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Management of Woody Biomass:
a review of the literature

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EXECUTIVE SUMMARY

New Zealand forestry practices are critically due for improvement with regards to the treatment and utilisation of residual woody biomass. To preserve the continued acceptance and growth of forestry into the future, biomass management must be economically feasible, environmental feasible and socially acceptable. Particular opportunities for woody biomass include; having a marginal nutrient cycling benefit; reducing downstream sediment deposits; reducing erosion from forest roading; and use in the production of energy biomass.

Fire via slash pile burning has long been the most common treatment amongst forestry operations across the globe. This treatment is gradually phasing out due to realised environmental and health concerns. Burning woody biomass is becoming increasingly high risk and unfavourable due to global warming and growing social concerns. It is predicted that authority agencies will make it substantially more difficult to burn residual woody biomass in the future.

An alternative to burning this biomass is the production of biochar using kilns of varying sizes and specificity for various operation sizes. The use of biochar is contentious, with evidence existing in support and against the use of biochar as a long-term carbon reservoir and nutrient provider within the soil. Further investigation will be required to delineate whether this material is a viable soil enhancer.

Air curtain burners may be used to produce ash from woody biomass in a manner that produces less harmful greenhouse gases (GHG) and reduces the risk of an unintentional fire.

Forest mastication is another residual woody biomass treatment which utilises specialised mechanical mulching heads. Mulching biomass is a promising option, and has been shown to limit negative environmental processes.

Utilisation of biomass to produce energy is the ideal management strategy for woody biomass. However, limitations such as mechanical costs, transportation issues and market security make it uneconomical to extract value from most biomass. Chipping or grinding is typically used to create merchantable bioenergy products. These machines are variable by size, power and location to suit a range of operational requirements. Opportunities have been suggested which may increase the economic incentive to utilise woody biomass in this way. When more biomass is extracted and given an economic value, the potential risks for post-harvest sites will decline. Several other approaches may ameliorate biomass utilisation challenges such as bundling, drying, barging, hook-lift trucking, rail, amending the carbon price, and integrated harvesting systems.

INTRODUCTION

New Zealand maintains a strong forestry sector contributing 1.6% of the nation's GDP with wood products being the third highest export earner. A contribution of 1.1% to the global supply of industrial wood and 1.3% of trade in forest products can be attributed to the New Zealand forestry industry. Approximately 1.7 million hectares of land is utilised as forested plantations and exported wood products were valued at $6.32 billion in December 2019 with logs contributing over half of this. Of the 35.9 million tonnes of harvested volume in 2019, 21.8 million was exported as logs (mostly to China) and 13.8 million tonnes was processed domestically (NZFOA 2019/20).

Following harvest, it is common practice to leave residual material on-site at the landing or spread over the cutover. This method of management is problematic in that it underutilizes residual woody biomass, is often a hindrance to future land use and leaves high volumes of material on-site with the potential to cause large-scale environmental and infrastructural damage (Visser and Raffaele, 2020). Consequentially, in the past these issues have thrust the New Zealand forestry sector into a position of scrutiny by both the public and governing agencies.

Residual woody biomass can become mobilised, commonly triggered by periods of high-intensity rainfall. Debris flows and erosion are natural processes within the landscape and can be dramatically worsened by the presence of large residual biomass. Subsequently, the management of woody biomass must manage this risk. These events can have devastating implications to local communities and the wider ecosystem, with a primary example being the Tolaga Bay incident in Gisborne in June 2018. Following prolonged rainfall over 24 hours, large volumes of woody material were deposited from harvested sites onto roads, catchments, private land, and beaches (Figure 1). Biomass mobilisation exemplified in Tolaga Bay is a considerable risk to the industry and the wider community. As forests in New Zealand continue to be planted onto steeper unstable landscapes, these events will become an increasingly pressing issue. It is widely accepted that an event of this destructive magnitude should not occur again. Developing woody biomass management strategies to mitigate the risk of large-scale mobilisation is paramount to the sustainability of forest harvesting operations.

Figure 1. Slash washed up on the beaches of Tolaga Bay. Source: Flaws, 2020 Chris Mckeen (https://www.stuff.co.nz/business/farming/agribusiness/121983842/environmental-devastation-at-tolaga-bay-may-take-a-century-to-recover-says-councillor)

The long-term sustainability of handling this biomass will become an even greater pressure as the nation is set to phase out chemical fumigation using methyl bromide at New Zealand ports. Stem debarking is the preferred alternative to meet the biosecurity requirements of export markets. This alternative if undertaken in the forest is expected to produce greater volumes of residual woody biomass (i.e. bark). Consequentially, the need for effective management will significantly increase in the near future.

There is a need to develop better risk management strategies and improve the utilisation of traditionally unmerchantable woody material. New Zealand has yet to develop prescribed residual woody biomass treatments that approach concerns at the forefront of the forestry sector (Phillips *et al.*, 2017; Visser, 2018). This report aims to delineate technologies and systems that may be suitable to achieve greater sustainability in woody biomass management practices.

Objectives

Presented in this study is a review of residual woody biomass management systems currently utilised within New Zealand and across the globe. The objectives of this research were as follows;

- Define residual woody biomass and its significance to New Zealand production forests

- Establish the environmental, social and economic needs for sustainable woody biomass management and opportunities in achieving these

- Inform the industry about technologies for biomass processing
- Inform how New Zealand forests can better utilise and reduce the volume of this biomass produced

Literature used in this review have been accessed primarily through FGR records, Google Scholar and academic search engines like Research Gate and Science Direct.

LITERATURE REVIEW

Residual woody biomass in New Zealand timber harvest operations

Biomass is a term which can refer to the merchantable wood products extracted from felling and harvesting. It may also pertain to the residual material remaining after these products have been harvested. For the purpose of this study, there is a focus on the utilisation and management of large woody biomass. Residual biomass is defined in the Resource Management (NES-PF) Regulations (2017) as "…any tree waste left behind after plantation forestry activities". In this sense, residual woody biomass refers to the pieces of large stem wood or branches remaining after conventional harvesting operations. This biomass may be created from the act of felling trees in the forest and the act of processing which may occur partly in the cutover or entirely at the landing. In a typical forest operation, the bulk of this material will collect at the landing and be left in large piles.

The expected volume of woody biomass produced is highly variable, being mainly dependent on contributing factors like the experience and ability of crew to extract value. Factors such as harvest systems, environmental conditions and felling direction also impact the volume of waste produced from a given harvesting operation (Visser, *et al.* 2010a; Andrews 2015).

The NES-PF outlines the baseline legal requirements for sustainable forest harvesting practices. Some requirements listed include ensuring the following: soils are stabilised to reduce sedimentation; slash traps comply with standards; slash and debris management is implemented; the residue is removed from certain areas. Management of residual woody biomass is a legal obligation of forest owners to uphold all facets of sustainable land use (MPI, 2018).

Needs and opportunities for sustainable biomass management

A sustainable woody biomass management strategy must be economically viable, environmentally feasible and socially acceptable. The inability to meet these requirements will curate the conditions existing presently in the New Zealand forestry sector. Treatments must have a minimal environmental impact, be economical and acceptable to standards held by the public and governing agencies. Operating otherwise will continue to threaten the industry's social license to operate. Woody biomass may also have the potential to offer several opportunities to benefit forest operations. These factors must be considered when developing an effective biomass management strategy.

Maintaining woody biomass may offer the benefit of cycling nutrients back into the soil for the next rotation of growth. Mendham *et al.* (2003) tested the implications of different biomass treatments on the soil nutrient resource after harvesting *E. globulus* from two sites. Retaining biomass had the short-term effect of increasing the amount of exchangeable potassium (K), calcium (Ca) and magnesium (Mg) after establishment. The most significant differences were observed in the less fertile site, indicating that soils with limited fertility may benefit most from residual biomass retention. This testing concluded that nutrient pools are positively impacted from residual biomass on-site, however, these benefits are likely to be short-lived due to rapid decomposition and leaching of nutrients.

Smith *et al.* (2000) investigated how residual biomass management impacts the fertility of *P. radiata* stands across various regions in New Zealand. Tree diameter on recent sandy Woodhill forest soils, with the forest floor and biomass removed, was negatively impacted. No other significant impact could be found at the other sites when removing organic matter. Sites with greater natural fertility showed less of a benefit to biomass and organic matter retention, corroborating with the findings of Mendham *et al.* (2003).

