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Residual woody biomass in New Zealand’s harvested, steepland plantation forests

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A thesis submitted in partial fulfilment of the
requirements of the
degree of Doctor of Philosophy

by

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University of Canterbury

2022

“Scrap doesn't come for free, we pay someone to make it.”

W. Edwards Deming

1900 – 1993

PREFACE.

The genesis of this research has been my early-career experiences in New Zealand's plantation forests. There is widespread agreement that quality woody residues are wasted on a large scale, and that the waste is a lost opportunity. This assertion extends from bushmen on the slopes to city residents with wood fires. I would be grateful to see the material generating jobs, income and spinoff businesses, rather than simply adding cost to harvesting operations or contributing to negative environmental impacts.

The forest industry's growing interconnectedness with the rest of the New Zealand economy is now one cornerstone to achieving the nation's decarbonisation targets. Could this be the impetus required to turn harvest residues into products of value and uplift them from steepland harvest sites?

In order to do that, we need to understand woody harvest residues in terms of quantity, quality, where the material accumulates, and also agree on how it should be managed. This will ensure the forest industry can be an effective participant in decarbonisation efforts, create new supply chains, improve profitability, and be proud to manage much of the country's most vulnerable productive land.

ABSTRACT.

The woody residues generated by harvesting plantation forests in New Zealand present significant management challenges, but also opportunities for productive use. Lack of commercially viable demand for the residues results in large quantities left on harvested cutovers and/or stored at landings. The challenges are most acute on steepland sites, typically characterised by aspects such as difficult extraction and longer distance to market. Demand for the residue material is changing; for example as a substitute for fossil fuels. In a market where greenhouse gas emissions are increasingly monetised, woody biomass is becoming regionally important as an energy source for medium-high heat industrial customers.

Forest owners and/or managers' participation in the developing biomass market requires knowledge of the harvest residues; how much is generated, where it is distributed, and what options are available to manage it. This research aimed to close the divide between producers and potential users and has three main components; (1) using in-field survey, set a current benchmark for residual woody biomass in the steepland harvested cutovers, (2) using geospatial technology, survey residue piles that accumulate at landings and (3) a Delphi survey with industry experts to develop consensus where possible on how best to manage the material. For potential biomass consumers, questions of a regional forest industry's ability to supply woody biomass are important, with significant capital investments in plant relying on the quality of that information.

Woody residues on harvested cutovers have seen little investigation over the previous two decades. Mechanisation has resulted in significant changes to harvesting systems during this time, with an unknown effect on residue volumes or distribution. For the first part of the study, using a refined Line Intersect Sampling method based on the US Forest Service Down Woody Materials survey method, a total of 17 cutovers were measured across six regions of New Zealand, totalling 185 plots. Plot results for volumes of woody residues >25 mm in diameter ranged from 0 to 580 m^3/ha, with a median of 88 m^3/ha. Of the 88 m^3/ha, 7 m^3/ha was older material ('dead'), the remainder fresh from the harvest ('sound'). When considering a minimum piece size that might be feasible to extract from the cutover (>0.8 m in length and >10 cm in Small End Diameter), 30 m^3/ha was of 'sound' quality. Cable-harvested sites carry higher residual woody biomass volumes on the cutover than ground-based harvests (a statistically significant result). Comparing manual versus mechanised felling methods reveals no significant difference in total residue volumes found in the cutover. This study quantifies the opportunity for greater utilisation of large woody residues across New Zealand's steepland plantation cutovers.

Whole tree harvesting in New Zealand's steepland plantations also results in relatively large volumes of residues (needles, branches and stem offcuts) accumulating at the landing. This by-product of the log-making process is typically piled near the landing and represents a more readily available opportunity for utilisation than cutover residues. Measurement of residue piles is uncommon, however. This second part of the study provides a contemporary benchmark for volumes of residue piles and new remote-sensing methodologies for collecting volume information. UAV imagery collected from 16 harvested sites was used to compute digital surface models of landing residue piles. Through manual interpolation of the terrain obscured by the residue piles, the average bulk residue volume found was 0.23 m^3 per tonne of logs harvested, or 170 m^3 per hectare harvested; with results varying from 40 to 350 m^3/ha. Piles were also assessed for depth using the surface models, as depth is proposed as a key indicator of a pile's self-combustion risk. The average maximum pile depth was 2.6 m: the majority of piles achieving accepted best practice in New Zealand harvesting operations (maximum 3 m). The new methodology allows safe and low-cost data capture and could become an increasingly regular part of forest measurement where forest owners need to make informed decisions about the management of the woody biomass resource, as a product or as an environmental hazard.

A further refinement of the photogrammetry method was proposed and tested in a case study of one steepland landing. The refined method enabled an improved render of the terrain surface under the pile by capturing georeferenced data both pre- and post-harvest. Operational benefits from the procedure include being able to accurately inspect pile depth against best practice guidelines and direct pile rehabilitation efforts with more accuracy. Whilst the improved methodology eliminated an estimation procedure, it also required a second visit to the site and more photogrammetry processing, therefore required more resources. The methodology has been demonstrated as a potential tool for operational foresters to support decision making for residue pile management.

Plantation forests in steepland areas have often replaced pastoral farming due to underlying natural and induced soil erosion processes. Under these circumstances conversion to plantation forestry is intended to provide both improved economic returns as well as longer term land stability. Challenges that are inherent to the terrain are transferred with land use change. In addition to adhering to the respective Regional Plans, the forest industry has sought to manage these environmental challenges

by implementing Best Management Practices published by the New Zealand Forest Owners Association. Gaining consensus and support for new practice standards can be challenging; although many participants may already be demonstrating suitable standards with the experience gained from exposure to ongoing operations. Focussing on residual woody biomass in remote steepland forests in this third part of the study, a Delphi survey was completed with twenty forest industry experts across New Zealand. The Delphi process was successful in allowing the participants to put forward opinions, unencumbered by affiliations or personal conflict. The outcome improves our understanding of specific practices and knowledge that could inform the advancement of Best Management Practices and how residual woody biomass might be brought to the market (e.g., where it is not currently). The results of the Delphi indicate an intent to participate in the developing biomass market with harvest residues and also a widespread knowledge of practices and processes that lead to woody residues posing risks to operations, the wider environment and communities. Delphi participants identified practices, specific to scenarios near waterways or at the landing, such as retrieving reside piles off slopes steeper than 15-20°, whether on natural ground or engineered fill which give a measurable target for future operations. There was a strong preference for site-specific management of residues, rather than ‘one-size-fits-all’ approaches. An example of this philosophy lies in the management of mature crop trees within waterway margins. Leaving standing trees exposes the riparian margin to the risk of windthrow, while removal of the trees risks soil disturbance and unintentional loading of the waterway with felled woody residues. In the Delphi panel’s opinion, limiting the number of management options available could result in adverse environmental, or economic outcomes.

Woody harvest residues can provide a new income stream for steepland forest owners and new supply chain participants. Their productive use also promises to drive better environmental outcomes for erodible steepland forests. With improved knowledge of the production of residues in New Zealand plantation forests, inventories and forward projections can be made by forest owners to provide security of supply for new biomass customers investing in biomass-specific equipment. Without supply security, long-term investments in high capital equipment are tenuous. Where the market cannot reach, residue management will continue to innovate to meet the environmental and social expectations of the time. This thesis provides answers and direction for both market situations.

DECLARATION.

This is to certify that:

1) This thesis is of my own and original work in partial fulfilment of the degree of Doctor of Philosophy,
2) The papers in Chapters 2 and 4 were produced with co-authors. I lead the conception, design, planning, data collection, analysis, writing and review of the articles. My co-authors provided valuable assistance with concepts, planning, data collection and review of the manuscripts. In all cases, I have made the most significant contribution to the studies and the manuscript production.
3) This thesis comprises the results of more than 18 months study at the University of Canterbury, and;
4) This thesis is less than 100,000 words in length, in alignment with University of Canterbury policy.

Signed: ________________________________

Name: Gibson Campbell Harvey

Date: 3 August 2022

ACHIEVEMENTS.

The study towards a PhD is primarily focussed on quality research, with the thesis being the main output. Within the scope and timeline of my PhD study at the New Zealand School of Forestry I was able to engage in a number of aligned academic activities. These are summarised here.

PUBLICATIONS

Note: The publications denoted with an * are directly used in the thesis:

- Riedinger, L., & Harvey, C. (2021). Structure-from-Motion photogrammetry as a tool for harvest residue pile measurement. *New Zealand Journal of Forestry, 65*(4), 6-11.
- Harvey, C. (*Awaiting publication*). Harvest Roading *in Forestry Handbook* (editor E. Mason). Online: New Zealand Institute of Forestry - https://nzif.org.nz/assets/NZIF-Handbook-HiRes.pdf
- Harvey, C. (2021) RoadEng software tutorials for the NZ Forest Industry. Rotorua, NZ: Forest Growers Research (FGR). Available on request from: Forest Growers Research.
- *Harvey, C., & Visser, R. (2022). Characterisation of harvest residues on New Zealand's steepland plantation cutovers. *New Zealand Journal of Forestry Science*, 52. 12 p. doi: https://doi.org/10.33494/nzjfs522022x174x
- * Harvey, C. (2022). Measuring harvest residue accumulations at New Zealand's steepland log-making sites. *New Zealand Journal of Forestry Science*, 52(12), 11 p. doi: https://doi.org/10.33494/nzjfs522022x186x
- *Harvey & Drummond (2022). Managing forest landing residue piles: A case study on the use of photogrammetry to support decision-making. *New Zealand Journal of Forestry*, 67(1), 4 p.
- *Harvey, Campbell (2022). *Management of Harvesting Residues: Results from a Delphi survey of forest industry experts.* FGR Report (FGR-057). 26 p. Rotorua, NZ: Forest Growers Research (FGR).

RECOGNITION AND COMPETITIONS

- Co-winner of the 2020 Jon Dey Memorial Award for research into new technology for Forest Engineering. The award is administered by the New Zealand Institute of Forestry Foundation.
- Nominated by the NZ Forest Owners Association for the International Blue Sky Young Researchers Award (2021).
- University of Canterbury Three Minute Thesis Competition: 2nd Place in UC College of Engineering Final 2021.

CONFERENCE AND WEBINAR PRESENTATIONS

- HarvestTech 2021 (Rotorua): '*Managing Harvest Residues on Steeper Slopes*'.
- Co-presented an online webinar for an international IUFRO audience titled 'Forest Roads in New Zealand' with Dr Rien Visser, including an associated co-authored publication. IUFRO Division 3.01.02 Webinar Series: Forest Roads – Regional Perspectives from Around the World.

TEACHING

- Forest Transportation & Road Design (FORE423) course taught in full at the School of Forestry, University of Canterbury, in 2019, 2020 & 2021.
- Guest lectures at the School of Forestry, University of Canterbury, including:
    - FORE205 and 422: Wildfire management in production forests. 2020, 2021 & 2022.
    - FORE422: Cable Harvest Planning Software (CHPS then RoadEng) in 2020, 2021 & 2022.
    - ENFO410 Forest Engineering Research: Setting up and completing a research project. 2021.

INDUSTRY WORKSHOPS

- Developed course content and co-taught 1-day UC Professional Development Workshops on:
    - Managing Harvest Residues, November 13th, 2019; November 4th, 2020; and November 25th, 2020
    - Stream Crossing Design. November 12th, 2019; November 3rd, 2020
- Taught three 2-day professional development sessions with industry professionals on the use of Softree RoadEng software

ACKNOWLEDGEMENTS.

Forest engineering at the School of Forestry has been directly supported by the Forest Growers Levy Trust, administered by the NZ Forest Owners Association. The support for my position as researcher and instructor was funded from this financial support, for which I am very grateful. This PhD study was supported throughout by Forest Growers Research Limited (FGR) under the Steepland Harvesting Programme – a Primary Growth Partnership with New Zealand's Ministry for Primary Industries.

I'd like to express my sincere gratitude for the support, guidance and counsel offered by my Primary Supervisor, Dr Rien Visser. His boundless enthusiasm for forest research and the capabilities of the people who represent our industry is truly inspiring. I'd like to thank Rien not only for his impact on my studies, but also for what he does for New Zealand's forest harvesting community.

I'd like to thank my second supervisor Peter Hall from Scion, together with Keith Raymond of FGR, for our insightful discussions and their enthusiastic backing of my ideas. I have always come away from my discussions with a new and valuable angle or perspective to consider.

To our summer research students, Luke Riedinger, Jim Walsh, Perry Han and Dougal Shepherd; some of whom didn't quite believe me when I said it was going to be hard work, thank you. Thank you for your toil on those steep cutovers, in the sun, wind and cold. You will remember moments of those days (like our encounters with the awesome Kārearea) for a long time to come!

To my co-authors, Rien and Ryan, thank you for your shared enthusiasm and desire to push us that little bit further ahead with our understanding. I very much valued every bit of your contributions to these studies.

I'm sincerely grateful to forestry industry and the industry's passionate support of the study. The involvement of key individuals and companies remains anonymous but needs to be mentioned. We asked difficult questions, and everyone appreciates the time you took to be a part of the conversation and the progress.

Thanks goes to my family who have maintained a surprising level of interest in my studies but are probably waiting to hear about my next 'project'.

And finally, to Jean, who has been with me on this PhD journey since the very start. Firstly, as a girlfriend, to a fiancé, to now my wife. Thank you. This really has been a shared adventure. I am ready for our next one.

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Chapter 1 – INTRODUCTION.

BACKGROUND

The New Zealand plantation forest industry is challenged with improving its management of woody residues from forest harvesting. The industry's collective understanding of the benefits and the risks associated with the material continues to build through research and experience. Woody residues play a role in promoting biological activity of forest soils through nutrient recycling (Bray & Gorham 1964) while also sustaining ecosystem processes, such as through the supply of food to invertebrates (Huhta 1976). Woody residues additionally provide opportunities for enterprise as New Zealand reduces reliance on fossil fuels (Hall & Jack 2009). They can also present risks, often in association with other natural systems or processes (Swanson et al. 1976). Finding balance between the competing interests by understanding the distribution of the material and its interactions with natural systems will assist the New Zealand plantation forest industry to meet its sustainable production goals (NZFOA et al. 1995).

New Zealand's primary production capability underpins an economy that makes significant returns from food and fibre exports (Callaghan 2009; Stats NZ 2022). Forestry is a significant contributor to the economy when considering the whole value chain from forest to wood product. For proportional context, forest harvesting activity alone delivered an average of 0.6% to the national Gross Domestic Product (GDP) from 2015-2020 (FigureNZ 2021). This excludes downstream wood products manufacturing. An increase in private and commercial forestry planting from the 1980's through to the 1990's (Purey-Cust & Hammond 2005) has caused log production from plantations to accelerate since 2010 (NZFOA 2020). The majority of the outturn is destined for overseas roundwood markets, leaving approximately 40 per cent to be further processed onshore (NZFOA 2020). Forest production far exceeds domestic demand for wood products, and also exceeds domestic wood products manufacturing capacity (Forest Economic Advisors LLC 2019). Owing to favourable international log market conditions, the excess forest outturn has been allowed to contribute to the profitability of the sector.

