp & paper, and co-gen (co-generation of both steam or heat and power) require a significant amount of residues as a fuel for generating heat and steam.

Generally, material supplied to the mill is in the form of raw materials (logs, branches, tree-tops and off-cuts), chips, hog fuel, bark, and sawdust. Some of this biomass is used as fibre input to pulp and panel plants Similar to other countries, combustion of woody biomass is the prevailing processing method and is the cheapest way to provide heat and electricity in New Zealand. Some of this biomass is used for mulch and composting depends on quality and moisture content (Hall and Evanson 2007a). A small proportion of processed biomass, as wood pellets, is used as a fuel for households. In the future, a variety of biomass products in various markets might be in demand, but the processing of forest residues in New Zealand is in a developing stage (Hall and Evanson 2007a). In order to attract better prices to higher value biomass products, market development is required with a better understanding of the quality of the materials (Visser *et al.* 2009), due to product prices are influenced by product quality in the market (Spinelli *et al.* 2019).

Forest biomass is now growing in interest with the emergence of new markets and technological advances. A summary of forest biomass markets in New Zealand is given in Table 2.

Table 2: Examples of forest biomass markets in New Zealand, as retrieved from an internet search.

Name	Location	Product	End-use & end-user	Amount of production
Reharvest	Auckland www.reharvest.co.nz/	Garden bark chip	Landscapes and spaces from large site public areas to home gardens	
		Bark and woodchip mulch	Kindergartens and playground surface	
		Woodchip	Animal bedding and Horse riding arenas	
		Coloured wood chips	Landscape mulch	
Pedersen group-Kinleith pulp & paper mill	Kinleith www.pedersen-group.co.nz/operations/kinleith/	• Chip & bark-stationary eucalypt twin ring debarking plant	• Fuel for the onsite-co-generation plant	From 250,000 tonnes to over 600,000 tonnes per annum 30,000 truck movements annually, Hogging up to 120,000 tonnes per annum through a Morbark mobile hogger.
		Hog fuel	Carter Holt Harvey (CHH) Pulp & Paper	

Natures Flame	Taupo www.naturesflame.co.nz	Wood pellet	• Rotorua Girls' High School- (converted 42 school boilers from coal boilers to wood pellet boilers) nationwide • Householders • Commercial/industrial businesses • NZ army, Walouru	
Green Gorilla	Auckland www.greengorilla.co.nz	Wood chip	• Golden Bay Cement as the fuel source • Landscape • Animal bedding	Over 100 tonne per day
Central Wood Recyclers Ltd	Taupo	Chipper fines	Animal bedding &trade stands	
		Hog fuel	Standing pads for cows	
		Boiler fuel	Co-gen fuel/bio fuel	
Materials Processing Ltd	Hamilton www.materialsprocessing.co.nz	• Solid waste recovery company • Recovering wood waste at the OJI Kinleith Mill for co-gen boilers Developing a new process to produce syngas and torrefied wood • Syngas-fuel for torrefaction plant and for combustion in dual fuel generator for electricity		
Panpac Forest Products Limited	Napier www.panpac.co.nz	Whole log chipping Chipped residuals from sawmill	Pulp	Up to 450,000 tonnes of wood chip a year
		Bark, sawdust and shavings	Boiler fuel	

Azwood Ltd	Nelson www. azwood.co .nz	Biomass hog fuel	• Medium to large hospitals • Large process heat users • Large greenhouse complex users • Dairy processing industry	• 1,000,000 m^3 of product a year • Supply about 65% of the domestic wood pellet market
		Wood energy chip	• Medium to large process heat factories • Medium to large schools • Small to medium hospitals • Large building accommodation • Greenhouse flower and tomato growers	
		Wood pellet fuel	• Large homes • Motels/hotels • Small to medium schools • Small to medium office buildings • Small to medium process heat users	
Wholesale Landscapes Ltd	Nelson www.wholesalelandscapes.co.nz	Sawdust	Animal bedding Plant mulch nurseries	
		Peel bark	Large-scale plantings to help reduce weeds and improve a new plants chance to survive	
		Pine flake	Animal bedding	
		Mulch bark	Large landscaping projects Slope sections	
		Nuggets bark & chip bark	Residential garden Playgrounds Small flat sections	
Spark Energy	Queenstown www.sparkenergy.co.nz	Wood chips & wood pellets-using wood waste from forestry operations otherwise left unused	Selected clients around New Zealand	
Tailored Energy Solutions	Rolleston www.taylorcoal.co.nz	Wood pellets		
		Wood chip		
		Fire wood		
		Hog fuel	Animal bedding as a garden mulch/weed suppressant	

H.A. Foote Haulage Ltd H. A. Foote Haulage Ltd.	Dunedin www.footehaulage.co.nz	Wood chip	landscape	
		Firewood		
Pioneer energy (Formerly Wood Energy NZ (WENZ)) Pioneer energy	Alexandra www.pioneerenergy.co.nz	Wood chip	Industries, hospitals, councils, schools, and universities	
Niagara Sawmill and Timber Remanufacturing NIAGARA STRENGTH IN TIMBER	Invercargill www.niagara.nz	Pellet (6mm)	domestic pellet fires and commercial boilers	120,000m^3 of sawn timber
		Wood chip	industries, councils and schools in the southland/Otago area	
		Bark	gardening products and landscaping	
		Sawdust	fuel for drying kilns	
		Shavings	animal bedding and briquettes	
		Chip	medium density fibreboard	
		Offcuts	premium-quality firewood or chipped for boiler fuel	
		Fire briquettes	tests prove to be New Zealand's hottest burning manufactured wood-based fuel	