Examples may be to minimise the volume of large material in steep unstable areas, or where water collects and drains. Instigating a greater utilisation of woody biomass would minimise the amount of slash, in turn, reducing the risk (Phillips *et al., 2017;* Visser, *et al*., 2018).

If managed appropriately, woody biomass material can be used to mitigate surface erosion particularly along forest roading where it is most prevalent. In New Zealand, strategic residual biomass use is recommended to protect soil, improve the quality of forest roads and the quality of mechanical tracks (FOA, 2020; MPI, 2018). Forest road construction can encourage erosion by stripping resistant topsoil, creating vulnerable cut slope and fill slope surfaces. It is estimated that over 90% of sediment produced from a given harvesting operation is derived from forest roading.

Turk (2018) details a study undertaken in the Aksu district of Turkey to investigate the impacts of using wood chips and slash to reduce sheet erosion on forest roads. Figure 2 shows the chip, slash and control plot set up on a secondary forest road.

Figure 2. The setup to collect runoff from different surface cover plots of woodchip, slash and a bare control plot (Turk, 2018).

Runoff was collected and analysed for sediment content and a significant difference between samples was concluded. Figure 3 Illustrates the difference in sediment content between plots. Sediment runoff was highest in the bare control plot with an average suspended sediment content of 1.409 g.m^{-2} and was lowest in the chip plot with an average of 1.136 g.m^{-2}. The biomass has essentially formed a protective barrier between the topsoil and erosive elements such as rainfall, flowing water and strong winds. When used appropriately, this material has the potential to stabilize slopes and minimise erosion (FOA, 2020). Evidently, this may be most effective when woody biomass is chipped into smaller sized material.

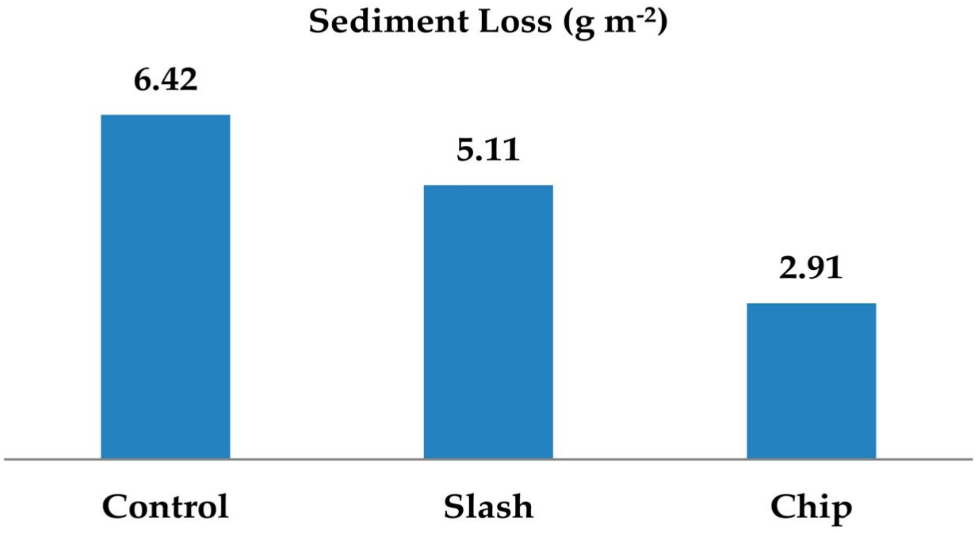


Figure 3. Total sediment loss from each of the different surface cover plots (Turk, 2018).

One concern with leaving harvest biomass to decay over the cutover is the potential for negative implications. Potential nitrogen leaching from soil and nitrogen poisoning have been highlighted by some forest industry members as possible causes for concern. This study was unable to find any formal literature or strong evidence to support these claims. Retaining biomass is generally unlikely to cause significant nitrogen poisoning or leaching. A number of other factors can impact whether these concerns will be present and their severity, such as the time of year and tree species. Some localised leaching can be expected in circumstances where there are high volumes of residue left concentrated in small areas. Subsequently, the benefit of residue retention must be handled on a case-by-case basis, although the risk to seedling survival and the environment in general is believed to be relatively low.

One economic management opportunity is to utilise woody biomass in the production of bioenergy products. This option provides an alternative source of revenue of previously un-utilized material. Europe is at the forefront of residual biomass utilisation for energy with recent developments in technology allowing for wider use of energy products. Roughly 4.5 million tons of residual material is produced annually from New Zealand operations. Regional variation exists, nonetheless, New Zealand generally has yet to develop the systems to support biomass utilisation to the scale of that which is demonstrated internationally (Visser and Spinelli, 2020).It has been suggested that prior to recently, there has been no push to develop these energy products in New Zealand. Forest owners feel that there isn't a strong market to justify producing the supply, whereas, energy consumers argue that there hasn't been a strong enough supply to drive the switch to bioenergy (Spinelli *et al.,* 2019).

This year in particular has illustrated that there is potential for this to change in the future. The New Zealand government recently announced a $70 million fund to reduce carbon emissions. Minister of Energy and Resources, Hon. Megan Woods, announced on 11 November 2020 that the government aims to take the lead in lowering harmful emissions. One of the actions driven with this fund will be an industry-wide shift from gas and coal to cleaner electric and biomass energy (Beehive, 2020). Phasing out of coal has already begun at Fonterra, with the large dairy company pledging to develop more environmentally friendly practices in an effort to help New Zealand achieve its goal of carbon neutral by 2050. Fonterra's Te Awamutu site switched to wood pellets in January 2020 and the business has committed to not install any new coal burners (Fonterra, 2020). These developments signal a national shift towards bioenergy, consequentially, energy production from woody biomass will likely increase in importance.

Designing harvest systems for improved biomass management

Forest harvesting systems may be optimized to control both the volume and distribution of waste produced. Systems can be classified as cut-to-length (CTL) where trees are processed in the cutover and biomass are left there in a moderately even distribution. Alternatively, whole-tree harvesting (WTH) is where the whole tree is extracted to the landing and processed. Biomass primarily accumulates at the landing in large piles termed ‘birds’ nests’ in WTH systems.

Various advantages and disadvantages are characteristic of both harvesting systems with regards to residual woody biomass management. Slash at the landing as with WTH and over the cutover with CTL systems both have the potential to instigate mobilisation and debris flow. Birds’ nests created in WTH need to be structurally stable on stable land to hold over long periods. Alternatively, CTL residual biomass on the cut-over must be removed from areas that are unstable, steep or where water drains moves through (Visser, *et al*., 2018).

The Forest Owners Association’s published a series of “Forest Practice Guides” which attribute increased cut-over slash with an increased risk of inflicting negative economic, social, and environmental consequences. The window of vulnerability is a term used to describe the period of up to approximately six years directly after harvesting when the landscape is at its most vulnerable state (Figure 4). Slopes are at their highest risk of failing during this period. In this event, any residual material left over the cutover will come down with it. FOA’s recommendation to mitigate this risk is to minimise the amount of slash left on the cut-over.