Woody residue production is coupled with harvesting production (Hall 1994). In many regions the woody residues generated during harvesting are currently unlikely to leave the harvest site. Those residues will typically be either piled (Figure 1-1) or distributed (Figure 1-2) to decompose during the subsequent forest growth cycle. In isolated cases, residue piles are burnt.

Figure 1-1: Piled woody harvest residues at a forest landing.

Figure 1-2: Woody harvest residues distributed over a steepland cutover post-harvest.

New domestic markets for woody residues are now being stimulated. The recent surge of forest harvesting activity is producing vast volumes of the product, estimated to be around 15% of the total harvest volume, or 4.5 million cubic meters per year (Visser et al. 2019); which exceeds current demand. This supply/demand imbalance is long-standing but poised for change (Hall et al. 2009, Millar

& McGinty 2013, Pooch 2021). Nationwide efforts to de-couple commodity production from fossil fuel use are resulting in new demand for industrial-scale renewable energy sources. Woody residues are viewed favourably for industrial-scale energy applications (Pooch 2021) and hence are now providing more realistic opportunities for forest owners.

However, markets for woody forest residues are unlikely to utilise all the material that is produced. This is analogous to domestic mills being unable to process all the logs that are currently harvested. One Wood Availability Forecast (with few constraints on harvesting) details a nationwide spike in forestry outputs in 2022, before a steady decline to around 2035 (MPI 2021). This infers the long-term sustainable yield of residues may be that associated with an annual national harvest of approximately 23M cubic meters of timber, occurring somewhere between 2035 and 2039 (Hall 2017). Closer inspection is required, however. The cost of distributing residues for fuel typically favours small distribution radii from forest sources (Kanzian et al. 2013) and therefore firstly, inspection of the regional (rather than national) wood availability is vital. Figure 1-3 details the forecasted harvest in two notable regions, illustrating the potential peaks, but also low harvesting output between 2025 and 2040. Inter-regional distribution of fuel residues may become increasingly important unless targeted afforestation occurs, or other energy sources continue to be used in affected regions.

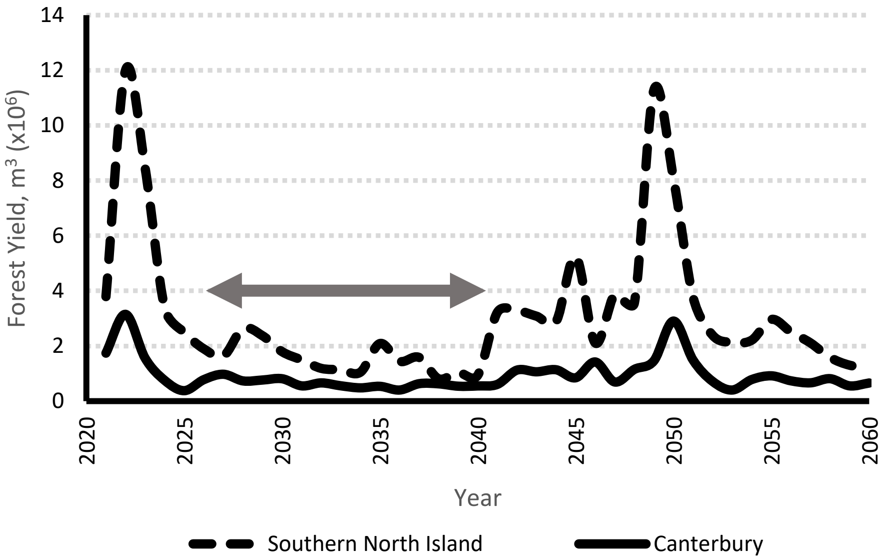

Figure 1-3: New Zealand Wood Availability Forecast (Scenario 1) for the Southern North Island and Canterbury regions, assuming that large-scale owners harvest at stated intentions and then at non-declining yield, and regional target harvest ages (MPI 2021). The arrow indicates a period of low supply.

Notwithstanding the need to understand how to connect residue production with regional (or inter-regional) demand at reasonable cost and over longer timeframes, less is known about the accumulation of woody residues at harvesting coup-scale. This is the start of the supply chain. The location, volume and makeup of woody residue accumulations determines the feasibility and the cost of bringing the material to market. Knowing more at the coup scale allows forest owners and managers to improve residue planning whilst also giving confidence to supply projections.

Increased knowledge of the resource also allows for improved risk management where it cannot be sold. As a result of residue production in excess of the market's biofuel demand, onsite management of residues (waste storage) will need to continue. Inside and outside forest boundaries, woody harvest residues have proven their abilities to cause operational problems and environmental damage, up to several years post-harvest (Cave et al. 2017; Dale 2019). In response, the industry's Best Practice Guidelines (BPGs) intend to *"provide options and information on a range of practices and methods to manage effects of the operations on the environment"* (NZFOA 2022). These BPGs have been developed under the current understanding of acceptable risk. As the industry reviews and improves residue management with updated knowledge of residue accumulations and also opportunities for future markets, what options are there for clarity or refinement in residue management practice? Managing residues that remain on site remains a key focus and need for greater understanding.

Woody residues left on harvested cutovers have been studied intermittently in New Zealand since the 1960's. Warren and Olsen (1964) first proposed a practical sampling method to quantify residual merchantable logs on a cutover. This was born of necessity due to contract structures in commercial plantations, with each party's intention to maximise their returns (harvest contractor and tree crop owner). When considering only the extraction of a single small log, as part of a typical clearfell harvest, the exercise is typically profitable to the tree crop owner, but loss-making for the harvesting contractor (McMahon 1999). This could lead to conflict and (in many cases) the need for a measurement system such as Warren and Olsen's (1964) with agreed residue limits. The conflict could be needless and depends on the timber harvest contract structure. Counter-intuitively, by abandoning pieces of small stemwood on the cutover, the tree crop owner could yield higher returns (McMahon et al. 1998); a result of better logging productivity. This interaction provides a valuable understanding as to why smaller stem sections are so commonly left on forest cutovers.

Issues arise where woody residues generated through harvesting move off-site in an uncontrolled manner. Regions of New Zealand (or parts thereof) have suffered from major soil erosion disasters, with impacts lasting long after the triggering event (Page et al. 1999). These erodible regions each have zones of sensitive bedrock and/or young soils which are periodically exposed to extreme rainfall. For example, the highly erodible belt that passes through the Tasman region that is of granite (Reed 1958) while significant areas of the Gisborne/East Coast region are of marine mudstone and sandstone (Mazengarb & Speden 2000). Topographic characteristics and lithology are the fundamental drivers for the accelerated erosion (Bloomberg et al. 2011; Korup 2008), and plantation forestry has been promoted as the solution to stabilise erodible land (Olsen 1970). The erosion issue(s) are however, tightly coupled with residue management practice. In New Zealand, BPGs are the apparatuses used to lessen the reoccurrence of these erosion events. As the plantation forests on highly erodible land are harvested and/or windthrown, the land is exposed to the '*window of vulnerability*' where erosion risk is elevated (Phillips et al. 1996). Landslip material can combine with water and harvest residues to create debris flows, which can damage terrain, streams and/or infrastructure. While rainfall-induced debris flows are inevitable at some level (Bloomberg & Davies 2012), entrainment of harvest residues adds to damage and drives negative sentiment, therefore requires demonstrable improvement in management practices.

There are clear challenges and opportunities for improving the management of residual woody biomass in New Zealand's plantation forests. Many of the acute challenges are associated with steepland forests on erosion-prone sites, where plantation forestry has been promoted as a solution for erosion while maintaining some productive capacity from the land. Forest managers need relevant, pragmatic research to ensure that these new opportunities can be capitalised on, especially where these can also serve to reduce exposure to environmental risks. Where those opportunities cannot be capitalised on, forest managers require practical guidance on managing residue accumulations in an environmentally and socially acceptable way.

RESEARCH OBJECTIVES

OBJECTIVE 1

Establish a robust method for measuring harvest residue volumes on steepland cutovers and use it to gain understandings about the volume and distribution of woody harvest residues.

Limited research has been published on the application of residue sampling on local, steepland sites. In the 1990's the Logging Industry Research Organisation published results from relatively small study sites at high sampling intensities (e.g., Hall 1999). Chapter 2 outlines an adapted manual methodology for measuring distributed large woody residues on cutovers and presents the results of a data collection programme across seventeen steepland cutovers.

OBJECTIVE 2

Establish method(s) that a practicing forester may use to gain understandings about the dimensions and volume of landing slash piles and use that to establish a contemporary steepland landing pile benchmark for the forest industry.

There is an opportunity to support operational foresters with better data and data acquisition to improve landing residue management decisions. Pile volumes and depth remain difficult to measure in a pragmatic way, particularly where they drape over complex terrain. Chapter 3 presents an investigation into landing residue pile volumes on steepland landings with photogrammetry methods. Chapter 4 then develops on this with a case study of a revised survey methodology – aimed at the practicing forester.

OBJECTIVE 3

Investigate the understanding of Best Practice management of harvest residues across the spectrum of steepland harvesting activities from the learned perspective of forest operations experts.

Demand for woody harvest residues is increasing in New Zealand as a result of decarbonisation efforts. While it is clear that the material is generated and accumulates in the forest, many management scenarios are available for foresters to find balance between environmental, harvesting, silviculture and market objectives. Chapter 5 focusses on the management practices for harvest residues, uncovering common understanding of what constitutes Best Practice in challenging environments. This research is intended to facilitate the development of Best Practice where environment is concerned, aiding continuous improvement and bettering outcomes for the environment and all parties involved in forestry. It additionally intends to inform on the feasibility of extraction of woody residues under different scenarios. The management of residues is a complex and site-specific balance, and this objective seeks to investigate what drives those management decisions.

RESEARCH CONTRIBUTION

The research presented in this thesis is timely for New Zealand's plantation forest industry. It provides new information, methodologies and understandings to confront the management of woody harvest residues in steepland plantations in a pragmatic way.

Woody harvest residues can be managed as an opportunity or a risk. This thesis takes a holistic view of the harvest residue challenge, with the understanding that a single management strategy (i.e., store on-site or else, market) will not suit all forestry situations. It recognises that holding the optimistic view that 'all harvest residues will be traded in the expanding bioeconomy' would be not simply unlikely, but also a disservice to the industry participants who cannot participate in the future. It is important therefore, that advances are made on both knowledge fronts.

This thesis contributes a better understanding of the accumulation of woody residues on harvested steepland sites. The results may be broadly applied to management plans for new harvests, or the methodologies used, modified or improved to gain an understanding of a residue resource in an individual estate. It additionally contributes learnings of Best Practice where current uncertainties allow conjecture among practitioners. Collating, understanding and publishing these learnings can better inform forest managers' decisions on strategic direction for extraction of the resource and/or supply to the market. The research is intended to be tangible and relatable to foresters who manage the material with multiple objectives.

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Chapter 2 – CHARACTERISATION OF HARVEST RESIDUES ON NEW ZEALAND'S STEEPLAND PLANTATION CUTOVERS.

This Chapter is based on the publication:

Harvey, C., & Visser, R. (2022). Characterisation of harvest residues on New Zealand's steepland plantation cutovers. *New Zealand Journal of Forestry Science*, 52(7). 12 p. doi: https://doi.org/10.33494/nzjfs522022x174x

ABSTRACT

BACKGROUND:

Timber harvesting in New Zealand's plantation forests results in relatively large volumes of woody residues being generated. While a proportion of these residues are concentrated at the landings where the trees are processed, the majority of residues are distributed throughout the cutover. Harvest residues present a biomass market opportunity, however managing un-merchantable residues remains essential as the material can present a mass mobilisation risk. Quantifying cutover residues in terms of volume provides an important step for marketing and for improving post-harvest management.

METHODS:

A refined Line Intersect Sampling (LIS) method was used to measure the cutover residues at 17 recently harvested steepland sites. These covered a range of whole tree harvesting systems, silviculture and geographical locations. The harvesting sites varied in size from 2.3 to 41.1 ha, with an average of 11x 60 m LIS transect plots completed at each site. Woody harvest residues >25 mm in diameter were measured.

RESULTS:

The median volume of woody residues was 88 m^3/ha, ranging from 0 m^3/ha in an area swept bare, up to 580 m^3/ha in an area severely impacted by windthrow prior to harvest. A distribution of volumes by plot showed a positive skew with an interquartile range of 87 m^3/ha. Timber that was considered merchantable as a log at the time of harvest, being >10 cm in small end diameter and >4 m in length, accounted for a median of 11 m^3/ha. Residues >10 cm in small end diameter and >80 cm in length that could make a viable biomass product, described as ‘binwood’, accounted for a further 19 m^3/ha at the median. Cutovers harvested with cable-based systems had greater median total residue volumes than those harvested with ground-based systems (110 m^3/ha versus 68 m^3/ha) however the felling method employed made no significant difference to total residue volumes.

Conclusions:

This study provides cutover residue measurements that can be used to improve post-harvest management, as both a substantial opportunity for improved crop utilisation and also for reducing mobilisation risk. It also provides a contemporary benchmark against which to measure change as harvesting technology or methodology develops.

KEYWORDS

slash; biomass; environmental impacts; harvesting operations

INTRODUCTION

The volume of timber harvested and sold from New Zealand production forests has increased rapidly from 20M m^3 in 2010 to over 30M m^3 since 2018 (NZFOA n.d.). The commonly-accepted goal at the time of harvest is to maximise the value of the products that can be processed from the extracted trees, which are typically transported from the forest as logs (Murphy 2005). Un-merchantable materials left behind after harvest are known as residues, but can also be referred to as slash or woody debris (MPI 2017). There are two broad categories of above ground biomass relating to clearfell, Whole-Tree Harvesting (WTH). The first is on or near the landing; that is residues that are discarded from the processing operation once the trees are extracted. The other is residues in the cutover as a result of processing or breakage during harvesting and also natural attrition during the growing cycle. While stumps and below-ground root systems are also residual biomass, they are not typically regarded as harvesting residues.

Residue volumes and distribution can vary in the cutover; depending on a range of factors including: felling method, terrain, crop type and extraction method (Hall 1999b). There are a range of generalisations in New Zealand-based literature of the typical volume of residual biomass from harvesting plantation-grown Radiata pine. Hall (2001) noted that a typical pine tree harvested in New Zealand yields 0.10 m^3 of above-ground residual biomass. Extrapolating Hall's figure, typical crops that range from 250-350 stems per hectare at economic maturity (Mead 2013) could be expected to yield residue volumes ranging from 25–35 m^3/ha. Goulding (2005) presents experiential evidence, stating harvest residue volumes may range from 5 - 30% of Total Standing Volume (TSV), depending on terrain, silviculture and degree of malformation. In a review of literature for residue mobilisation risk, Visser et al (2018) reported a range of study values from New Zealand and international studies, but indicated an expected average of 75 m^3/ha for New Zealand plantation conditions.