Potential markets

Name	Location	Potential market	Amount of production
DB Breweries	Timaru	Plan to switch its coal-fired steam to biomass for steam supply at its Washdyke plan	Expect to be require almost 3,000 tonnes of wood chip a year
Z energy &Norske Skog	Kawerau www.norskeskog.com/	Bio-diesel (Stump to pump project 2014) A sufficient volume of forest residues is available to support biofuel production in New Zealand Technology exists that converts forestry residues to hydrocarbon liquid biofuels But the product does not yet fully meet New Zealand fuel specifications	The total estimates for New Zealand's forest residues are in the vicinity of 3.9 million m3 in 2014 increasing to 5.8 million m3 by 2025
Red Stag Timber	Rotorua www.redstagtimber.co.nz	Drying more than 400,000m3 of timber each year with energy from Red Stag Timber's own biofuels, the 7 kilns operate 24/7. The Bark is used as bio-fuel for boilers to generate electricity and heat the kilns.	

In the United States, materials such as forest residues, fuel wood, and wood waste are comminuted to biomass fuel (Anderson *et al.* 2012). This biomass fuel, called hog fuel, is used as heating the facilities or institutions and generating electricity. Based on the U.S Department of Energy (2011) report, about 40 million dry tons of forest residues generated from conventional harvesting operations would be expected to use annually, and 32 million tons of forest residues provided from primary and secondary mills is used as a combustion fuel in the United States. Wood-energy facilities are currently being supplied with mill residues or chips rather than roundwood, but the wood-energy market is expected to grow rapidly and compete with the conventional forest products industry (Conrad *et al.* 2011).

In Sweden and Finland where forest resources are sufficient, most of the fallen trees are used as wood and pulpwood, and nearly half are used to produce energy (Ericsson *et al.* 2004). Sawmills produce various forms of by-products such as wood chips, bark, and sawdust. Wood chips are used as pulpwood and wood fibres are used as fuel in the wood fibre industry. In both countries, the forest industry accounts for more than half of the energy demand and a small number of demands is in the pulp mills, district heating, households, and service sectors.

Trømborg *et al.* (2008) concluded that firewood as a fuel for heating is the major consumption in the production of bioenergy in Norway. Forest biomass derived from forest industry residues such as sawdust, bark, and black liquor accounts for 15% of total domestic heat market in Norway. However, biomass is traded at a relatively high price that other countries, owing to higher labor costs and wood prices in Norway. In the 1990s, for several reasons (e.g., high supply costs of biomass and varying quality of products), there had no market for professionally trading biomass within Austria (Stockinger and Obernberger 1998). However, combustion of wood chips at combined heat and power plants are a prevalent method of using biomass as a fuel currently in Austria (Kanzian *et al*. 2009). Increased demand for relatively small amounts of fuel has increased due to the increase in new municipal and home heating systems; chips for fuel are provided from sawmill.

In Australia, energy production using wood biomass is at a relatively early stage compared to other countries (Ghaffariyan *et al.* 2011b). A significant amount of forest biomass is generated from plantations in form of tree tops and branches and forest industry as by-product (Stucley 2010). The prevailing utilisation of this forest biomass is as a fuel for generating heat, steam, and power in the forestry industry and household. Also in some coal-fired power plant, forest biomass are partly substituting coal as co-fired fuel (Moghtaderi *et al.* 2007). Some groups recently generate wood pellets using forest residues, then export to European power stations as a fuel (Stucley 2010). In Australia, bioenergy technology is extensively developing to meet the demands of high-quality production and various markets for the forest biomass.

To secure sustainable long-term supply of forest biomass and to accomplish successful use of biomass, development of technology for forest management system and biomass procurement must proceed with large investments in research organizations, forest and energy industries, and end users (Routa *et al.* 2013; Tolosana *et al.* 2014). Market demand for biomass, however, depends on season; high in winter and low in summer (Eliasson *et al.* 2017). One possible way to solve this obstacle is trade internationally. In the past, biomass was generally traded within its country, but in recent years the growing market demand for biomass increases the international biomass trading market between countries (Trømborg *et al.* 2008). Further investigation would be needed for development of an international biomass trade market.

CONCLUSION

All harvesting operations produce residues. This material can both affect operations as well as potentially create a downstream risk if mobilised. Harvest residues that accumulate at landings are of key interest in that their removal is relatively low cost compared to cut-over retrieval, but also is the material most likely to impeded processing operations.

There is a growing interest in harvesting residues with the emergence of new markets and technological advances. Integrated harvesting of log products and residues, combining the production of diverse products from the same forest area, now represents the most common strategy to further utilise the forest resource and create additional revenue opportunities to forest owners. The growing bio-economy is creating new markets for low-quality woody materials presenting new opportunities to match the new market demand. Wood fuels are recognised as a renewable energy alternative to fossil fuels to mitigate global issues such as greenhouse gas emissions and climate change.

This report has provided a summary of harvest residue extraction systems in the international literature, and provided estimates of costs and productivity of these systems. In summary, many factors influence the production rate and delivered cost of biomass, and site characteristics and the complexity of harvesting and biomass recovery operations are almost unique in each study.

In the future, a variety of biomass products in various markets may develop, but the processing of forest residues in New Zealand is still in an early development stage. Product prices are influenced by product quality in the market and in order to attract better prices for higher value biomass products, market development is required with a better understanding of the quality of the materials.

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