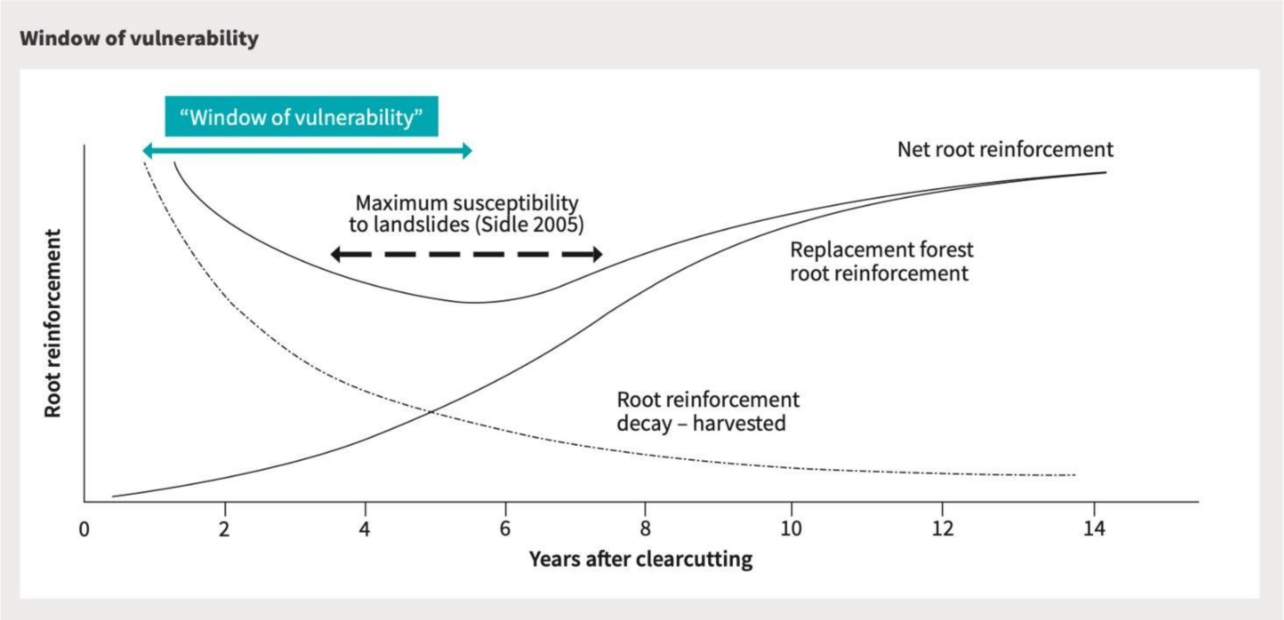


Figure 4. A diagram of the “Window of Vulnerability” following forest harvest

Spinelli *et al.,* (2018) reviewed integrated harvesting systems which may enhance the operational efficiency and feasibility of biomass recover for bioenergy production. An integrated forest harvesting system would involve harvesting both energy biomass and roundwood products within the same system. Figure 5 illustrates how these systems may be structured.

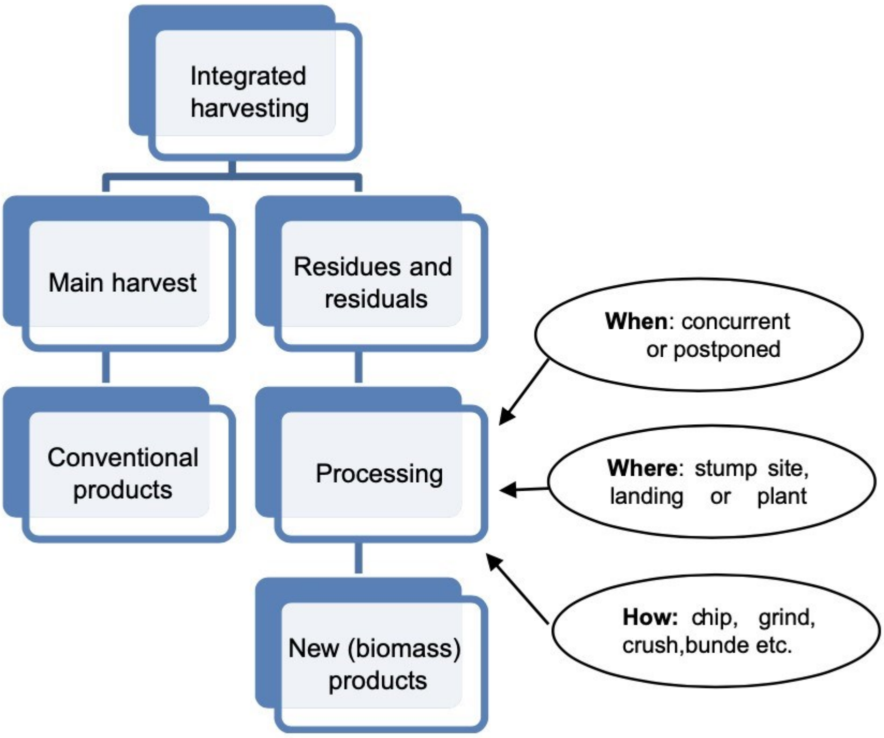


Figure 5. A conceptual scheme of integrated harvesting (Spinelli et al., 2018)

Single-pass systems commonly involve WTH with roundwood and bioenergy processing occurring concurrently or postponed at the landing. Double-pass systems are typically CTL, where bioenergy and roundwood are sorted then transported from the stump separately. Higher integration of processes within harvesting systems will likely offer greater profitability and optimization of woody biomass extraction. However, these systems will introduce added complexities and require greater technological demands to achieve.

Another aspect to consider when designing an ameliorative system for woody biomass management is waste production. Hall *et al.,* (2010) identify that operator skill, crop type and harvesting system are the primary determinates of how much residual biomass is produced for a given harvesting operation. Crew and operators must ensure that they extract the maximum value possible from every tree. In doing so, residual biomass production is minimised, reducing the environmental risks and costs spent on management after harvest.

Warren and Olsen (1964) developed the ‘Line Intersect Sampling’ method, the first sampling method to measure merchantable material left on the cutover. Van Wagner later modified this to measure all biomass, producing the “Wagner Method of Waste Assessment”. This sampling method can be implemented as a quality control measure to estimate volumes of residual biomass produced and remaining post-harvest. Active and passive remote sensing to measure woody biomass is still in development. It is likely that these methods will phase out Olsen and Wagner’s transect surveying in the future (Harvey 2019; Visser, *et al.*, 2018).

Distance to the landing is another consideration when designing harvesting systems with residual woody biomass management in mind. Hall (2000a) found a positive relationship between residual biomass volume over the cut-over and distance from the landing (Figure 6). At a distance of 20m, residue volume was recorded at roughly 35 m^3 per ha which increased to over 55 m^3 per ha at 200m distance from the landing.

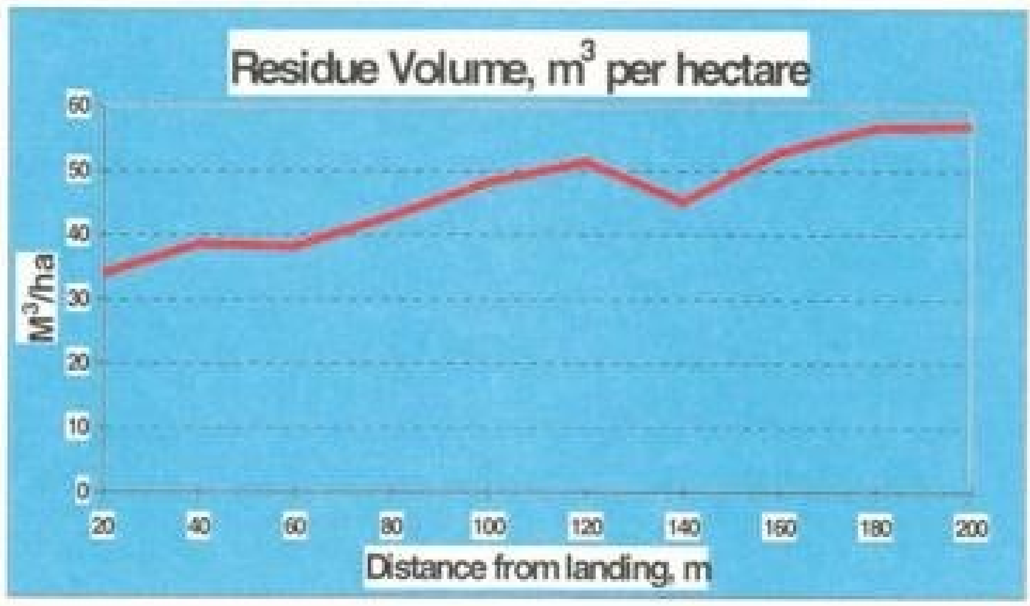


Figure 6. The trend in residue volume with distance from the landing

Andrews (2015) investigated whether any significant difference in the amount of breakage in *P. radiata* trees exists between motor-manual or mechanised felling. This study found that felling directly into the stand caused an increased proportion of stem breakage in comparison to felling directed outside of the stand. The study also suggested that other factors such as stems, rocks, slope and soil conditions may influence the amount of residual biomass produced. Additional research is required to conclusively determine and quantify their implications.

Burning biomass

Pile burning is a method of woody biomass disposal traditionally used in New Zealand, however, there is some regional variation. Burning is less common in dry regions, highly prone to wildfire risks, like Canterbury and Marlborough. In contrast, burning as a management strategy is known to be used in regions such as the East Coast, parts of Bay of Plenty and Northland. High-density burn piles can be created using bulldozers which compact material together by driving onto the pile. By using a grapple or log loader, dense piles can be created with less contamination from soil and other material. A consequence of mechanical pile burning may be some degree of soil compaction and structural change. Piles may also be constructed by hand at lower density (Page-Dumroese *et al.,* 2017).