Harvest residues have been studied intermittently in New Zealand since the 1960's. Manual surveys of residues are inherently difficult to complete, and it is not practicable to measure all residue volumes over large areas. Early work focussed on quantifying only the residual, merchantable logs on a cutover, and Warren and Olsen (1964) produced the first recognised method for economically quantifying those residues, referred as the 'Line Intersect Sampling' (LIS) method. LIS is based on the principles underpinning Buffon's needle problem (Buffon 1777) and has been refined for applications such as forest fire research for quantifying ground fuels, or log waste fields (Fraver et al. 2018; Sikkink & Keane 2008; Van Wagner 1968).

Messinger (1974) published the first New Zealand-based literature review of total residual biomass (merchantable and un-merchantable) which appears to have been prompted by “public criticism due the obvious waste and cluttered appearance” of harvesting residues on forest cutovers. Messinger reported New Zealand radiata pine cutover residue volumes ranging from 298 to 1068 ft^3/ac (21 – 75 m^3/ha) in the years spanning 1971–1974. More recently, the New Zealand Logging Industry Research Organisation published a series of studies on the volume and management of harvesting residues (Hall 1994, 1995, 1996, 1998, 1999a, 1999b, 2000a, 2000b, 2013; Hall & McMahon 1997). This spanned multiple facets with a particular focus on reducing cost and risk associated with the long-term storage of the material post-harvest.

Hall (1999b) used a detailed LIS survey to demonstrate the spatial variation of residue volumes across a cutover. The study found residue volumes ranging from 1-280 m^3/ha across six sites with three different harvest systems. Notably, the cable harvests resulted in large accumulations of residue in the lowest point of the cutover (the gullies) whereas the ground-based systems resulted in a more uniform distribution with a trend of higher residue accumulations at greater distance from the landing.

There has been significant variation in methodology and results from biomass assessments in Radiata pine cutovers across the world. Cut-To-Length (CTL) harvest operations in Australian Radiata pine plantations have been reported to retain 52 oven-dry tonnes of residues (needles, cones bark and wood) per hectare on the cutover (Smethurst & Nambiar 1990) and more recently, a range from 43–151 green tonnes per hectare (Ghaffariyan 2013) before post-harvest biomass extraction. Many studies report the extracted volume from biomass harvesting operations. In Chile, harvested Radiata pine plantations are expected to yield 12–14 tonnes of dry biomass per hectare on average (Acuña et al. 2017), where earlier estimates were in the range of 45–80 m^3/ha (Guzmán 1984). In Spain, a case study of the Oka river basin estimated that the 8764 hectare Radiata pine resource may be able to supply 0.72 tonnes of residual biomass per hectare per year to an energy market (Mateos & Edeso 2015); implying a yield of approximately 22 tonnes per hectare at an average harvest age of 30 years (Mateos & Ormaetxea 2018). Merino et al. (2004) argue that a ‘lack’ of decomposing Pinus radiata slash on a sensitive Spanish cutover site may be 35 tonnes per hectare. The variation is reflective of the various climates, topographies and biomes in which Radiata pine is grown along with the silvicultural and harvesting methods employed on individual crops.

Volumes of residue on the cutover following harvest can be of importance to forest owners if the material represents waste or unrealised value. Harvesting system selection is critical to the economic viability of the operation. Most harvesting operations choose to split stem-wood extraction and residual biomass extraction into two separate harvesting processes. McMahon et al. (1998) demonstrated that a cable harvesting operation could be 26% more productive if only extracting stems >30 cm diameter at the large end (LED) & >3.7 m long, when compared to extracting all material >10 cm in diameter at the small end (SED) & >3.7 m long. It highlights that if the removal of residue material from the cutover is integrated into a cable harvesting operation, the added inefficiencies may result in increased harvesting cost.

Biomass for bioenergy has surged in popularity in parts of the European Union since the 1970's oil crisis (Telenius 2006); for example Sweden has recently invested over 1.68 billion Euros in larger scale combined heat and power using forest biomass, with further projects also planned (Haaker 2017). Emergence of new bioenergy markets has renewed interest in large-scale harvest residue recovery alongside traditional harvesting in New Zealand plantations (Hall 2013; Hall & Evanson 2007; Visser et al. 2019; Visser et al. 2009, 2010). These new bioenergy markets include fuel for industrial heat, domestic heat, transport and more (East Harbour Management Services & Scion n.d.) and involve processing raw harvest residues into different forms for specific applications.

To date there has been limited market opportunities for harvest residues in many New Zealand regions (Visser et al. 2018). Transport costs, due to long cart distances, low material density and inconsistent quality (Hall & Evanson 2007) have been suggested as reasons for underutilisation to date – importantly viewed in context with alternative energy sources (e.g. coal). Hall (2001) suggests that energy density (as a function of moisture content) has little effect on transport cost in modelling biomass distribution networks, yet Kent et al. (2011) advise the contrary. Critical to the question of optimising transport efficiency is the nature of the load (raw/bundled/comminuted, wet/seasoned/dry), local standards for heavy vehicle design and permissible loads on road networks.

It also needs to be acknowledged that forest residues play an important part in the nutrient cycle in living soils (Bray & Gorham 1964) and also aquatic ecosystems. Needles, flowers and woody biomass form the nutrient-rich layer of litter (or 'duff') (Ballard & Will 1981a) that decomposes and releases nutrients which sustain soils. Silviculture, windthrow and harvesting largely dictate the timing of large changes of litter volume on the forest floor and hence nutrient input. Harvest residues in the form of Large Woody Debris (LWD) in streambeds provide stability to highly mobile stream beds such as pumice substrates, and complexity to flow, allowing higher populations of invertebrates to be sustained (B. Baillie et al. 1998). However high concentrations of LWD contribute to high measures of dissolved organic carbon which can promote bacterial slime growth and exacerbate oxygen depletion (Collier & Bowman 2003). Harvesting and also stream cleaning practices can therefore be shown to have positive or negative impacts on soils and the life of waterways (B. R. Baillie 1999; Froehlich et al. 1972; Swanson et al. 1976).

The role of residues in soil nutrient recycling is presently given little regard in New Zealand planning frameworks or forestry best practice guidelines, for example the Environmental Code of Practice (NZFOA 2007) only highlights the protection of soil. A case study where 100% of harvest residues and litter fall were removed over 16 years on a pumice site in Kaingaroa Forest showed that residues on the forest floor do contribute to forest productivity (Ballard & Will 1981b). In the Eastern USA, incorporating residues into the top soil layers improved early site productivity with diminishing benefits as the stand aged (Maier et al. 2012). Some plantation forests where soil fertility has traditionally been poor are carefully managed for nutrient loss (Beets et al. 2001; Wilks & Wang 2009). Developments in tree breeding and mycorrhizal fungi have improved growth and nutrient availability for plantation Radiata pine (Theodorou & Bowen 1970), potentially reducing the dependency on harvesting residues for crop yield.

Plantation forestry land in New Zealand's most erosion-prone regions is susceptible to slumping, landslides, debris flows and debris avalanches following harvest (Phillips et al. 2012). These erosion processes can mobilise and deposit harvest residues far from their source on the cutover (Cave et al. 2017). Landslip risk increases when soil moisture levels exceed a site-specific critical water content (Crozier 1999) amongst other factors such as the declining strength given to soil by root networks as they decay (Phillips et al. 2015). Forest harvesting of any type (clearfell, coup, selective etc.) decreases rainfall interception (Phillips et al. 2012), increasing the volume of rainfall hitting the forest floor, contributing to soil moisture levels and therefore increasing landslip risk during extreme rainfall events. While mass movements are part of natural erosion processes (Bloomberg & Davies 2012; Phillips et al. 2012), the increased frequency and entrainment of harvest residues as a result of cyclical growing and harvesting fuels debate about production forestry as an appropriate land use in erosion-prone catchments (Phillips et al. 1996).

Steepland forest harvesting is almost exclusively done as clearfell in New Zealand (Visser 2018), which is where large, contiguous areas of similar age-class forest are felled, leaving forest land temporarily un-stocked with trees. It is predicted that *steepland* forests will yield 40 - 60% of the annual harvest volume over the coming years (FFR 2010) and it is expected that most or all of this volume is clear-felled. The word *steepland* is not officially recognised however (Oxford University Press 2018) , nor is it universal (Gomez et al. 2010) yet *steepland* is used frequently throughout published literature on forestry in both New Zealand and overseas. This manuscript adopts the definition of steepland as *'an area of land generally unsuitable for ground-based logging systems to operate without significant earthworks or traction assistance'.* The breakpoint is typically where rolling hill country, which can be traversed by wheeled or tracked harvesting machinery with little trail construction, transitions to *steepland* – where significant construction, traction assistance or cable-based systems must be used to extract timber from the cutover. Notably however, ground-based harvesting systems are frequently used on steep terrain (Berkett 2012) but with increased earthworks requirements.

While technically, *biomass* refers to the mass of living organisms, including plants, animals, and fungi, for the purpose of managing the residual woody biomass as either potential resource, or a mobilisation risk, it is important to define a lower bound for the size of biomass being considered. Various studies have set different limiting diameters between Coarse Woody Debris (CWD) and Fine Woody Debris (FWD). The USFS Down Woody Materials Field Guide sets the limit at 3 inches (USFS 2011), and Hall (1999b) refers to branches 0 - 25 mm as "small"; not defining a diameter boundary between CWD and FWD. In other studies, the CWD-FWD diameter boundaries have been set to 25 mm (Wei et al. 1997), 70 mm (Manies et al. 2005) and 100 mm (Harmon et al. 1995). While there is no clear precedent set in literature, Hall (1999b) showed that for the pine plantations, approximately 90% of LIS transect intersections occur with woody biomass <25 mm in diameter, while only contributing on average 17% to the volume on site. As such, 25 mm is considered to be a reasonable lower-bound diameter for the purposes of this study and allows direct comparison with Hall's previous work.

The purpose of this research is to establish a current estimate for harvest residue volumes remaining on steepland cutovers, and also provide a detailed characterisation of size (both diameter and length) of 'potentially merchantable' residual timber. Such detailed information serves to improve our understanding of cutover harvest residues as a resource, and also gauge for risk if mobilised by erosion processes. It is recognised that both silviculture and harvesting practices change over time, so this is a snapshot that reflects current practices and sets a benchmark to measure future performance against.

METHODS

The sampling procedure was based on the US Forest Service (USFS) method for measuring 'Down Woody Materials' (DWM) (USFS 2011). Harvesting boundaries of each site were reconstructed in a Geographic Information System (GIS) with a grid of plot centres overlaid. The approximate coverage was one LIS plot per 1.8 ha of harvest area. Each LIS plot consisted of three transect lines, the first oriented in a random direction (random number from 1–360°), and the following two lines oriented at 120° to the first, making a trigonal planar shape when viewed from above. The shape reduces orientation bias in sampling compared to a transect in a single direction, or one with a right-angle (e.g. Van Wagner 1968) while remaining relatively straightforward to establish on a steep site. Each transect line is length-corrected to 20 m on the horizontal plane by measuring the average terrain slope along the axis of the transect with a handheld clinometer and adjusting by the cosine of the slope.

Equation 2-1 is Van Wagner's (1968) governing equation which relates the diameters of residues and length of transect line to volume (per hectare). The equation is used on the plot scale, rather than on individual transects to reduce orientation bias impacting the results.

Equation 2-1: Van Wagner's equation for the volume per area on a flat surface.

$$V = \frac{\pi^2 \sum d^2}{8L}$$

Where: V is volume per hectare (m^3/ha), d is the diameter of the intersected particle (cm) and L is the horizontal length of transect line (m).

Three preliminary sites (Site codes: GT, MH and TP – see Table 2-1) were measured with the plot dimensions described, capturing the mid-length diameter of all 'sound' pieces of harvesting residue that were >25 mm in diameter where they intersected the transect. Results from the three initial sites were used to refine the method, including a reduced transect length for residues with diameters <50 mm at the intersection point. The refined method for the remaining 14 sites involved measuring mid-length diameters of all residues >25 mm in diameter at the intersection point, from the plot centre to 5 m (horizontal) along each transect. From 5–20 m along each transect line, only residues with a diameter >50 mm at the intersection point had their mid-length diameters recorded. The effect of the refined method is a reduced workload due to the relative abundance of material <50 mm in diameter on a cutover.

Sample plot centres were moved or transects shortened (with the actual length recorded) due to safety concerns on occasion; usually due to terrain features such as bluffs. Transects that extended beyond the harvesting boundary also had length to the boundary measured to ensure the results were not impacted by apparent low volume.

High spatial variance of individual plot volumes was expected in this study; therefore, each plot was also classified by its location; either ‘Spur’, ‘Gully’ or ‘Face’. Average terrain slope, aspect, measure of terrain shape, distance from the landing and the nearest track were either collected at the plot or measured in a GIS post-visit. Other data collected, where available from the hosting forest company, included stand age, silviculture regime, harvesting system (felling / extraction / processing), expected merchantable volume and actual volume recovered. From these supplied data, log grade outturn could be aggregated, for example ‘Large Industrial’ was one category, being ‘Korean Industrial’ (KI) grade logs, and another was ‘Large Structural’, being export A-grade logs and domestic structural-grade logs. Aggregated log grade outturn can indicate the ‘quality’ of a particular stand of trees, with certain characteristics about the stand inferred from the relative proportions of each aggregated classification.

A total of 17 recently harvested sites were measured across New Zealand as a part of this study. Sites were selected by the supporting forestry companies, with all being steepland and of typical silviculture and harvesting practices (see Table 2-1).

The dataset was analysed to describe the influence of key variables on the total volume of woody residues found in a location on the cutover. Generalised linear regression was used, iterating over all continuous and categorical variables to find a linear regression model that minimised the Mallow’s C_p value.

Table 2-1: Harvesting site details.

Site Code	Region	Study Area (ha.)	Number of Plots	Approx. TRV (m^3/ha)	Felling	Extraction
GJ	Canterbury / Waitaha	8.7	7	472	Mechanised	Ground-based
GT		31.0	17	546	Mechanised	Cable
MH		12.6	7	-	Motor-manual	Ground-based
GN	Tasman / Te Tai-o-Aorere	9.5	8	611	Mechanised	Cable
MG		36.8	20	392	Mechanised	Ground-based
HT	Gisborne / Te Tai Rāwhiti	25.3	18	553	Motor-manual	Cable
PK		23.0	10	507	Motor-manual	Cable
MA		16.7	7	594	Mechanised	Cable
MC		8.3	6	866	Mechanised	Cable
PE		6.9	9	507	Motor-manual	Cable
HF		13.9	11	553	Motor-manual	Cable
MO	Marlborough / Te Tauihu-o-te-waka	41.1	18	-	Mechanised	Ground-based
TP		21.2	13	407	Mechanised	Ground-based
PG	Wellington / Te Whanga-nui-a-Tara	2.3	2	746	Mechanised	Ground-based
PC		5.9	6	746	Mechanised	Cable
RK		6.1	8	795	Motor-manual	Cable
TK	Otago / Ōtākou	33.5	18	841	Mechanised	Cable

RESULTS

The summary data of all 185 LIS plots shows the median value for total residue volume (>25 mm diameter) on the cutover was 88 m^3/ha, with 11 and 19 m^3/ha for merchantable logs (≥4 m long, >10 cm in SED & of reasonable quality) and binwood (≥0.8 m long, >10 cm in SED & of reasonable quality) respectively (Table 2-2). Figure 2-1 details how the average total residue volume (all material >25mm in diameter) varied from site to site, and also the variation of volumes found on each site, expressed as standard deviation to the mean. Given that the average reported total harvest volume was 599 m^3/ha, total residue volume is 15% of the TRV and 2% and 3% for merchantable logs and binwood respectively.