Burning has the environmental advantage of reducing the risk of wildfire by burning the bulk of the post-harvest fuel in a controlled environment. Additionally, slash pile burning may be necessary to control the proliferation of diseases and pests which may otherwise thrive in the untreated woody residue.

This management option is commonly chosen as it is economical, being cheaper in comparison to most other residual woody biomass treatments (Page-Dumroese *et al.,* 2017).

Smoke and chemical release is a hindrance to human health which is another negative aspect of biomass burning. Sifford (2016) investigated pile burning in the western United States of America and used modelling to show the distribution of particle matter (seen in Figure 7) and other potential hazards to human health from slash pile burning.

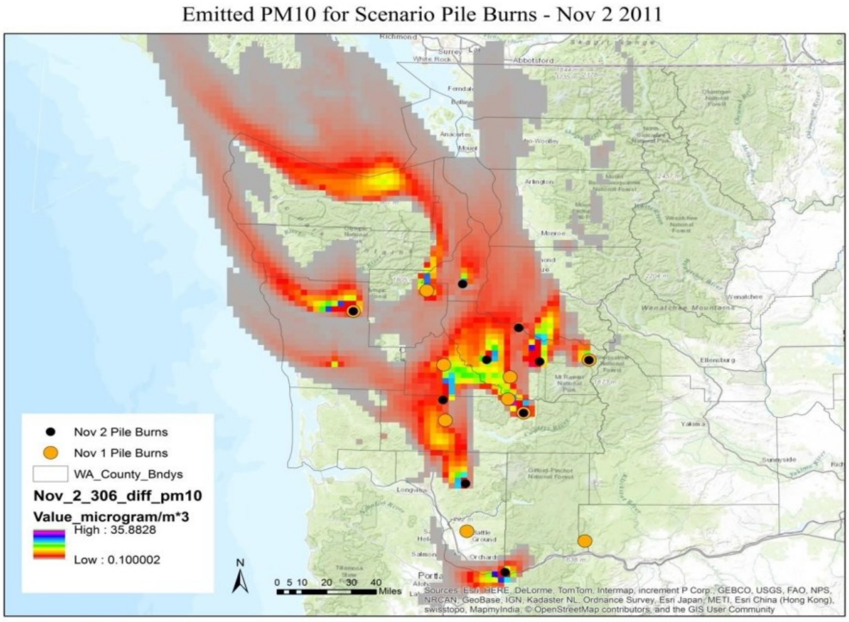


Figure 7. Distribution of particle matter over Western USA following two days of pile burning (Sifford, 2016)

This study exhibited how particle matter and pollutants such as carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx) and nonmethane organic compounds (NMOC) pose a significant threat to the health of local communities. Individuals particularly influenced will be elderly, pregnant or children, as well as those afflicted with asthma and lung disorders. Fire as a residual biomass management treatment can also have lasting detrimental impacts on the underlying soil due to heating (Page-Dumroese *et al.,* 2017).

Culbert (2020) on behalf of the University of British Columbia in Canada reviewed residual biomass management at the Malcolm Knapp Research Forest. Pile burning was used here to manage the biomass, however, this method was problematic due to timing and local regulatory constraints. Legally, woody biomass can be burnt within a short period in winter when lighting piles becomes difficult. The daily ventilation index or how well smoke will disperse is often an added restriction with this biomass treatment (Baillie & Bayne, 2019).

Fire permits, burn plans, fire control plans and general fire authority compliance is required in New Zealand when utilising this method. Future prescribed fire treatments are likely to become more contentious as fire risks are set to increase with climate change which is not helped by the GHG emittance from burning. A growing environmental awareness will influence greater social pressure to reduce burning practices. Additionally, further restrictions in the future will likely jeopardize the economic viability of prescribed fires as a management tool (Baillie & Bayne, 2019; MPI, 2018).

Biochar and air curtain burners

Biochar is an alternative woody biomass product created in nearly or outright anoxic conditions, burning at 250-500℃ through a process called pyrolysis. Biochar (as pictured in Figure 8) is a porous substance made up of carbon (C) with some portions of hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), and ash. The rising use of biochar within landscapes globally was inspired by the Terra Preta de Indio or Terra preta soils. The use of Biochar over 2,500 years ago by the indigenous people of the Amazonian Basin is attributed with creating the nutrient-rich Terra preta soils present to this day. (Govindarajan *et al.* 2016). Biochar utilisation is advantageous because biomass is not required to meet strict quality conditions like with the production of bioenergy and biofuel.

Figures 8. A small-scale biochar operation using a metal kiln. Source: https://thisnzlife.co.nz/how-dr-compost-ben-elm-makes-biochar-in-a-bathtub-and-how-he-uses-biochar-in-the-garden/

Govindarajan *et al. (*2016) argued that there are numerous benefits from biochar utilisation in soil. Biochar can improve soil fertility and should be used alongside fertilizer. Biochar provides a stable long-term source of nutrients, particularly phosphorus (P) and sulphur (S). Additionally, Biochar's porosity and charged surfaces allow it to retain soil moisture, reduce groundwater contamination and retain nutrients that would otherwise be leached from the soil.

The proposed structural benefits of this substance include increasing aggregate formation, retaining moisture and decreasing soil bulk density. In turn, these features enable greater plant available water holding capabilities within the soil. Soil biota responds strongly to the presence of biochar, aggregating around the substances and prompting greater activity and diversity. However, this material is best used when incorporated into the native soil of a site and requires mixing in to limit erosion (Govindarajan *et al.,* 2016).

Page-Dumroese *et al.* (2017) supported these findings by describing how biochar can be utilised to hold water, change the cation exchange capacity and distribution of essential mycorrhizal fungi. Carbon is stored within the soil longer, having the added environmental benefit of reducing the rate of GHG emittance from residual biomass to the atmosphere. It is estimated that approximately 10-35% of biomass volume can be stored in the soil as biochar. They also recommend using this product in rehabilitating constructed forest roading like skid trails and even landings. Agegnehu *et al.,* (2015) found that biochar positively impacted peanut yield by increasing the soil organic carbon by 34%, soil water content by 28% and cation exchange capacity by 16%.

In contrast, attitudes towards biochar production in New Zealand are substantially different and there doesn't appear to be a market or use for biochar in the immediate future. Ho (2010) offered an alternative perspective, detailing the concerns and incompetency of biochar.

Studies referenced reveal that biochar may not be the stable carbon sink its promoted to be. For instance, Czimczik *et al.,* (2005) reviewed Siberian Scots Pine forests where fires frequent the landscape. These historical fires typically produce black biochar at a rate of 0.7-0.8% of organic carbon, however, biochar stocks were smaller than what was expected. Erosion and translocation of black carbon from the area is unlikely as terrain is relatively flat. Subsequently, the smaller than predicted stocks can likely be attributed with *in situ* erosion of biochar.

An additional point made by Ho is that biochar can influence greater carbon loss from soil humus. Wardle *et al.,* (2008) provides evidence for this in their 10-year study of mesh bags consisting of 100% charcoal, 100% humus and a 50% mix of both. It was found that the mixed bags experienced a greater loss in mass than what was to be expected. It was concluded that the charcoal triggered the rapid decline in humus and carbon within native soils.
A study by Huang *et al.,* (2017) found that adding biochar increased the pH and organic matter content of the soil. Adding biochar initially increased bacterial 16S rRNA gene copies. A significant change occurred when increasing biochar concentrations to 5%. The increase led to a 74% decrease in 16S rRNA gene copies, likely because of the increased acidity which limits microbe growth and survival.

Page-Dumroese *et al.* (2017) outlined the different technologies currently used to create biochar from woody biomass. Burning piles may be constructed to maximise biochar production during pile burns as seen in Figure 9. This is achieved by elevating the loose material on logs for greater airflow and less moisture transfer from the ground. They predict a 10-15% conversion rate using this method, however, this may vary with different environmental and construction conditions.

Figure 9. A machine constructing an elevated pile. Source: J. G. Archuleta (PageDumroese *et al.,* 2017)

Kilns are old technology and have great potential for use in residual woody biomass management. Metal kilns are cylinder-shaped with a conical top and outlets on the bottom and process biomass without requiring prior processing like chipping. Both biochar quality and quantity can be controlled with these outlets as per an operation's requirements. Multiple kilns will typically be used as one kiln can take 2 days to finish producing biochar. An estimated woody biomass reduction rate of 65% is expected.

Mini kilns are essentially smaller versions of the larger metal kilns, additionally, they are easy to use at a low capital cost. These kilns are mainly used for small-scale operations or casual use as demonstrated in figure 8. Kilns are highly mobile due to their lightweight and simple design, enabling them to be loaded onto trailers or lifted with ease.

Figure 10. Biochar produced in a rotary kiln. Source: S. Bell retired, USDA Forest Service (Page-Dumroese *et al.,* 2017)

Rotary kilns, as pictured in Figure 10, produce biochar from biomass by creating a nearly anoxic environment and heating a metal rotating tube to temperatures from 400-600℃. These machines are primarily used in large-scale operations to create biochar, bio-oil, and syngas. Large volumes of roughly 20 tonnes can be processed within 24 hours, and the quality of these products is controlled by adjusting the heating temperature.

Air curtain burners are another residual woody biomass management alternative, utilised for large forestry operations. This technology does not require prior processing of biomass or removal of contaminants. It is estimated that these machines can process between 1-10 tons of biomass every hour. Air curtain burners were developed in Florida USA by Air Burners Inc. Their "Firebox series" (as depicted in Figure 11) is an efficient tool utilised to produce clean ash from harvest biomass. The "Firebox series" claims to break material down to 1-2% of the original volume, significantly reducing handling costs. (FireBox Series, 2020; Page-Dumroese *et al.,* 2017).

Figure 11. The Firebox 100 Series from Air Burners Inc. Source: (FireBox Series, 2020)

An advantage of air curtain burners is their ability to reduce air pollution emitted from burning woody biomass. Figure 12 shows how air blowing at 1600-2000 revolutions per minute creates an "air curtain" which limits the dispersal of smoke, particle matter and embers. Comparatively, it is estimated that these machines produce 80% less carbon monoxide and particle matter than with open pile burning. Additionally, air curtain burners are built to be transported in shipping containers for easy transport. They may be either stationary or mobile in a truck-mounted system (Lee and Han, 2017).

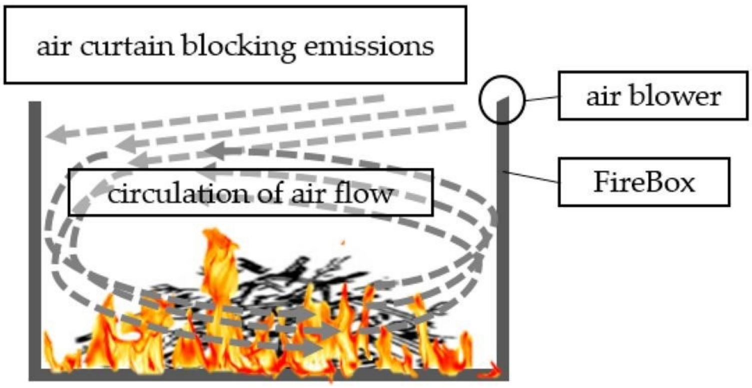


Figure 12. A diagram of how the "air curtain" air blowing traps emissions and particle matter. Source: (Lee and Han, 2017)

In a trial by Lee and Han (2017) two air curtain burners, the S-220 and BurnBoss, were trialled with woody biomass from a mixture of pine, oak and shrub species. The S-220 was trialled at one location and had a consumption rate of 5.7 - 6.8 green metric tonnes per scheduled machine hour (GmT/SMH). Accordingly, the costs for this operation were US $12.80 - $10.80 per GmT. This air curtain burner varied in burning rate by species type, however, was not impacted by differences in age or moisture content.

Trials of the BurnBoss at two locations found that this machine burnt at a rate of 0.6-1.7 GmT/SMH with no difference between biomass size. This came to a cost of between US $17.90-47.70 per GmT. Additional trials with aged residual biomass found a 70% increase in consumption at one site when biomass were left to dry for 12 months. Compared to hand pile burning, consumption was 40-80% higher using this air curtain burner. The cost-benefit and productivity of air curtain burners will need further investigation to establish whether this technology is viable for use within New Zealand forest operations.

Forest Mastication

Forest mastication, or mulching, is the action of changing the size or orientation of vegetative material in a forest. Prevalent in North America, this woody biomass treatment is a popular solution to reduce the risk of wildfire and restore natural landscapes. Ground-based equipment is typically utilised with a front- or boom-attached hydraulic rotary head for shredding and chipping residual woody biomass. Heads typically feature a rotating cylinder with rotating knives or moving blades. (Kreye *et al.,* 2016). Figure 13 depicts the Denis Cimaf mulching attachment from the DAH boom-mounted mulcher series.

Figure 13. Denis Cimaf mulching attachment from the DAH boom-mounted mulcher series. Source: https://www.morbark.com/products/mulching-attachments/

Hall (1996) ran a trial in New Zealand with LIRO to investigate the implications and costs of mastication technology for site preparation. “The Scrub Muncher”, a 16 toothed disk rotating at 600 RPM, was mounted on a Komatsu PC120 excavator and used for this study. Treatment to branch material and native scrub saw a significant reduction in the volume of these vegetation types. Hindrance of vegetative material to land preparation and planting was decreased. Additionally, this treatment proved to be ameliorative to walking ease and ease of planting. Before treatment, 58% of the site could not be planted, this was mostly amended as 82% of the site was assessed to have only light or no hindrance to planting. Before treatment, this figure was only 26%. An added benefit was a visual decrease in weed height and proportional distribution. The Scrub Muncher had a 76% productivity rate per time allotted. It is estimated that the machine was available 97% of the time and utilised 87% of the time. A cost of $85 per hour or $1,060 per hectare was estimated for this treatment.

In a study by Prats, *et al.,* (2012), the effectiveness of mulched biomass in reducing post-fire sediment and runoff was analysed. Mulched 10-15cm wide eucalyptus bark was applied to a burnt eucalyptus plantation site in Portugal. Comparatively, treated sites experienced a reduction in runoff by 45% and sediment loss by 85%. Subsequently, there may be some potential for forest mastication in limiting surface erosion and sedimentation following tree removal. Further research into the application and implications of mulched residual woody biomass on New Zealand landscapes is required. The study mentioned previously by Turk (2018) demonstrated that sediment runoff was reduced by the application of slash and even more so by the application of chipped biomass. Residual woody biomass mastication may have the potential to offer the same benefits in New Zealand harvest operations, however, this will need to be investigated.

Optimizing bioenergy utilisation

Bioenergy is an opportunity which aligns with New Zealand's growing societal and political pressure for environmentally friendly energy alternatives. Wood fuel chips are an example of this and may be used to substitute fossil fuels for transportation and heating (MPI). Transportation costs and low market value are the primary limitations of residual biomass conversion to bioenergy (Han *et al.,* 2018). Logistic constraints drive the cost and price of biomass recovery up, limiting bioenergy's economic viability. (Ghaffariyan *et al.* 2015; Spinelli *et al.,* 2019).

Another argument made in Hall *et al.,* 2019 is that the New Zealand carbon unit price must increase substantially to prompt a wider adoption of bioenergy as fossil fuel alternatives. (Improvements to the New Zealand Emissions Trading Scheme). Currently, the financial incentive is not there to support a booming national bioenergy market and nation-wide adoption of fossil fuel alternatives.

Chipping and grinding

Residual woody biomass comminution is the process of breaking down woody material into smaller units. Comminution via chipper or grinder is the two primary methods of creating merchantable energy biomass products from woody biomass. Additionally, the supply chain for bioenergy production typically employs comminution of biomass either in the forest or at a landing. Presently, high operational costs and difficult high-risk terrain are primary limitations of optimal biomass recovery. To instigate greater woody biomass utilisation and reduce the volume of biomass left on site, these hurdles must be minimised (Spinelli *et al.,* 2020).

Spinelli *et al* (2019) describe how chippers are best used when processing clean woody material largely free of contaminants due to the sensitivity of the blades. Alternatively, grinders use blunt hammer-like surfaces to break up woody material, therefore, are less sensitive to contaminants. They state "Grinders … offer a rather coarse product, unsuitable for use in some plants, especially smaller plants or ones with delicate infeed systems". Grinders may also be more expensive due to added operational complexities. In North America, these machines are preferred for their power and resistance to wear from contaminants. Chippers are preferred when operations are focused on producing a clean, high-value product.