Table 2-2: Summary of volumes of harvest residue components measured across 17 steepland cutovers.

	Average (m^3/ha)	Median (m^3/ha)	5th Percentile (m^3/ha)	95th Percentile (m^3/ha)	Interquartile range (m^3/ha)
Total Volume	109	88	17	269	87
Merchantable Logs	17	11	0	63	23
Binwood	27	19	0	88	32
Dead wood	25	7	0	93	24

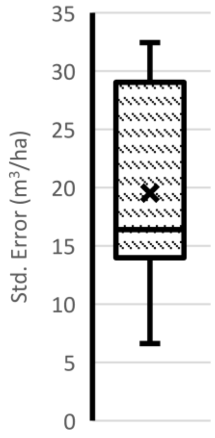

Figure 2-1: Distribution of standard errors for total volume.

The distribution of the total volume showed positive skew due to a significant number of plots returning high residue volumes (Figure 2-2). The minimum volume was 0 m^3/ha on one plot and 23 plots returned residue volumes greater than 200 m^3/ha (maximum was 580 m^3/ha, see Table 2-2). The distribution of total residue volumes is best described by the Bounded Johnson function with the parameters: $\gamma = 3.78$, $\delta = 1.35$, $\lambda = 1670$ & $\xi = -9.46$ (see Figure 2-2).

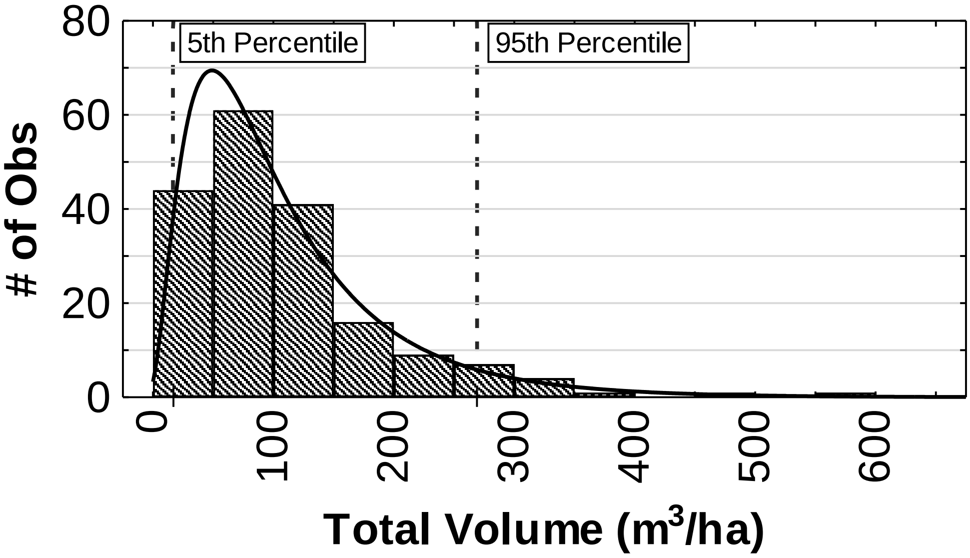

Figure 2-2: Distribution of total volume of residues >25 mm in diameter as measured at each LIS plot.

The volume of potentially merchantable residues on the cutover yields similar distributions (Figure 2-3) to that of total residue volume (Figure 2-2) with a positive skew. For the 185 plots, the 5th and 95th percentiles values were 0 and 63 m^3/ha for merchantable, and 0 and 88 m^3/ha for binwood. Seventeen and 31 plots had volumes >50 m^3/ha of merchantable pulp (or higher specification) and binwood respectively, which might be considered a high volume, approximately equivalent to two truckloads per hectare. However, 52 and 29 plots recorded no volume at all for merchantable pulp (or higher specification) and binwood respectively, highlighting the nature of the materials' distribution.

In addition to the volumes of merchantable logs and binwood, Table 2-3 provides a summary of the diameters and lengths of the material. A total of 1000 pieces of 'potentially merchantable' material were measured across the 17 sites. The median merchantable log was 6.4 m long, with a mid-point diameter of 180 mm which indicates much of the material may be suitable as a 'small industrial' export log, subject to quality. Binwood on average had a smaller diameter (160 mm) than merchantable logs with the average closer to the minimum specification of 100 mm at the small end.

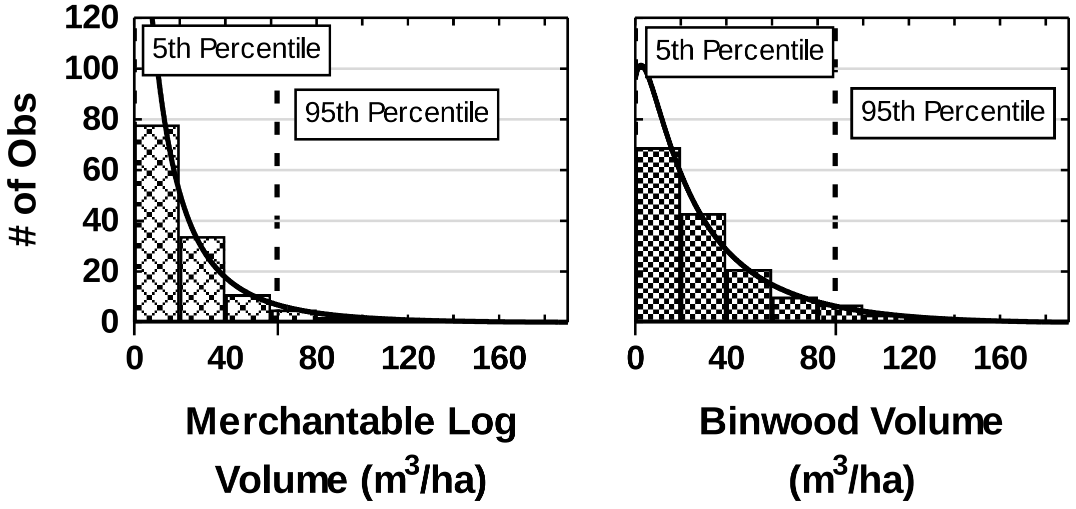

Figure 2-3: Distributions of residue volumes with merchantable potential on steepland cutovers.

Table 2-3: Summary statistics of potentially merchantable residues measured on the 17 sites.

		Merchantable Logs	Binwood
N Pieces Measured		365	635
Length (m)	**Average**	7.4	2.9
	Median	6.4	2.6
	Interquartile Range	3.6	1.7
Mid-point Diameter (mm)	**Average**	195	163
	Median	180	145
	Interquartile Range	90	85

Of the 17 sites, 11 were harvested with cable yarders (118 LIS plots) and 6 with ground-based systems (67 LIS plots). The median total residue volume for cable yarder sites was 110 m^3/ha, and 68 m^3/ha for ground-based. One-way ANOVA demonstrates that the effect of harvesting system on total residue volume is significant ($p<0.01$). Six sites (63 LIS plots) were felled motor-manually (chainsaws) and 11 sites (122 LIS plots) with mechanised systems. The median total residue volume for motor-manual sites was 94 m^3/ha; against 86 m^3/ha for mechanised felling (which was not significantly different:

p>0.05). While these results show some comparative differences, it should be cautioned that these are based on a relatively small sample of sites. Harvesting systems and felling methods are also not always interchangeable.

General linear regression was used to establish which variables contribute to the total volume of residues at a given location on the cutover. Seven model variables minimise the Mallow's C_p factor for the dataset tested (see Table 2-4). Those meeting the $p<0.001$ significance level as predictors of the box-cox transformed total residue volume ($\lambda = 0.297$) were the proportion of the log production from the stand meeting large structural log specifications (scale 0-100) and terrain slope (in degrees), followed by planform curvature (x10) – an objective measure of the 'sharpness' of a spur or gully derived from an 8 metre resolution digital terrain model (ESRI 2019). At lower significance level and contributing little to residue volume were categorical variables describing whether the area of interest was on a spur or not, whether pulp and/or binwood was on the cutting instructions, felling method and profile curvature – a continuous variable and an objective measure of the concavity/convexity of a slope in profile (ESRI 2019). All seven variables in the regression model present a low likelihood of multicollinearity, with variance inflation factors <10.

Table 2-4: Effect of significant variables on the volume of residues remaining on the cutover post-harvest (Adjusted R^2 = 0.27 from 17 sites and N = 185 LIS plots).

Effect	Regression Coefficient	F Value	p Value	Tolerance	Variance Inflation Factor
Intercept	-53.4	0.51	0.5		
Planform Curvature (x10)	-3.40	10	0.002	0.91	1.1
$(\text{Stand Age})^2$	0.266	9.4	0.003	0.37	2.7
$(\text{Terrain Slope})^2$	-0.0553	11	0.001	0.89	1.1
Spur (1 = yes, 0 = no)	21.7	5.5	0.02	0.95	1.1
Motor-manual Falling (1 = yes, 0 = no)	-25.3	4.6	0.03	0.40	2.5

Isolating the 118 cable-harvested LIS plots and applying general linear regression to the box-cox transformed total residue volume dataset ($\lambda = 0.324$) reveals that predicted residue volume on at any given location on a cable-harvested sites is most influenced by the terrain slope, proportion of large structural timber in the stand and also the planform curvature measure of the terrain. Four additional variables contribute to the regression model (Figure 2-4) and satisfy the minimised Mallow's C_p criteria; Table 2-5. Likelihood of multicollinearity is low, with variance inflation factors <10 for all contributing variables.

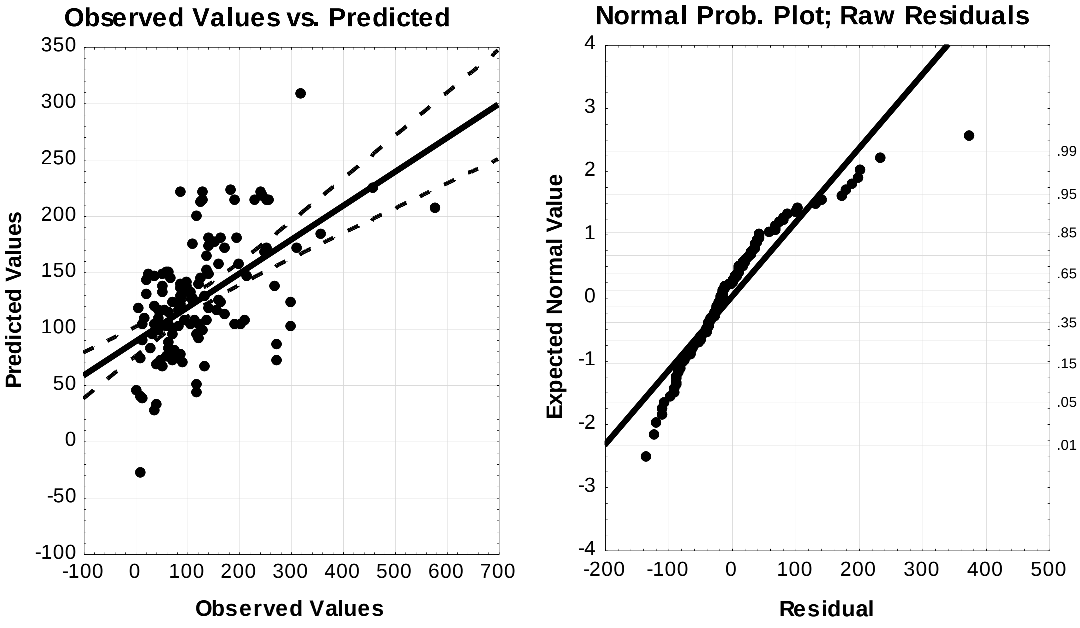

Figure 2-4: Results of multiple regression for total residue volume, including a 95% confidence interval.

Table 2-5: Effect of significant variables on the volume of residues remaining on a cable-harvested cutover (Adjusted R^2 = 0.26 from 11 sites and N = 118 LIS plots).

Effect	Regression Coefficient	F Value	p Value	Tolerance	Variance Inflation Factor
Intercept	-268	3.0	0.09		
Stand Age	15.2	8.1	0.005	0.33	3.0
Planform Curvature (x10)	-3.42	10	0.002	0.91	1.1
(Terrain Slope)^2	-0.0564	11	0.001	0.89	1.1
Spur (1 = yes, 0 = no)	21.4	5.1	0.03	0.94	1.1
Motor-manual Falling (1 = yes, 0 = no)	-25.0	3.9	0.05	0.36	2.8

DISCUSSION

Hall (1999b) represents the most recent study of residue volumes on New Zealand's steepland cutovers. Two intensively surveyed, cable-harvested cutovers yielded an average volume of 61 m^3/ha, ranging from 1 to >200 m^3/ha. The sites additionally indicated significant accumulations of residues in the lowest point of the harvest setting. Harvesting practice around gullies may have improved, but this study has showed that some concentration of residues in low-points continues to occur. For cable-harvested sites, the significance of the planform curvature variable in the regression analysis confirms the observation of a difference in residue volume between gullies and spurs.

Despite a step-change in harvesting mechanisation over the previous two decades (Raymond 2019), cutover residue volumes on harvesting sites appear to remain similar. Increasing demand for wood fibre could lead to greater residue recovery from the cutover where the market conditions allow; however there remains competition from residues accumulating at landings, super-skids and central processing yards (processing sites) as a more readily available and equivalent resource. Having accounted for residues at processing sites, this study enables a forest owner to understand some of the drivers for woody residue accumulations on cutovers, assisting decision-making for specific cutover residue management interventions or discussions with potential residue customers. In steepland forests, the resource remains an opportunity for greater recovery and utilization until there is a significant shift in the market for the product.

This study has demonstrated that tree breakage during either or both of the felling and extraction phases of harvesting on steepland sites remains a key opportunity for improved value recovery. Murphy (1982) investigated how value loss due to felling breakage could be minimised and revealed that trees with larger diameters were more susceptible (than small diameter trees) to multiple breaks along the stem during felling. This implies that older stands or stands with low stocking may be more likely to produce high residue volumes. This hypothesis was not directly evidenced by the regression models in this study, though a stand with a high proportion of large structural logs may lead to lower residue volumes in the cutover. Importantly, data was collected post-extraction, where further breakage can occur. Therefore, the residue volumes measured cannot be definitively attributed to either felling or extraction. Innovations in machinery design and harvesting methods, aimed at reducing stem breakage will result in lower volumes of large woody biomass remaining on steepland cutovers following harvest. Whilst this progress would be undoubtedly beneficial for forest owners and contractors if considering value recovery from the stem, increasing the volume of branches extracted to landings may transform what is currently a distributed ‘problem’, into a concentrated one at processing sites, if the product is un-merchantable. On sites prone to landslips and debris flows, concentration at processing areas may be beneficial by ensuring debris can be piled/stabilised on low-risk landforms. Development of harvesting technology and methods is important and will continue, but strong biomass demand is key to avoid harvest residue piles at the processing site becoming a more significant constraint or cost associated with harvest operations.