There is a surplus of chipper and grinders available for use within the industry. Visser *et al.* (2010a) outlines the different types of chippers and hoggers (grinders) recommended to produce energy biomass in New Zealand;

- Disc chippers – These machines are used to create high-value products mostly for pulp and can be electric. Mobility can vary from stationary to truck or trailer mounted. This machine struggles to process short material less than 1m long. An example of a disk chipper can be seen in Figure 14.

Figure 14. The Bruks siwertell horizontal fed disc chipper.

Sources: https://www.youtube.com/watch?v=1c4hQsgnmr8&t=3s
https://www.brukssiwertell.com/chipping

- Drum chippers – They are recommended for use to create wood fuels like wood fuel chips due to lower quality output. These machines can easily cope with processing highly variable material. For convenience, self-feeding grapples may be attached and operated remotely. A major drawback to drum chippers is that they require another machine to pushed or deposit material near them as they have a limited reach. An example of a drum chipper can be observed in Figure 15.

Figures 15. The Mobark 50/48X whole tree drum chipper (left) and Mobark 1300B tub grinder
Sources: https://www.morbark.com/product/50-48x-whole-tree-drum-chipper/ &
https://www.morbark.com/product/1300b-tub-grinder/

- Drum hoggers – They are remotely controlled, fed by an excavator and truck-mounted in some models.
- Tub grinders – These machine uses horizontal hammers within a rotating tub. They are most efficient when over half full and accumulate wear quickly, subsequently requiring more frequent maintenance than other hoggers.
- Horizontal disk hoggers or Universal Refiners – These machines ensure contaminants are separated from the biomass which increases its value. Less wear is accumulated in comparison to the tub grinders as cutting is slower and screens/anvils are not used.
- Vertical disk hoggers – They are a combination of hoggers and a trommel screen. Contaminants are separated from the biomass, incurring less wear, and producing a higher quality end material.

Spinelli *et al.* (2020) described how chipping may occur at many places and times within a forest harvesting operation. Examples included chipping on the cutover, at the road, or, at the end user’s plant. Early comminution within the supply chain using mobile chippers was recommended.

Comminution may take place on the cutover as typical of CTL harvesting systems. Harvesting in a manner that concentrates biomass into piles is recommended, collection for chipping becomes more difficult and costly when material is dispersed. High mobility comminution machines on highly mobile vehicles like forwarders and tractors are required when processing residual biomass on the cutover. This report suggested utilising “four-wheel-drive farm tractors equipped with double- or triple-axle bin trailers,” as a cheap option. Chipping on the cutover has been phased out of Swedish forest harvesting due to exceptionally high costs relative to the product value. It is suggested that higher productivity can be achieved when moving residual biomass to a landing to be processed by a large, powerful chipping machine.

Chipping on the roadside or landing is efficient when using off-road vehicles like forwarders and tractors to collect biomass at distances up to 500m. Chippers should have a level of transportability that relates to the requirements of the operations. Where many smaller landings are used over larger distances, a vehicle-mounted chipper would be most efficient. Additionally, costs are minimized when chipping and transportation work cohesively with little delays (Spinelli *et al.,* 2020).

Hybrid chippers have been proposed as an environmentally friendly and cost-effective comminution method. A case study by Spinelli (2014b) studied the productivity of the Kelsa C860H hybrid chipper with residual biomass and pulpwood in comparison to two conventional chippers. As shown in Figure 16, the productivity of this electric hybrid was found to be lower than the other two machines. The hybrid was processing at an average rate of 13.06 tonnes per effective hour for biomass and 11.27 tonnes per effective hour with pulpwood. Primarily, this was attributed to large differences in engine power. Using the Kesla C860 machine, chipping achieved 53-81% of average running time, loading was 14-32% and feeding took up 6-15% of average effective working time. Further testing will be required to test the effectiveness of hybrid chippers for use in New Zealand forestry.

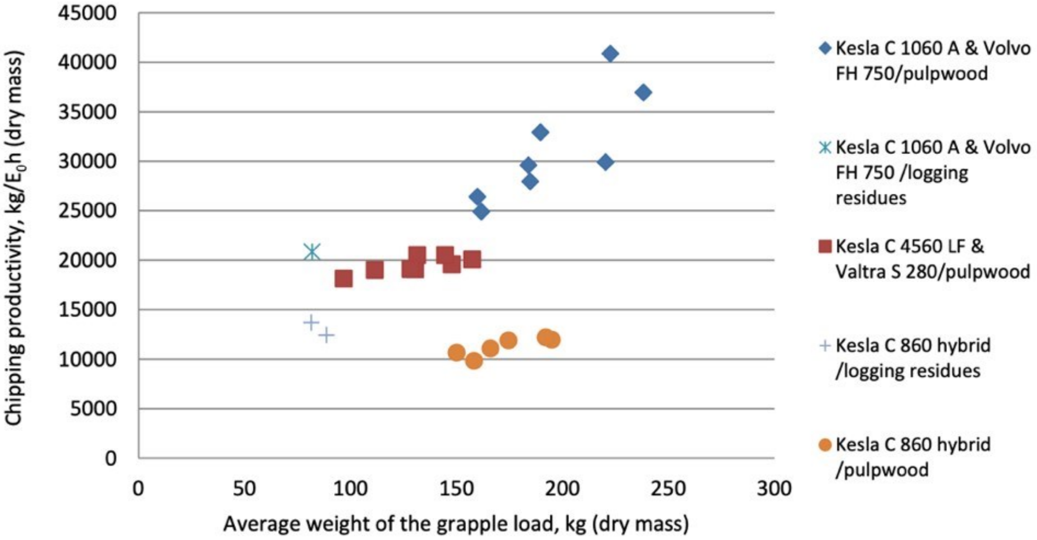


Figure 16. The chipping productivity of different Kesla chippers by grapple load and processing material

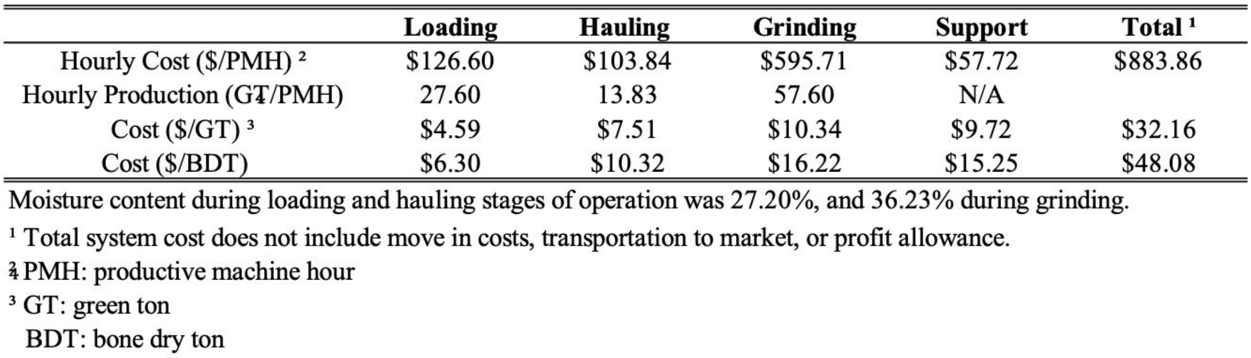
Transportation

Currently, transporting biomass short distances directly to the consumer is the most cost-effective method. Greater optimisation of residual woody biomass transportation is necessary to prompt a higher use of residual biomass. Subsequently this will aid in reducing the volume of potentially hazardous biomass left on site. Spinelli *et al.* (2019) supported the integration of roundwood and energy biomass harvesting. It is neither economically nor physically feasible to recover all residual biomass. A 40-70% recovery rate can be expected with operator skill being a primary determinant of this. However, integrated systems will increase the efficiency, profitability and ease of biomass handling in harvesting operations.

Forest access for the transportation of biomass can introduce complexity and costs to residue recovery. Difficult terrain and steep sloped forest roading often make forests inaccessible to transport like chip vans. This is problematic as these vehicles are typically cheaper than most other options. Hook-lift trucks (pictured in Figure 17) are an alternative to traditional chip vans and use large roll-off bins which can be loaded by a hydraulic arm.