This study relied on tried and tested in-field line intersect survey methods. An emerging method for measuring harvest residue volumes is via passive and active remote sensing technologies (Davis 2015; Joyce et al. 2019). The benefits of this technology promise to be substantial when considering the increased speed, safety, and control of spatial and temporal resolutions (Tang & Shao 2015). Early applications of deep learning on aerial imagery show significant promise for capturing merchantable volume measurements on steepland cutovers (Herries 2021).

CONCLUSION

This study sets the latest benchmark for measuring progress on stem breakage and value recovery in New Zealand's steepland plantations. Plantations continue to offer potential for greater utilisation with a median total volume of residues remaining on the cutovers of 17 sites measuring 88 m^3/ha. Total volume follows a well-defined right-skewed distribution showing that small areas of harvesting sites contain high volumes of harvest residues. Extraction system appears to impact total residue volume, with cable yarder operations leaving behind more cutover residues than ground-based operations. Prediction of harvest residue concentrations on steepland sites ahead of harvest is possible using the regression coefficients presented. Variables collected in this study can account for 32% of the variation observed on the 17 sites measured. Markets for harvest residues are developing and opportunities remain to innovate harvest systems to reduce the production and distribution of harvest residues.

DECLARATIONS

Competing Interests:

The authors have no competing interests to declare.

Funding:

This research project is supported by Forest Growers Research Limited and the New Zealand Institute of Forestry Foundation.

Authors' Contributions:

The project idea and methodology was developed by Campbell Harvey within the scope of his PhD, under the guidance and direction of Rien Visser. Campbell prepared the literature review and completed all of the field work, with the support of Rien for the data analyses. The manuscript was prepared jointly.

Acknowledgements:

We gratefully acknowledge the support and consultation of Peter Hall (SCION) and Keith Raymond from Forest Growers Research (FGR).

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Chapter 3 – MEASURING HARVEST RESIDUE ACCUMULATIONS AT NEW ZEALAND'S STEEPLAND LOG MAKING SITES.

This Chapter is based on the publication:

Harvey, C. (2022). Measuring harvest residue accumulations at New Zealand's steepland log-making sites. *New Zealand **J**ournal of **F**orestry **S**cience*, 52(12), 11 p. doi: https://doi.org/10.33494/nzjfs522022x186x

ABSTRACT

BACKGROUND

When harvesting plantation forests of Pinus radiata (D. Don) in New Zealand, large residue piles commonly accumulate on or adjacent to processing sites. While the merchantable volume that is transported to market is carefully measured, little is known of the quantity of the piled, residual material. A working knowledge of residues is becoming more important as they represent potentially merchantable products for the bioenergy market; but where stored in perpetuity the material can present a risk of self-ignition, and specifically on steep slopes, it presents a mobilisation risk if not stored correctly.

METHODS

The area, bulk volume and depth of residue piles at 16 recently harvested steepland sites were measured from a wide geographic spread across New Zealand. Unmanned Aerial Vehicle imagery was used to build georeferenced photogrammetric models of residue piles (94 per cent of the studied volume). Pile area was determined from interpreting boundaries from orthophotos and volumes determined by interpolating the obscured terrain surfaces on duplicate photogrammetric models. The remaining 6 per cent of pile volume was measured with handheld GPS tracking of the perimeters and on-site estimation of average pile depth.

RESULTS

For a mean harvest area of 18.9 ha, there was a mean of 2.4 piles per harvest site, 2600 m^3 bulk volume and 2900 m^2 of area covered. For every hectare harvested, a bulk volume of 170 m^3 is piled at the landing, or alternatively, 0.23 m^3 of bulk pile volume per tonne harvested. The manual terrain interpolation methodology was tested against georeferenced pre-harvest terrain surfaces, yielding an average percentage difference of 19% across two sites and six residue piles.

CONCLUSIONS

This research demonstrates the ability to investigate the bulk volume and site coverage of landing residue piles with equipment and software tools available to today's forester. Mean values for pile area and volume are presented to reflect the current state of knowledge and can be a reference point for future initiatives.

KEYWORDS

Plantation forestry, slash, harvesting operations, biomass.

INTRODUCTION

Most plantation-grown *Pinus radiata* (D. Don) is typically harvested between the ages of 25 and 35 in New Zealand, depending on a range of factors including market conditions, site and stand management (Maclaren 1993). Currently the average felling age is 29.5 years old (MPI 2020) with a modelled average Total Recoverable Volume (TRV) of 585 m^3/ha (clearwood regime) or 593 m^3/ha (framing regime) across New Zealand (MPI 2015), with comparatively lower stockings and larger tree size in clearwood regimes (Maclaren 1993). The recovered volume, taken as logs to market, is accurately measured and can be reconciled against the inventory data that is typically available to forestry companies (Gordon 2005). A recent study detailed the residues left in the cutover, which showed the median volume of Course Woody Debris remaining was 88 m^3/ha (Harvey and Visser 2022). However, little is known about the residues that are left behind at the landings (processing areas).

The majority of plantations currently being harvested have been tended as clearwood regimes; a result of markets and common practice in the 1990's (Maclaren & Knowles 2005). In recent times there has been an increasing proportion of stands transitioned into framing regimes across New Zealand (MPI 2020). The regime change is expected to increase final crop stocking and decrease average piece sizes at harvest with time. Goulding (2005) estimated that in an average stand, 85 per cent of the total standing volume will be merchantable, leaving residues that will range from about 10 per cent in good condition, well-tended stands, to over 20 per cent for untended stands on moderately steep terrain.

Murphy (1982) showed that value loss at harvest due to stem breakage increases with increasing Diameter at Breast Height (DBH); one consideration when assessing alternative regime(s). Breakage at any point along the stem results in a change in the objective function for maximising the stem's value; establishing a new, lower optimum for the remaining value. Stem breakage means a logging contractor needs to manage more stem 'parts' and inevitably less log volume will leave the site; however, depending on where the break-point is along the stem, the value loss may only be trivial (Murphy 1982). Several studies have shown that most production trees are broken during felling in New Zealand and that the typical break height (for the first break) is around two-thirds of the height of the stem (Fraser et al. 1997; Lambert 1996; Twaddle 1987). Breakage typically results in generation of un-merchantable woody debris, where the final section of stem before (and after) the break cannot conform to any available log grade specifications. Managing this additional debris provides only indirect benefits to logging contractors (e.g. tidy work area, reduced hazards) and can result in considerably reduced production.

Harvesting systems can be categorised as Cut-to-length (CTL) or Whole Tree Harvesting (WTH). In CTL systems the trees are processed in the cutover where the residues are left and only the logs extracted to roadside or a landing for subsequent transportation. In WTH the stems are extracted to a landing where they are processed into logs. WTH remains the preferred harvest system on steep slopes as it offers greater productivity and value recovery by enabling a larger number of log sorts that meet both domestic and international demand. Even with the widespread adoption of mechanisation on steep terrain and expanding slope limits for CTL, WTH remains the preferred extraction option for steep slopes (Berkett 2012; Raymond 2018; Visser 2018).

Where markets for the piled material remain elusive, or no alternative management is applied (e.g. incineration), harvesting residues resulting from WTH accumulate at landings (Figure 3-1). Residues are not only the branches and tops, but also stem offcuts from felling breakage (Hall 1994). Poor form of some Radiata pine crops means larger diameter segments will also accumulate at the landing. However, few market opportunities have developed to make use of the convenient accumulation of residues at steepland landings (Visser et al. 2019).

Figure 3-1: An example of a residue pile at an operational landing in a Radiata pine plantation.

Large residue piles remaining after harvest not only exclude land from re-establishment, but they can also present ongoing management problems. Piles generate heat internally by decomposition and those that generate heat at a greater rate than what can be shed (typically deep piles) are prone to self-combustion (Buggeln & Rynk 2002). Piles located on unstable, steep terrain can mobilise and cause significant impacts on the natural and built environment (Phillips et al. 2012). While there are risks posed by storing large residue piles on steep terrain over long periods of time, the resulting accumulation at landings from WTH systems can benefit biomass extraction programmes due to easy access to the material.

Over the years 'fit-for-purpose' management approaches have developed to ensure that permanent residue piles pose acceptable risk while they decompose *in situ* (Hall 1998; Visser et al. 2018). The Best Management Practices (BMPs) applicable at any particular site principally depend on the stability of the underlying soils and values at risk (NZFOA 2020). Those BMPs range from piling on a natural terrain bench adjacent the landing, to end-hauling loads to a nearby, unused landing; with several other management options between.

Research was conducted in the 1990's on various aspects of NZ's landing residue piles, including work studies on the management of them (Hall 1993a, 1993b, 1994, 1998, 1999; Hall & McMahon 1997). Various methods for bulk volume measurement have been used previously, including measuring dimensions of individual woody residues as-cut (Hall 1994), volumes of piles using broad approximations of geometry (Hardy 1996) or measuring cross-sections of piles as they are deconstructed with heavy machinery (P. Hall, personal communication, 14 April 2021). Hall (1993a) established that the typical solid volume of residues discarded into the piles was approximately 4 per cent of Total Extracted Volume (TEV) for cable-based harvest operations. Additionally the relative proportion of various tree 'parts' that made up the pile mass were reported through a detailed study of log-making residues, as the material was produced. They established that 66 per cent of the pile volumes were made up of woody stem sections, with the remainder being branch material (Hall 1994). These studies were a snapshot of harvesting residue production at the time and a benchmark for future change.

There is a gap in recent literature and operational knowledge around the physical characteristics of landing piles. With a national increase in harvest mechanisation and greater incentive for industrial process heat users to transition to renewable energy sources (Climate Change Commission 2021), an up-to-date knowledge of the resource is necessary for the forest owners and managers aiming to make material available for the developing bioenergy market.

New tools are now available for measuring piles with complex shapes. Structure from Motion (SfM) photogrammetry has become an increasingly useful tool for detailed measurement and terrain modelling, with assessments of piles (of any material) an established research and commercial application of the technology (Tucci et al. 2019). Model construction pipelines use the known camera dimensions, identifying tie points on overlapping digital images to precisely define the camera pose in each image. Known camera locations and common points on overlapping images contribute to calculations of geometry by the principle of motion parallax and a ‘cloud’ of points (point cloud) of the scene is constructed, with each point assigned a location in three dimensions. With georeferencing, point clouds can additionally be given geographic or projected coordinates for use in mapping. Davis (2015) investigated the use of photogrammetry with UAV imagery to assess the volume of small (<10 m^3 each) slash piles on near-flat cutovers. Measurement of small accumulations of woody debris in natural and modelled fluvial systems has also been completed, with a key focus on SfM workflows (Spreitzer et al. 2019, 2020). A common limitation is the estimation of surfaces occluded by piled material. This is typically handled by automated interpolation of datum surfaces for small piles or simple (i.e. flat) ground (Ajayi & Ajulo 2021; Davis 2015), and manual inference/interpolation for more complex datum surfaces (Spreitzer et al. 2019). While both techniques result in model error, where resources permit, temporal change of georeferenced surface models can reduce or eliminate surface estimation, ensuring highly accurate models of all relevant surfaces, as demonstrated by Baldi and others (2007).

This research aims to provide the latest benchmark for the bulk volume of harvest residues accumulating at New Zealand’s steepland landings by using modern and accessible measurement methods, demonstrating and discussing modern procedures that a forest owner/manager may use to gain a better understanding of their own resource. Improving our understanding of landing residue volumes promises to assist marketing the material, and/or decisions concerning containment where residues are to remain on site in perpetuity.

METHODS

Sixteen recently harvested steepland sites were made available by participating forest companies for this research. All sites were plantation-grown Radiata pine, of typical silviculture and covered a wide geographic spread across New Zealand (Table 3-1). Forest managers provided data on regime, pre-harvest inventory, volume of each log grade sold, and harvesting method where available. With the exception of stands MH and GN that were grown under framing regimes, all other sites were clearwood regimes.

Table 3-1: Harvesting site details.

Site Code	Region	Extraction System	Harvest Area (ha)	Stand Age (yrs)	Extracted Volume per Hectare (m^3/ha)
GJ	Canterbury Waitaha	Ground-based	8.7	29	472
GT		Cable	31.0	30	546
MH		Ground-based	12.6	No data	No data
GN	Tasman Te Tai-o-Aorere	Cable	9.5	29	611
MG		Ground-based	36.8	25	392
HT	Gisborne Te Tai Rāwhiti	Cable	25.3	27	553
PK		Cable	23.0	25	507
MA		Cable	16.7	28	594
MC		Cable	8.3	27	866
PE		Cable	6.9	26	507
HF		Cable	13.9	27	553
MO	Marlborough Te Tauihu-o-te-waka	Ground-based	41.1	No data	No data
TP		Ground-based	21.2	27	407
PC	Wellington Te Whanga-nui-a-Tara	Mixed	8.2	28	746
RK		Cable	6.1	26	795
TK	Otago Ōtākou	Cable	33.5	33	841

For each site, all landing residue piles associated with the harvest area were measured for area and bulk volume. Three techniques were used for measuring the landing residue piles. The first technique (applied to the majority of piles) made use of photogrammetric models derived from Unmanned Aerial Vehicle (UAV) photography (example see Figure 3-2). The second technique made use of portable

Global Positioning System (GPS) tracking for pile perimeters (±6m accuracy) coupled with estimation of average pile depth. The second methodology was used on five small piles only – accounting for approximately 6 per cent of the total volume surveyed. The third was used on two sites only as validation for the first method. This involved collecting georeferenced pre and post-harvest photogrammetric models of the sites.

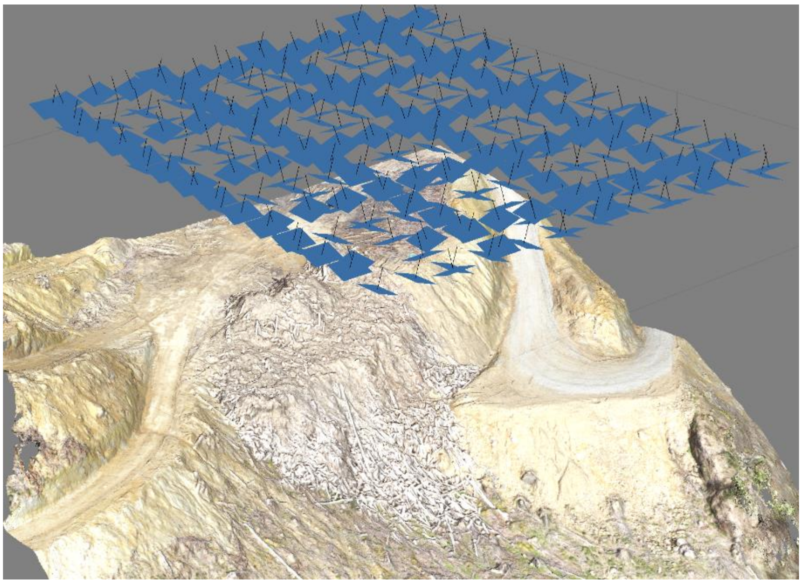

Figure 3-2: Example Agisoft Metashape point cloud of a residue pile and surrounding terrain. Blue squares show the location and orientation of the camera on a grid above the pile.