Figure 17. A hook-lift truck at Hebgen Lake. Source: Dobson (2009)

A study by Harrill and Han (2010) analysed how hook-lift trucks can be an effective alternative in managing adverse roading conditions. A trial over two weeks in California used a hook-lift trucking cycle involving unloading empty bins, loading loose residue, and travelling to a centralised grinder where material was deposited. This system had a total cost of US$32.16 per green ton.
A comprehensive breakdown of the costs of each phase can be seen in Figure 18. Another study by Dodson (2009) investigated the cost benefit of hook-lift trucks. At one of the trialled site, the cost for the truck and bins came to US$80.23 per hour and transport costs averaged US$9.63 per green ton. They concluded that hook-lift trucks are high cost, however, are justified in scenarios where chip vans are unavailable.



	Loading	Hauling	Grinding	Support	Total [1]
Hourly Cost ($/PMH) [2]	$126.60	$103.84	$595.71	$57.72	$883.86
Hourly Production (GT/PMH)	27.60	13.83	57.60	N/A	
Cost ($/GT) [3]	$4.59	$7.51	$10.34	$9.72	$32.16
Cost ($/BDT)	$6.30	$10.32	$16.22	$15.25	$48.08

Moisture content during loading and hauling stages of operation was 27.20%, and 36.23% during grinding.

[1] Total system cost does not include move in costs, transportation to market, or profit allowance.

[2] PMH: productive machine hour

[3] GT: green ton
BDT: bone dry ton

Figure 18. A breakdown of costs using a hook-lift trucking system (Harrill & Han 2010)

A SCION report by Hall *et al.,* (2019) for the Ministry for Primary Industries details various opportunities for increased residual biomass use on the East Coast. Barging is a transportation alternative proposed in this report and is taken from a study looking at barging logs from Hicks Bay to Gisborne or Tauranga. In this scenario, barging at $15/tonne is estimated to be substantially cheaper than trucking at $34/tonne. It may be worth investigating whether this is feasible and a useful alternative to trucking residue. Another transportation option would be to develop rail links between regions. Currently, Gisborne is isolated with no rail link to the other regions which is problematic as there is a cost difference between long-distance trucking and rail of about $0.06-0.07 per tonne-kilometre. Implementing greater rail connection can lessen transportation costs, however, this must be inclusive of additional handling costs with trains.

Sessions & Zamora described how moisture content and load density can be treated to reduce transportation costs. Their Oregon trial found that load density increased by 25% when loading biomass vertically into trailers. Processed residual biomass is generally more efficient to transport with a bulk density of 30-33%. One logistic limitation of processed biomass is that it can't be stored for long periods due to mould and fungi (Hall, 2000b).

Bundlers are a technology used to organise loose residual biomass into compacted bundles, almost synonymous to the production of hay bales used in agriculture. This technology allows unprocessed biomass to be transported with greater efficiency and ease. The biomass is fed through rollers by a boom where it is scanned using a sensor to check volume. This material is then compressed to roughly 2 ft in diameter, bound by twine and may be cut to a selected length from 6 to 16 ft long, visible in figure 19 (Patterson *et al.,* 2010).

Spinelli *et al.,* (2019) highlighted how bundlers can influence greater integration and easier logistics for residual biomass transportation. These machines can create compacted logs which stack easily and have the same transportation requirements as roundwood products. The supply chain can become completely integrated, cutting costs and improving ease of handling residual biomass. However, Spinelli and Harrill (2018) recognised that the costs of bundling technology do not outweigh the benefits. Bundlers have been available for some time now, however, high capital cost and lower than ideal productivity are likely the primary limitations of their use in New Zealand.

Moskalik *et al.,* (2013) used the John Deere slash bundler 1490D to study bundling in Poland. They found that bundler use was most efficient when biomass was aggregated prior to bundling. When biomass was scattered, approximately 44.2% of the operating time was used to gather a load and feed it to be bundled. Pre-organising biomass into piles and strips improved the time spent loading from to 36.8% in strips and 31.5 in piles. Evidently, the spatial orientation of biomass will likely influence the ease of loading, potentially inhibiting bundler productivity when spread widely.

Figure 19. A bundle created in Arkansas. Source: (Patterson *et al.,* 2010)

In a study by Ghaffariyan *et al.,* (2015), integrated CTL harvesting was investigated in Australian softwood plantations. Their trial showed that introducing a 3.5 m energy log product resulted in a 3% product yield increase and lower biomass loads. Harvester productivity for the control came to 90 m^3 per productive machine hours (PMH) and 88 m^3/PMH under integration. This system reduced forwarder productivity by 17%, increasing the total operation cost by 9% (AU $0.51/ m^3). Figures 20 & 21 depict the differences in biomass left and the proportional time taken by each work phase for each product.

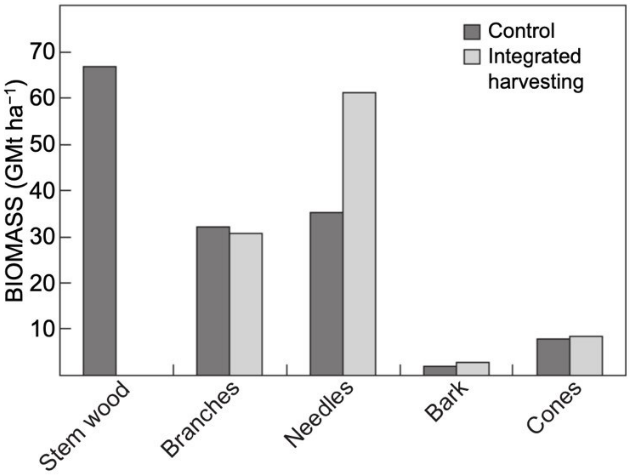


Figure 20. The biomass left in GmT/ha under both harvesting regimes

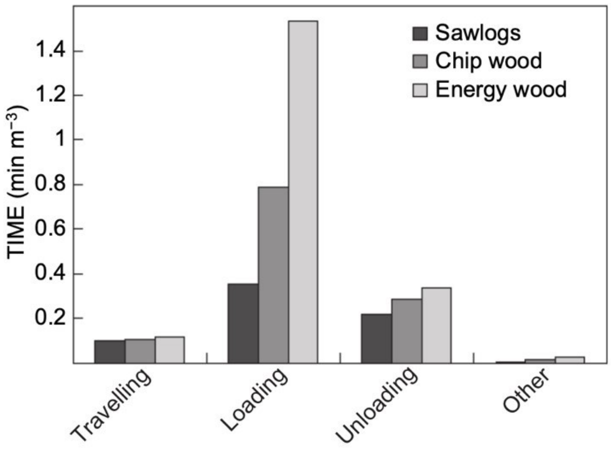


Figure 21. Forwarder allocation of time for different work phases and products

Drying Biomass

Sessions & Zamora described how up to 50% of transportation and processing costs can be attributed to trucking. Of these truckloads, 50% can be made up of biomass moisture alone. It is expected that trucking costs will be reduced when moisture content is reduced.

Hall (2000b) identified that residual biomass dried best without prior comminution. In 1999, two biomass drying treatments (tub-grinder processed and uncomminuted) were trialled and left to dry on a landing. Large uncomminuted biomass experienced a 40% decrease in moisture content and smaller uncomminuted biomass decreased by 21-25%. Alternatively, the processed biomass experienced an increase in moisture content from 62% at the start of the period to 68%. The difference in moisture content over time can be seen in Figure 22.