Two consumer-grade UAV's were used for this study. The specifications for each model are detailed in Table 3-2.

Table 3-2: Specifications of UAVs used to capture images of landing residue piles.

UAV Model	Camera Sensor	Positioning System	Rated Max. Flight Time per Charge
DJI Mavic Pro	1/2.3" CMOS Effective pixels: 12.35 million	GPS/GLONASS	27 min
DJI Mavic 2 Pro	1" CMOS Effective Pixels: 20 million	GPS+GLONASS	31 min

Image capture methodology adapted as fieldwork progressed. For the initial three sites (GT, MH & TP) images of residue piles were captured by manually controlling the position of the UAV camera, firstly capturing images in a wide arc around the residue pile(s) then directly overhead the pile(s), ensuring significant overlap between images. The process is described in Riedinger & Harvey (2021). Image capture was refined for the remaining sites by using the Pix4Dcapture flight control application. Pre-programmed flights standardised image capture (see Figure 3-2), ensuring image overlap exceeded 60 per cent at take-off elevation. Overlap, flight extents and UAV height were set to provide coverage beyond each pile's extent and a Ground Sample Distance lower than 3 cm/pixel at the take-off elevation.

Georeferencing was used to ensure accurate dimensioning of all except two models (Sites GT and MH). Four Ground Control Points (GCPs) were arranged around residue piles, in locations visible to the UAV camera sensor. GPS coordinates of each GCP were averaged over 60 seconds using a Trimble Zephyr 3 Rover receiver and subsequently post-processed to 5-15 cm accuracy using local base-station datasets.

Photogrammetric models were constructed using Agisoft Metashape according to the flowchart in Figure 3-3 (see p.48). Input data for each model were the aerial photos (including geotag information) and post-processed GCP waypoints. GCP centres were located on aerial imagery prior to assignment of post-processed waypoints. 'Medium' resolution point clouds (standard Agisoft Metashape setting) were constructed in Agisoft Metashape, which were then down-sampled to output 0.1 m resolution Digital Elevation Models (DEMs), along with orthophotos of varying resolutions; dependant on the limitations imposed on the pre-programmed flightpath.

The DEM for each pile was imported into Softree RoadEng9 Terrain and a Triangular Irregular Network (TIN) model generated. A duplicate model of each residue pile was created and terrain that was obscured by the pile was estimated by manual interpolation due to the unique geometry of most sites. Manual interpolation required features such as the fill batter top edge or fill batter bottom edge to be manually projected underneath the pile, forming an estimated terrain surface. The resulting difference between the unaltered, original TIN (with pile surface) and the duplicate TIN (with the interpolated terrain surface) yielded the bulk volume measure of each pile.

Maximum pile depths were additionally calculated by the difference in elevation between the interpolated surfaces and the unaltered, original surfaces using Cloud Compare software (2.5D Volume function). Histograms of pile depth on a 0.1 m raster grid were filtered for depths >0.1 m to eliminate noise on the pile boundaries. Maximum depth was established at the 90 per cent threshold to also eliminate noise at the upper threshold (random woody residues poking up out of the pile). Average pile depth was calculated for each site by dividing total bulk volume by the total pile plan area.

To establish a measure of the manual interpolation method’s accuracy, two sites were scanned after construction (but prior to harvest), then again post-harvest; with six residue piles total. The manual terrain interpolation method was completed ‘blind’ (prior to constructing the pre-harvest terrain model) and for each residue pile, two volume measures were calculated; one by computing the difference between the interpolated terrain surface and the post-harvest (pile) surface, and the other between the georeferenced pre-harvest datum (terrain) surface and the post-harvest (pile) surface.

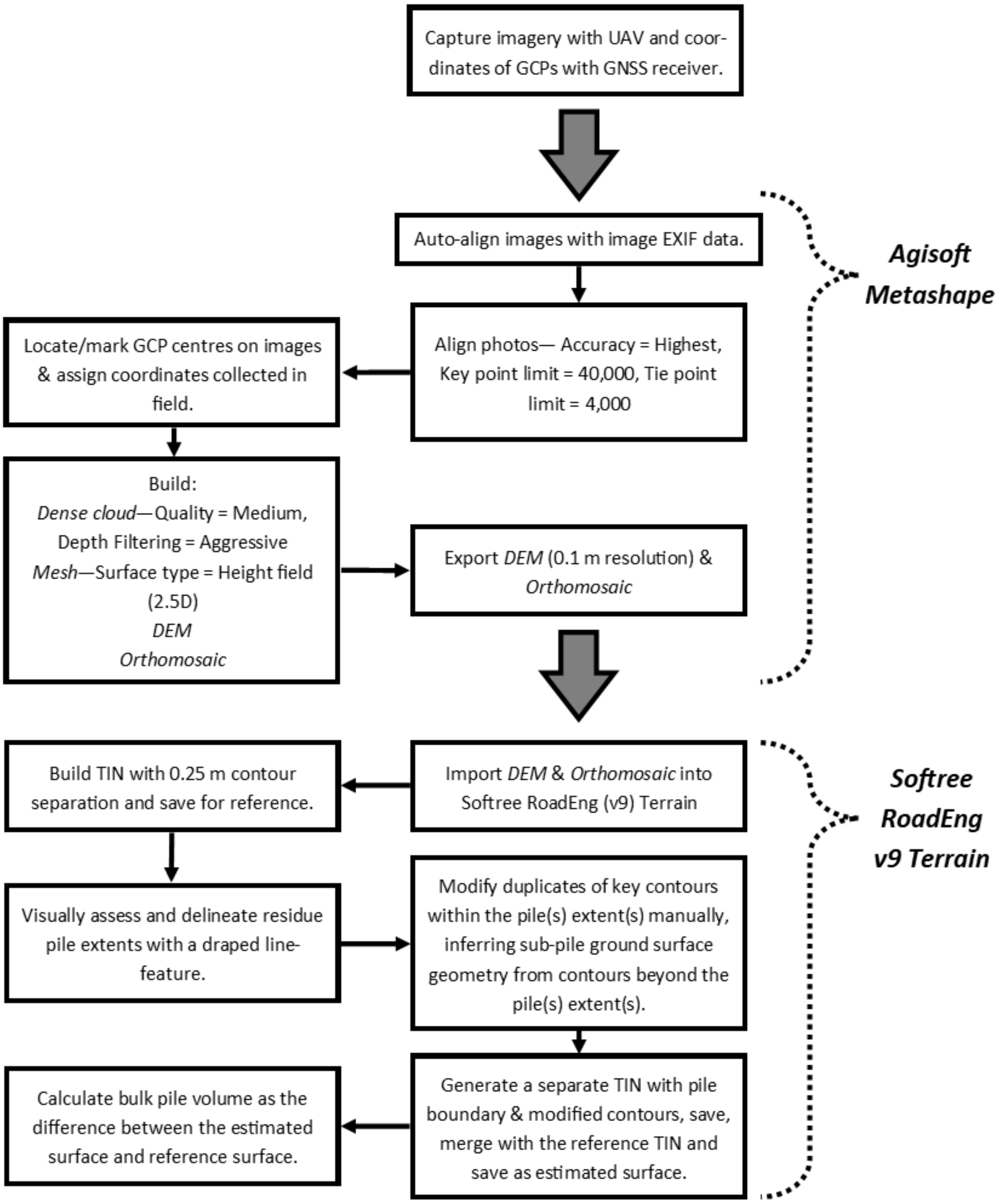

Figure 3-3: Surface and volume calculation pipeline.

RESULTS

The study sites represent a typical range of harvesting systems employed to clearfell steepland forests in New Zealand; from tracked ground-based to cable-based. Pile areas and volumes differ significantly between sites (Table 3-3). To compare in more equal terms, pile areas are also given in 'pile area per hectare harvested', as the harvest areas range in size from 6.1 to 41.1 ha. Of note is that several sites had residue piles that (when combined) covered approximately 0.5 ha each. Not all of the pile area is lost planting area however as landing surfaces are seldom replanted in New Zealand operations due to the need for soil rehabilitation and ongoing nutrient management (Hall 2000).

Table 3-3: Ground covered by residue piles and depth statistics.

Site Code	Total # of Piles	Combined Pile Area (m^2)	Pile Area per Hectare Harvested (m^2/ha)	Mean Pile Depth (m)	Max Pile Depth at the 90% threshold (m)
GJ	1	1360	160	1.6	4.3
GT	2	4730	150	0.7	2.2
GN	3	1500	160	0.7	1.7
HT	3	3680	150	0.8	1.7
HF	4	3450	250	0.7	2.1
MH	2	3730	300	0.5	2.8
MO	1	2630	60	2.8	5.5
TP	2	1040	50	0.9	2.1
PK	1	4910	210	0.9	2.3
PE	2	1340	190	0.9	2.2
MA	3	3750	220	0.5	1.6
MC	2	2680	320	0.7	1.9
MG	1	1480	40	1.4	3.7
PC	2	1920	230	1.2	3.1
RK	1	2280	370	0.9	2.3
TK	7	5560	170	0.8	-

Model accuracy was estimated using the Agisoft post-processing report feature and the user-specified GCP locations. The RMSE in the *x*-direction ranged from 1.4-4.9 cm, in the *y*-direction from 0.3-6.2 cm and in the *z*-direction from 0.2-5.9 cm for all sites; with three exceptions. Site TP used GCPs but no automated flight control, gaining an *x*/*y*/*z* RMSE of 4.5/8.3/3.2 cm. Sites GT and MH neither used automated flight control, nor GCPs, therefore gained *x*/*y*/*z* RMSEs for estimated camera locations of 85/59/68 cm and 78/72/40 cm respectively.

Similar to pile area, bulk pile volumes varied significantly between study sites. Table 3-4 details the volume measured, and also the directly comparable metrics of 'bulk volume per hectare harvested' and 'bulk volume per tonne harvested'.

Table 3-4: Volumes of residue piles.

Site Code	Combined Bulk Volume (m^3)	Bulk Vol. per Hectare Harvested (m^3/ha)	Bulk Vol. per Tonne Harvested (m^3/t)
GJ	2190	250	0.53
GT	3520	110	0.21
GN	1100	120	0.19
HT	2770	110	0.20
HF	2250	160	0.29
MH	1880	150	No data
MO	7235	180	No data
TP	940	40	0.11
PK	4474	190	0.38
PE	1104	160	0.32
MA	1831	110	0.18
MC	1958	240	0.27
MG	2096	60	0.15
PC	2317	280	0.38
RK	2160	350	0.45
TK	4396	130	0.16

The measures of average pile depth and maximum pile depth (see Table 3-3) indicate that for most harvests, there is little difficulty in achieving a pile height less than 3 m to align with current industry guidelines.

Table 3-5 provides the summary statistics from Table 3-3 and Table 3-4. Each site has been considered a data point in generating the mean values. A reduced dataset size is indicated where data could not be provided by the hosting forest manager.

Table 3-5: Mean values for all parameters across all sites (n=16).

Harvest Area (ha)	18.9
Number of Piles per Site	2.4
Bulk Pile Volume per Site (m^3)	2600
Pile Area per Site (m^2)	2900
Pile Area per Hectare Harvested (m^2/ha)	190
Bulk Pile Volume per Hectare Harvested (m^3/ha)	170
Pile Depth (m)	0.92
Max. Pile Depth (at the 90% threshold) (m) **15 sites*	2.6
Bulk Vol. / tonne harvested (m^3/t) **14 sites*	0.23

The assessment of accuracy for the six piles over two sites (Sites PE and HF) revealed an average percentage difference of 19% between the volumes yielded by the manual interpolation method and the georeferenced pre-harvest datum surface method, with a range of 49%. Five of the six pile volumes were underestimated by the manual interpolation method – where the assumption is made that the georeferenced datum surface method is ‘correct’ and the datum surface (landing shape/height etc.) remains constant between pre-and-post-harvest data collection visits.

DISCUSSION

In 1993, Hall completed a work study on the retrieval of residue 'bird's nests' (residue piles) at four hauler landings, which involved surveying the bulk volume of material moved and also that beyond the machine's reach (Hall 1993a). The mean bulk volume and mean TEV were 1400 m^3 and 6694 m^3 respectively. By generalising the density of freshly harvested Radiata pine at 1 t/m^3, this suggests that the bulk volume of residue piles per tonne harvested in 1993 was approximately 0.21 m^3/t harvested.

A further study carried out in 1994 by Hall measured the solid volume of branch and stem material discarded from 6 log making operations on Radiata pine cable hauler sites and 3 ground-based harvesting sites (Hall 1994). For the cable-based harvesting sites (assuming that they were steepland harvests, therefore comparable) solid log making residue volumes measured a mean of 13.8 per cent of TEV by excluding the Douglas-fir (*Pseudotsuga menziesii)* stand datum. Accepting the same assumption on Radiata pine density and additionally a bulk density approximation of 0.25 t/ m^3 for woody residues (Visser et al. 2010), the comparative bulk density figure for residues in the 1994 study is 0.55 m^3/t. That places the 1994 result at the upper end of the range measured in this study. Recognising that a series of assumptions underlie these comparisons, it is significant that the bulk volume per tonne harvested the 1994 result is more than double the result from one year earlier. This study corroborates with Hall's 1993 study, although market conditions, harvesting machinery and harvest practice have changed markedly during the intervening years.

Managing residue pile area requires balance of competing interests. Soil area covered by residue pile(s) can represent an opportunity cost by reducing land area available for establishing the succeeding crop. However, concentrating residues by piling high carries an increased risk of self-ignition. Self-ignition thresholds in Radiata pine residue piles requires further research to expand the working knowledge, however anecdotal evidence has formed the basis for the current BPG for residue pile height (3 m) (NZFOA 2020). For the piles measured in this study, the average maximum depth is below the current target BPG for height. Increasing the average pile height may allow more land area to be replanted, however high-stacking can only be done on 'stable ground' (NZFOA 2020), with the understanding that increasing pile height on a slope decreases its stability and increases risk of mass movement. The results show that on these study sites, maintaining low overall pile depth takes priority over maximising replanted area.

Further insight into the results of individual sites should consider operational factors. Additional reasons for a high or low pile area per hectare may be explainable by the log market conditions, landing layout, machinery used, management instructions or terrain form. Such finer details are beyond the scope of this study, and may require much larger datasets to establish meaningful conclusions.

New Zealand plantations are now trending more towards framing regimes. The majority of sites measured in this study were clearwood regimes, as is typical of most 1990's crops. Framing regimes when compared to clearwood (typically) have: higher TRV, higher stocking and smaller piece size. Reduced size (in turn) has been shown to lower the breakage rates (Murphy 1982), however with more stems per hectare the effect may be negated. Whether the physical differences between regimes results in a measurable difference in landing residue volumes (all other factors controlled) is yet to be established.

It can also be noted that this research was completed soon after a number of major mass mobilisation events (Cave et al. 2017). As such the measurements made for this study may already reflect changes to practices for both creating and storing harvest residue piles on or near landings in steep terrain. The author also recognises that the current strong emphasis on both minimising environmental risk as well as creating biomass market opportunities for renewable energies may have already resulted in changed residue management practices (Dale 2019; Visser et al. 2018). While this study cannot predict those changes, it can serve as a benchmark and reference point to measure future developments against.

This research demonstrates the ability to investigate the bulk volume of residue piles with the modern equipment and software tools available (or cloud-computing substitutes) to today's forest manager. Previous methods required measurement in association with heavy machinery or estimation of both the terrain below and also the surface of the pile (Hardy 1996), making use of the tools available of the time. The method employed in this study improves on previous methods by better modelling the pile surface. One way that terrain estimation could be improved upon may be by siting residue piles on as flat of ground as possible. Whilst clearly advantageous for measurement accuracy, several factors precluded the viability of the idea for this study. With additional time, more accurate results would be obtained by establishing a georeferenced datum surface of the completed landing formation, prior to piling with harvest residues – as used for the validation of the method employed in this study. Where serious consideration is given to removal of the product, accuracy may become increasingly important, and modelling landings (and surrounds) pre-harvest justified.

Results from this project can assist forest managers to predict the bulk volume of residues that may accumulate at a steepland landing during a WTH operation. Estimation of volumes is recommended by guidance documents for current legislation (MPI 2018) to ensure storage capacity is adequate – or alternatives are planned for. These results are advantageous for feasibility studies on a forest's ability to supply a biomass market with landing residues. Finally, this study sets the latest benchmark for residue volumes as harvesting machinery, methodology and markets develop over time.

There is little, recently published information on the volumes of harvest residues discarded at New Zealand's steepland landings. This study addresses the question, but much more can be done at a finer scale with the resources and data available to commercial operators. It is intended that this study provides accessible ideas and tools to foresters who are looking to supply (but not currently supplying) a biomass market. It is important that the industry collects information on the material as security of supply is critical to business cases for heat users considering conversion from fossil fuels to residual biomass. While international log markets continue to demand small-diameter or industrial logs, residual biomass will play a vital role in meeting bioenergy demand locally. The procedures discussed in this paper require limited training and many can be completed with cloud-computing services, reducing computing capacity issues.

CONCLUSION

This study takes a renewed look at residual biomass accumulations at landings and demonstrates how an investigation could be conducted in a forest or forest estate with widely-available tools to today's forester. It sets the latest benchmark for landing residue pile volumes in New Zealand's steepland plantations. Markets for harvest residues are developing, regime change is occurring, and innovations to harvest systems are promising to reduce the production of broken/low quality material. The information provided on current steepland pile volumes offers New Zealand forestry companies, forest owners and also the biomass market, a better understanding about the current availability of the material in steepland plantations and therefore potential for increased utilisation.

DECLARATIONS

Funding

This research project is supported by Forest Growers Research Ltd. and the NZIF Foundation. The Author gratefully acknowledges the support.

Acknowledgements

The Author would like to acknowledge the support by the forest companies and managers whom were part of this study and hopes these methods and results may assist developments in the market for steepland landing residues. This project is part of a PhD research programme, and the author acknowledges the guidance by Professor Rien Visser of the School of Forestry, University of Canterbury and Peter Hall of Scion

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Chapter 4 – MANAGING FOREST LANDING RESIDUE PILES: A CASE STUDY ON THE USE OF PHOTOGRAMMETRY TO SUPPORT DECISION-MAKING.

This Chapter is based on the publication:

Harvey & Drummond (2022). Managing forest landing residue piles: A case study on the use of photogrammetry to support decision-making. *New Zealand Journal of Forestry*, 67(1), 4 p.

ABSTRACT

The piles of woody residues that accumulate at forest landings across New Zealand present various operational, safety and environmental challenges for foresters and logging crews. Being able to measure the dimensions of these piles would help make decisions regarding both the potential recovery for a biomass market, but also for risk. For example, it is recommended that residue piles should be no deeper than 3 metres due to self-ignition risk. Depth can be difficult to measure, especially on undulating terrain. This case study used UAV-based aerial photography to first, improve the calculation of total pile volume and second, provide a three-dimensional map to help determine pile depth for targeted rehabilitation. A UAV was used to capture aerial photographs post-construction of a landing (prior to harvest), then again post-harvest with the residue pile formed. Georeferenced photogrammetric surface models were constructed and used to establish the relative height change of the surface pre-to-post harvest and therefore, over the plan area of the pile, total bulk volume. A 'heat map' of pile depth was generated, enabling assessment of areas requiring rehabilitation to meet best practice guidelines. This case study presents an improved methodology for assessing large piles over time along with learnings of the method's limitations for the practicing forester.

INTRODUCTION

Piles of harvest residues that accumulate at forest landings present operational, safety and environmental challenges, making their management a key focus for plantation owners (NZFOA 2007, 2019). The piles also provide increasingly tangible opportunities for utilisation due to growing demand for bioenergy (Pooch 2021). Management and measurement of the material can take many forms, from the application of 'rules-of-thumb' (Goulding 2005) to passive, material uplift monitoring to active pile measuring and dimensioning (Hall 1993, 1994; Hardy 1996; Riedinger & Harvey 2021). Standards and best practice allow for a range of slash prediction and measurement approaches, which can fit the resources available to the farm-forester or the estate manager.

Harvest residue piles can carry appreciable risk over the months or years post-harvest (Clifford et al. 2020). The selection of stable landforms for pile storage is a focus of improvement (Dale 2019) and instances of self-ignition only occur sporadically. However, for landing residue piles, landslip and fire remain the highest-consequence outcomes from error. The steep and variable terrain forms that dominate the New Zealand plantation estate can make observation or reconciliation of the depth or volume of piles difficult without intervention with heavy machinery. This represents a clear opportunity for harvesting process improvement and decision support.

With opportunities for biomass supply emerging, measuring the accumulated resource to provide short- and long-term availability projections is becoming increasingly important for suppliers (forest owners), but also potential customers to grow confidence in supply. Accurately measuring a pile of material, draped over undulating terrain can be complex, however. Safety considerations often preclude access to the pile surface by foot, so observations may need to be made from the pile edge. Early methods such as Hardy's (1996) geometric approximation can give an indication of volume with a few measurements and some broad assumptions. Hall (1993) measured cross-sections of landing residue piles draped over landing-edges to determine volume, aided by a hydraulic excavator for deconstruction. Modern active (LiDAR) and passive (photogrammetry) remote sensing technologies clearly show opportunities for increasing accuracy over these earlier methods.

Riedinger & Harvey (2021) demonstrated a method that used consumer-grade UAV's and photogrammetry software to assess the bulk volume of landing residue piles on relatively level terrain. The method made use of the relatively flat terrain to minimise error when estimating the terrain surface under the pile. Using georeferenced surface models, this case study demonstrates a proof of concept for a workflow that enables more accurate assessment of pile volume, by modelling the terrain under the pile ahead of harvest. It is intended to demonstrate that more accurate volume and depths can be measured on difficult terrain for inventorying residual biomass or for decision support on pile rehabilitation efforts.

METHOD

One small, recently constructed drive-through landing was selected for the study. The landing was located on rolling terrain and serviced a 4.8 ha harvest area of Radiata pine.

After completion of construction, and prior to harvest, the landing was aerially photographed with a DJI Phantom Pro UAV (non-RTK), controlled by Map Pilot software. Weather conditions were clear and calm. Four large Ground Control Points (GCPs) were laid at the outward extents of four quadrants of the expected slash pile. The site was imaged in a grid pattern on a flat plane, achieving an average Ground Sampling Distance (GSD) of 5.79 cm/pixel. Waypoints for each GCP were averaged over 60 seconds with a Trimble Geo7x paired with a Zephyr Rover 3 receiver on a 2 m staff. The waypoints were later post-processed in Trimble GPS Pathfinder Office software to ensure positional accuracy in the range of ±5-15 cm.

Post-harvest and with the residue pile in place, the same imaging procedure was carried out again. Weather conditions were overcast with a light breeze. GCPs were laid in the four quadrants about the residue pile, their waypoints collected (later post-processed) and images taken with the UAV, flying in a grid pattern. The average GSD achieved was 3.67 cm/pixel.

To eliminate performance bias, no attempt was made to influence the placement of the residue pile by the logging crew.

The pre-harvest and post-harvest georeferenced photogrammetric point clouds were generated in Agisoft Metashape software using the UAV images and post-processed GCP locations. Vegetation was minimal on both visits, requiring no additional filtering for ground points. Both point clouds were down sampled to 10 cm raster format, with orthophotos also generated.

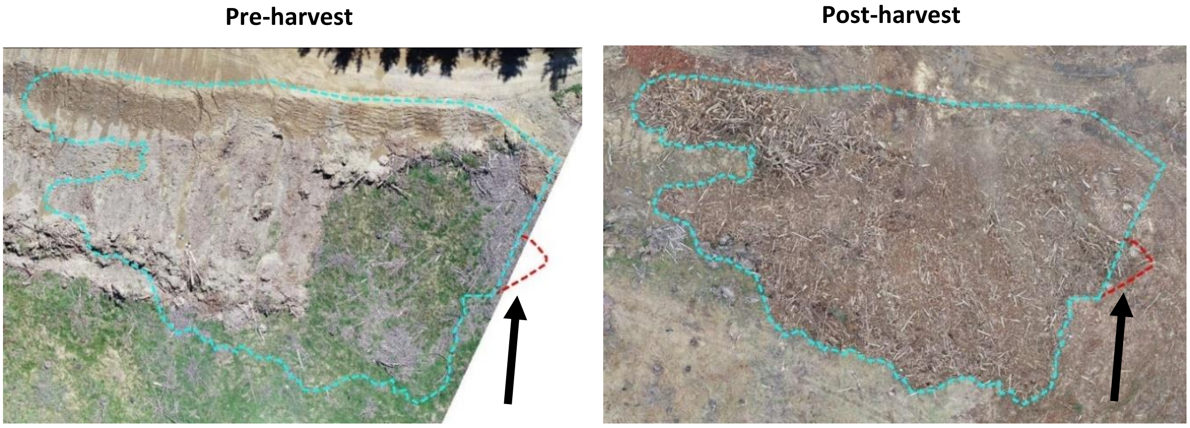
Pile volume was calculated in Softree RoadEng9 Terrain software. Visually delineating the residue pile boundary from the orthophotos and setting boundary as the TIN model limit, the volume was calculated using the software's 'Calculate Volumes' function. Depth maps were generated by computing the height differences between the pre- and post-harvest models in CloudCompare v2.10.2 software, using the 'Compute 2.5D volume' function.

The elevation of stationary check points (tops of stumps clearly visible in both pre- and post-harvest orthophotos) was assessed on pre- and post-harvest terrain surfaces to establish the accuracy of the terrain models.

RESULTS

On the completed models, the total RMSE of the location of the GCPs was 6.9 cm in the pre-harvest model, and 1.8 cm in the post-harvest model. A comparison of absolute Z-values (surface heights) on stationary check points, observable in both models showed an average height deviation of +17 cm, with a standard deviation of 6 cm over $n = 8$ check points. Applied over the 1800 m^2 pile, the initial volume is therefore reduced by 310 ± 110 m^3 to correct for the height difference found by the check points. This yields a total bulk pile volume of 2000 ± 110 m^3 (2 s.f.), with the pile having an average depth of 1.3 m.

The measures exclude a small section on the eastern extent, which was not modelled in the pre-harvest survey, as indicated in Figure 4-1. This does highlight the importance of surveying a large enough area for the pre-harvest survey as residue piles can often extend beyond planned areas.


Pre-harvest

Post-harvest

Figure 4-1: Comparison of orthophotos for the pile, showing a small area missed in the pre-harvest image (arrowed).

The distribution of the pile depth as an output of the CloudCompare analysis (Figure 4-2) shows that 99 per cent of the pile's area is below the best practice target depth of 3 metres (NZFOA 2019). This result is represented visually in the heat map of pile depth (Figure 4-3).

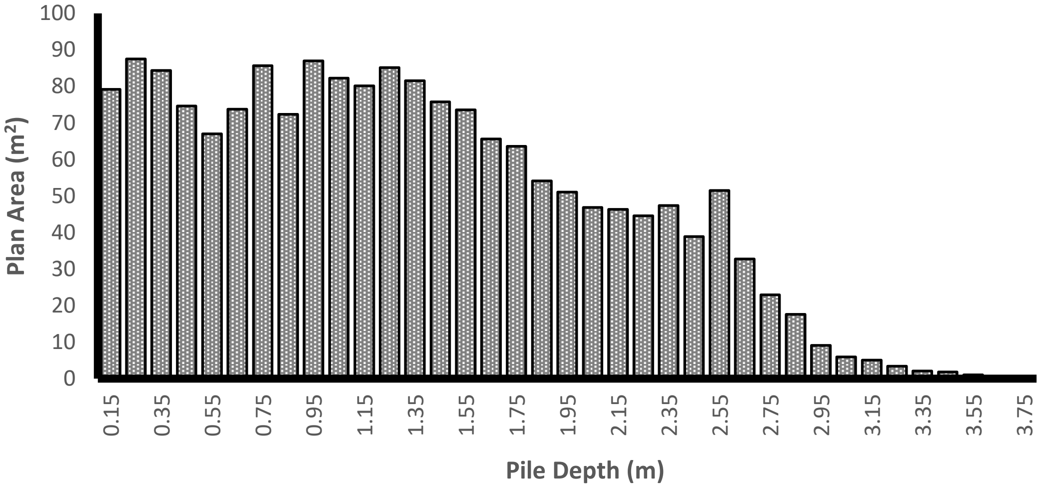


Figure 4-2: Pile depth distribution.