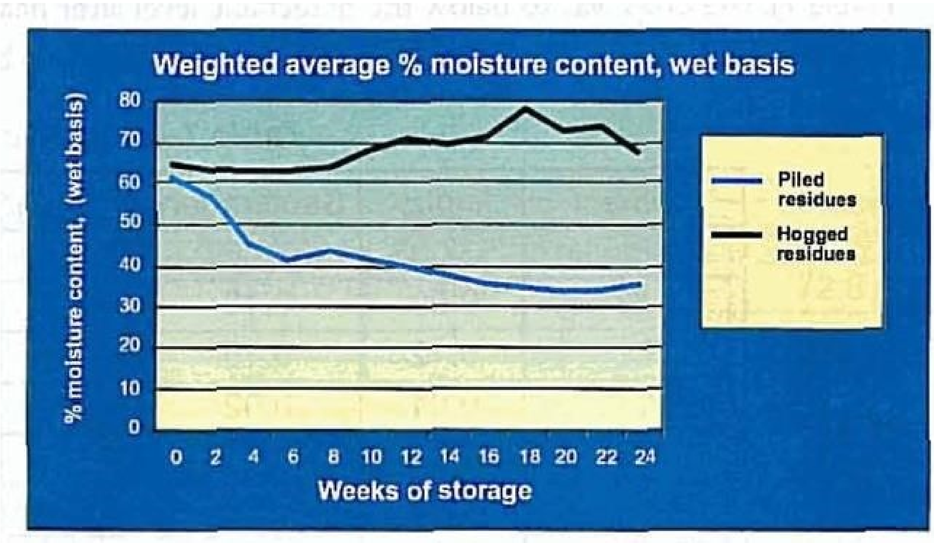


Figure 22. Moisture content change by treatment. Source: (Hall, 2000b)

A direct relationship exists between moisture content and the fuel value of biomass (as seen in Figure 23). Drying has the effect of raising the net calorific value of the raw biomass, creating higher-quality energy products. The fuel value of the non-processed residual biomass increased by 85%, however, the processed biomass decreased by 29%. Drying biomass as loose non-processed material has the potential to reduce trucking costs due to decreased moisture content and increase the value of energy biomass.

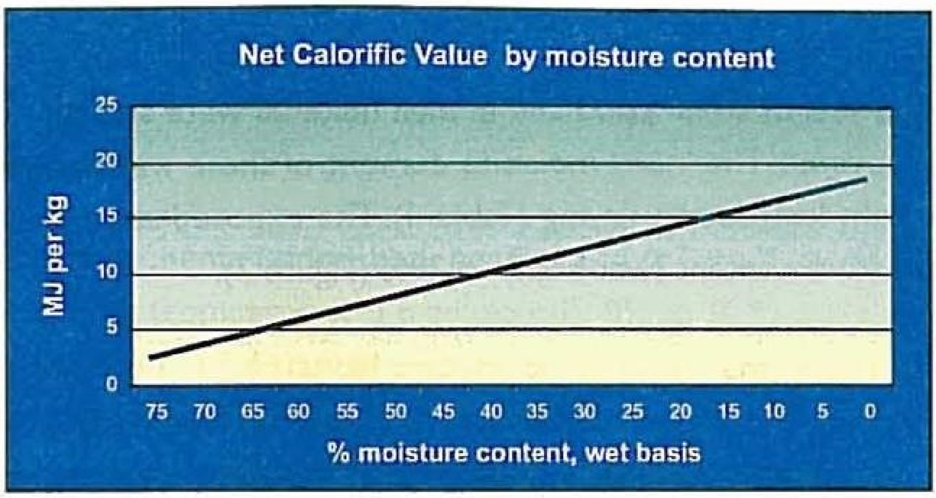


Figure 23. Net calorific value with moisture content. Source: (Hall, 2000b)

Visser *et al.,* (2010b) trialled the following four drying treatments on *P. radiata logs*; covering small diameter logs; covering large diameter logs; leaving uncovered small diameter logs; covering split large diameter logs. They found that the fastest drying occurred in the large diameter split logs, moisture content reduced from roughly 53% to 21% in 17 weeks. Apart from this treatment, the smaller diameter and split logs lost moisture content at a faster rate than the larger diameter logs. This study also found that covering logs was not beneficial to drying as the uncovered logs dried at a faster rate than the covered. These trends can be seen in Figure 24. Generally, a moisture content of below 30% is required to produce a high quality chip from woody biomass. Drying improved the energy density, however, the 30% moisture content could not be achieved.

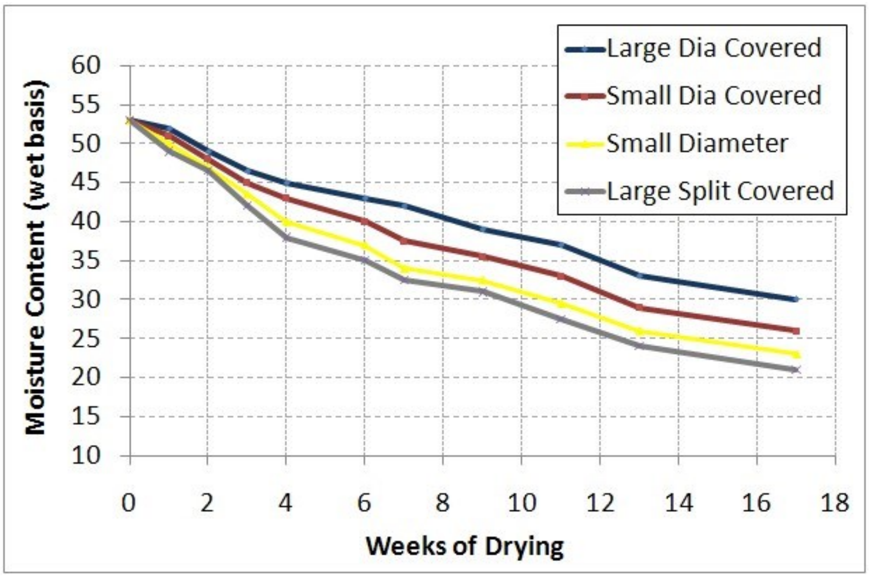


Figure 24. Moisture content of *P. radiata* logs over time with various drying treatments

In a recent trial by Hall (2020), two treatments (drying biomass and processing biomass) were reviewed to determine their impacts on the supply chain. Hall found that drying residual biomass resulted in a higher transportation cost per tonne, however, this cost per Giga Joule of the load decreased (as visible in Figure 25). The original cost of $1.15 per GJ decreased by 27% to $1.13.

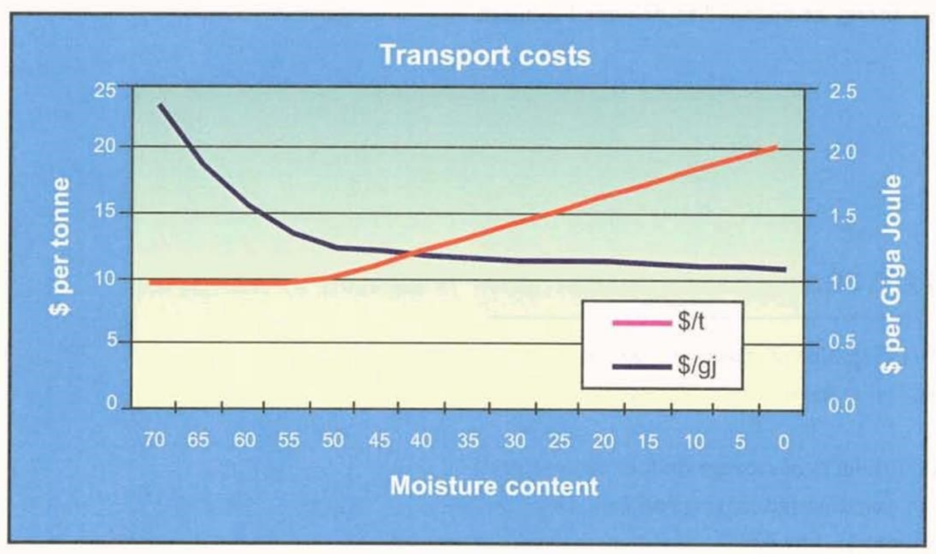


Figure 25. Transport cost by the tonne and gigajoule with decreasing moisture content. Source: (Hall, 2020)

SUMMARY

Prominent social, environmental and economic drivers will continue to push for innovative woody biomass management. The continued use of unsustainable practices will subject the national forestry sector to further criticism, risking its social license to operate. Unmerchantable biomass has value and there are many opportunities to utilise this material in unconventional ways.

Biomass treatments like pile burning which have been commonplace for years will have to change to accommodate the changing environment and social climate. Technology and systems have been developed to replace current practices, however, little is known about the effective performance of these treatments as viable alternatives. Additionally, several solutions have been proposed to minimize the limitations preventing greater energy biomass creation from biomass. These solutions may instigate higher woody biomass extraction, which ultimately would reduce their risk and magnitude of hindrance.

Woody biomass handling and management in many regions throughout New Zealand is still relatively underdeveloped. A lack of knowledge exists towards developing beneficial biomass management strategies. This deficit is a direct consequence of little formal research and published recommendations. Further trials and cooperative learning within the industry will be integral to the improvement of these forestry practices in the future.

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