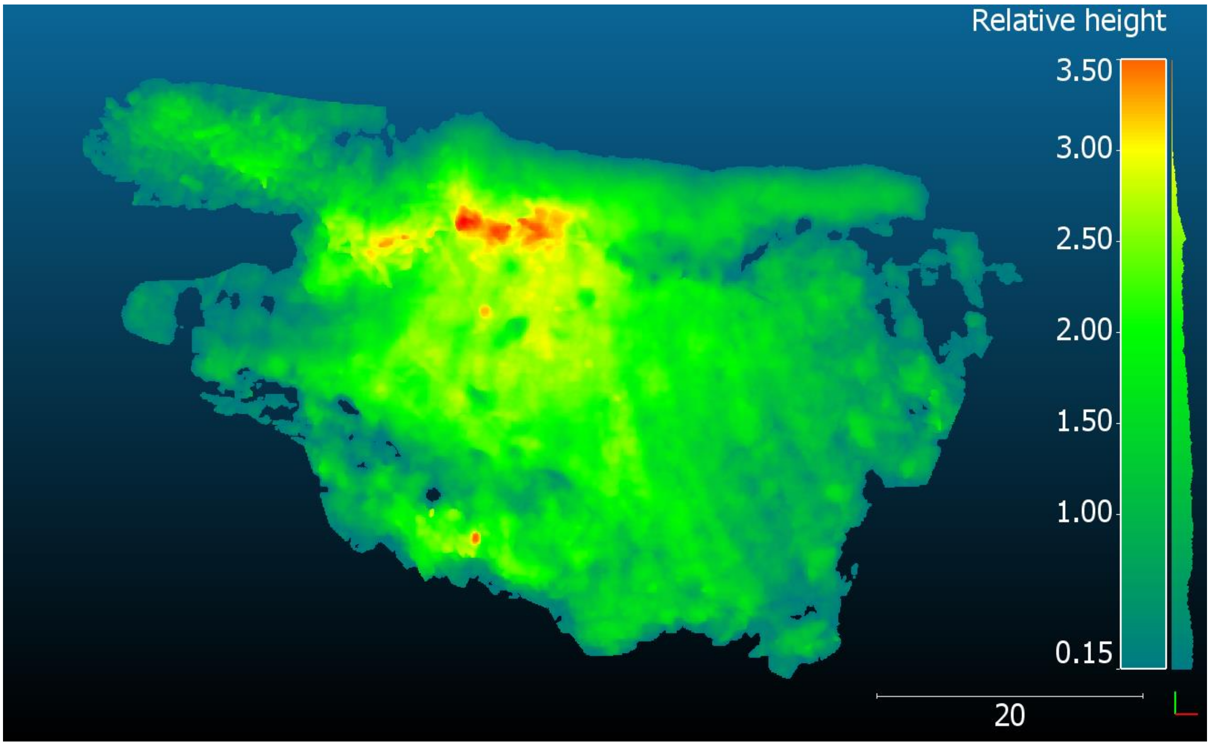


Figure 4-3: Full depth map of the residue pile, with the areas shaded in red exceeding the 3 m best practice threshold for fire risk.

DISCUSSION

This paper presents a modern and improved methodology for assessing the volume and depth of piles of harvest residues on any terrain, using tools that will be accessible to many foresters. Substitutes are also available for the hardware and software tools used in this example.

The methodology does not yield instantaneous results, with processing and model building taking approximately four hours in the office in addition to planning and carrying out each UAV flight and associated GCP waypoint capture. The total time invested may be one-to-two workdays for one person per landing. As such, this workflow has greater value when its use is targeted. Best use of this methodology (or similar) may be for monitoring large piles that develop over several harvests. An example can be a residue pile at a 'super-skid' where harvest volume is aggregated from multiple harvest coups and processed on the same site. Tracking pile growth over time would enable a forester to make informed decisions about pile rehabilitation efforts. Quality information may lower the chances of spontaneous ignition by incorrect visual assessments. As an extension of the result presented, georeferenced depth maps could additionally give direction to heavy machine operators carrying out pile rehabilitation, enabling accurate, efficient use of machinery and labour.

The methodology is not restricted to use on residue piles. It may be useful to foresters for other applications where storage of a material occurs on uneven ground, or where terrain changes occur such as river ag/degradation, earthworks, or quarry management. With any of these applications, typical current computing power limits the studies to relatively small areas at the point resolutions presented in this case study (100 ppsm). Related also to residue piles and the state of knowledge on self-ignition, the method provides an opportunity to combine with further study of pressure, humidity and temperature within a pile as the material settles and dries.

Two challenges to application of the procedure were noted during this case study. Firstly, without influencing the placement or management of the pile by the logging crew, the extent of the final pile can be difficult to predict during the initial flight and image capture of the terrain. This is evidenced by the studied pile extending over the boundary of the initial terrain model. The issue of eliminating performance bias may not be significant during the course of normal operations however, enabling some direction of the pile's management. The second challenge noted relates to roadline clearance of trees around the landing. Photogrammetry requires a clear line of sight from the camera to the ground from multiple locations to build an accurate terrain model. Occlusion of the ground by tree crowns (standing or felled) or dense undergrowth can require a terrain estimation procedure to be used, such as that embedded in Agisoft Metashape or CloudCompare (Zhang et al. 2016). Dependant on the complexity of the terrain, and the extent occluded, these processes may or may not be appropriate. Similar limitations are evident with aerial and ground-based LiDAR, but often to a lesser extent. While LiDAR pulses can generally penetrate vegetation to return ground points, the typical depth and density of landing residue piles is likely to preclude it from being any more use than photogrammetry in this application. One solution for occlusion of terrain at the future pile extents is to simply ensure an adequate roadline salvage boundary to enable the data capture – or to merge with existing LiDAR datasets (where available).

Consideration should be given to other factors also, if attempting to apply a similar methodology. Stationary machines, people or anomalies caught in the UAV photographs will be reconstructed in the photogrammetric model. These may be removed from point clouds manually by deleting points or by using a terrain estimation procedure; but at the expense of time and/or accuracy. Terrain forms can change between the capture of the first and second models due to machine tracking and soil settlement. The impact that terrain changes have on the results will vary and may not be easily measurable, except in the exposed, immediate surrounds of the residue pile.

Asides from aiding operational decisions, emerging biomass market opportunities may offer a secondary benefit for accurate measurement of the residue resource. Subsampling the production of woody residues in an estate could aid in building models of the volume (or the fraction of the volume) which could be supplied to biomass markets. While it is recognised that residue pile retrievals may be a localised, short-term solution while supply chains and harvesting processes adapt to faster uplift of log-making residues, this measurement approach enables data capture while those developments occur.

This case study highlights a question that inevitably arises with the increase in data resolution, especially where the research into spontaneous residue pile ignitions in New Zealand is sparse: what constitutes a pragmatic threshold for intervention to lower a pile’s height? Research into decomposition-related ignitions indicates that there may be seasonal, composition, moisture and density variables which all contribute to any one pile’s risk, and those change over time (Buggeln & Rynk 2002). The 3-metre target currently provides a pragmatic approach for foresters and loggers. Those variables that could better indicate ignition risk may remain impractical to monitor in New Zealand operations.

CONCLUSION

This case study has presented a methodology for monitoring the development of landing residue piles in relation to their depth and total volume. The methodology makes use of equipment and software that is increasingly available to operational foresters. By using georeferenced photogrammetry to create models of the landing surface prior to harvest, then again of the pile post-harvest enabled an improved calculation of volume (over previous methods), and also a depth map that could justify and aid pile rehabilitation efforts. With proper regard to the discussed limitations, the methodology can also be used for applications that require measurement of change over time; especially for complex surfaces such as the stepped landing formation in rolling/steep terrain as demonstrated in this case study.

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Chapter 5 – DELPHI SURVEY OF NEW ZEALAND FOREST INDUSTRY EXPERTS ON THE MANAGEMENT OF STEEPLAND HARVEST RESIDUES.

The following chapter has been published as a peer-reviewed Report by Forest Growers Research.

Harvey, Campbell (2022). Management of Harvesting Residues: Results from a Delphi survey of forest industry experts. FGR Report (FGR-057). 26 p. Rotorua, NZ: Forest Growers Research (FGR).

ACKNOWLEDGEMENTS

The results presented in this report reflect the opinions and experience of the group of forest operations experts at the time of the Delphi questionnaire, with subsequent analyses and interpretation by the author. We thank the participants for their contributions to this study.

EXECUTIVE SUMMARY

Woody residues that result from clearfelling steepland plantation forests present a significant opportunity for the New Zealand government's aim to de-carbonise the economy. The primary focus of plantation forest production has traditionally been roundwood, with woody residues commonly left on site to decompose, often due to limited market opportunities. The recent interest in woody residues, especially from sectors requiring fuel for industrial heating is relatively new to much of the plantation forest industry. The opportunity provided by this new biomass product stream has the potential to reduce risks posed by residue accumulations, improve profitability for the forest sector, generate employment for fuel processors and distributors and assist New Zealand in meeting its emissions reduction targets.

There have been several high-profile events where harvest residues have been entrained in floodwaters and debris flows. Already, many learnings from those events have been embedded in operational practice to better manage the risk of residue accumulations on steep terrain, especially around landings. However, there is an understanding that residues may remain uneconomic to bring to market for some forest owners. This research project explored the primary risks and solutions for managing those woody residues left on site.

A questionnaire was developed and administered using the Delphi technique. Delphi is used to arrive at a group opinion or decision by surveying a panel of experts. The survey was administered from July to October 2021. The questionnaire was circulated to around 40 forestry operations experts, of which 20 opted to be a part of the study. Questions were divided into five themes:

- General questions regarding woody residue sale activity and forecasts.
- Residues on the cutover.
- Residues in and around waterways.
- Residues at the landing.
- Alternative forest management options.

Two rounds of the Delphi survey allowed the participants the opportunity to form consensus on each of the questions. Results showed that 35 percent of the questions resulted in a simple majority, 58 percent resulted in a plurality (more people selecting one answer than any one other answer) and seven percent of responses resulted in no form of agreement.

The experts were either reserved or optimistic about the future of woody residue markets, with roughly half expecting demand to remain the same as present and the other half expecting greater demand on residues in the next five years. Extracting large woody residues (generally defined as >10cm diameter and >0.8m in length) from steepland cutovers comes at a cost. With current harvesting systems, the experts estimated the cost of harvesting would need to increase by $2.40 – $8.50 per tonne.

Risk of windthrow in adjacent standing crops drives many planning decisions in steepland forests and any future harvest coupe size restraints would be met with increased planning requirements, especially for wind on exposed stand edges, including bordering stands on gully-bottoms or consideration of differential silvicultural treatment at stand edges.

Regarding steepland landings, the experts advised that piles of residues on and around landings should be retrieved from slopes greater than 15-20 degrees and pulled back several metres clear of the fill edge. Benches installed around steep slope landings for retaining landing residues were considered appropriate, ensuring they remain visible along their full length and sloped inwards towards the landing (with drainage cuts to the out-slope).

Regarding the management of trees around waterways, sweeping of felling debris from cutovers to flow paths (primarily side gullies) was identified as a key risk in steep terrain. The experts cautioned that the solution is not solely riparian zone management, but this is part of a suite of debris flow risk reduction measures. A few windblown trees in a waterway or a floodplain can reasonably be left, but many in the same position would be cause for intervention.

Continuous improvement to ‘business-as-usual’ management techniques was favoured by the experts who took part in this Delphi survey. Managing woody biomass from harvesting, both as a marketable product or as residue from operations, requires a suite of best practices, whereby forest owners and managers must tailor a solution to the specific constraints of the site and environment.

INTRODUCTION

Harvesting plantation trees generates woody debris (harvest residues) at each stage of the process from the standing tree to the log truck. Woody residues can accumulate on the cutover or at the landing with the Whole Tree Harvesting (WTH) system that predominates in New Zealand operations. In contrast, for Cut-to-Length (CTL) systems, residue is more evenly spread on the cutover. Unintended stem breakage and delimbing accounts for a significant proportion of woody residue production. Somewhat unique to New Zealand is the relative absence of options for either selling or destroying woody residues that are both financially attractive and low risk.

Harvest residues have traditionally had negligible value (if any) to most small forest owners, or those with longer lead distances, regardless of where they accumulate on site. Where residues cannot be sold at a profit, management of the material follows 'best practice' whilst they decompose. However, specific to the management of residues, there is very little specific management guidance in documents such as the Environmental Code of Practice (NZFOA, 2009), except to ensure that any accumulation is contained and the risk of mobilisation is minimised.

The plantation forest sector is now seeing increasing demand for woody residues, particularly from industrial energy users (Pooch 2021). Noting however, that there are supply and demand imbalances at the regional level; woody residues that cannot be moved to market will still require some form of onsite management for risk reduction (Dale 2019).

As markets develop and best practice continues to evolve in New Zealand, various questions surround the appropriate management of harvest residues in steepland forests. The goal of this Delphi survey was to gauge the informed opinion of a group of New Zealand's harvesting operations experts, distributed across the country, in various roles and affiliations. For steepland plantation forests, the Delphi technique sought answers to some key challenges:

- What will it take to supply woody residues to a developing biomass market?
- Where are the opportunities for reducing the production and accumulation of woody residues?
- How should we manage residue accumulations to ensure they pose 'acceptable' risk?
- What alternative forest management options on steepland areas should be explored to improve environmental performance?

Chapter 5

METHOD

A Delphi process was chosen to administer the survey as: *"the problem does not lend itself to precise analytical techniques but can benefit from the subjective judgements on a collective basis";* and *"the individuals needed to contribute to the examination of a broad or complex problem have no history of adequate communication and may represent diverse backgrounds with respect to experience or expertise"* (Linstone & Turoff 1975).

The questionnaire was circulated to around 40 forestry operations experts, of which 20 opted to be a part of the study. While it is not implied that the group of operations experts who participated in this study have "*no history of adequate communication"* or "*represent diverse backgrounds with respect to experience or expertise*", the Delphi technique gives a framework for such communication which is particularly useful where the participants are large in number and are distributed geographically.

A series of questions was developed to explore the knowledge and perceptions of harvest residues among the group of experts as a collective. Questions asked the participants to either rate on a scale of 1-5, or give numerical answers (e.g., cost estimate in dollars), or provide validation (yes/no replies). Each question provided opportunity for a respondent to clarify in writing the reason for their position, and relevant questions provided opportunities for alternative answers for the group to consider in later rounds.

Seven initial questions were not part of the Delphi technique (that is, they were not intended for establishing any consensus), then 103 questions provided the participants with an opportunity to form a consensus. In the later rounds, respondents would be able to change their own answers from earlier rounds if convinced by the answers and/or justifications of the others.

Round One of the questionnaire was sent out to more than forty past and present forestry managers throughout New Zealand (deemed to be experts in forest operations). Twenty of those experts replied with completed Round One questions (50% response). Anonymity was maintained throughout to preserve the integrity of the Delphi technique, allowing participants to consider their positions without influence or concern of rebuttal for sharing personal opinions. The results were summarised from Round One, and individualised reports of their answers were returned to each of the twenty participants against those of the group.

In Round Two the same questions were asked again, providing each respondent with the opportunity to change any previous answers. Results of Round Two were returned by the participants and analysed, with only a few minor changes when measured against returns for Round One for any one question, therefore no further Round was undertaken.

By the conclusion of Round Two, 117 questions had been asked in total. The results presented in the next section are those received at the conclusion of Round Two, which was the end of the Delphi technique.

RESULTS

Below is a summary of the results of the Delphi process at the conclusion of Round Two. Note that questions referred to in the text are provided in the Appendix.

GENERAL (NON-DELPHI) QUESTIONS

The participants were either reserved or optimistic about the future role of steepland harvest residues as a product in the bioeconomy. Regarding Question 1: Over the next 5 years, do you anticipate the demand for forest residues in your region to increase/decrease/stay the same. Nine out of 20 respondents projected an increase in demand (45%), and 10 respondents (50%) predicted the demand to stay the same.

There was a wide spread of responses to the question regarding the potential difficulty of integrating biomass uplift into existing harvesting systems, and also the recent efforts on seeking/generating markets for harvest residues. This can reflect many things, but it is reasonably well established that market potential for woody biomass varies throughout New Zealand depending on supply, demand, and relative cost of competing energy sources (BioPacific Partners 2020; Hall 2017; Hall & Evanson 2007; Hall & Jack 2009).

What is clear, is that most participants (16 of 19, or 84%) have not recently measured harvest residue production, and therefore may benefit from assessing the available resource.

DELPHI QUESTIONS

The participants achieved a simple majority (>50% selected the same answer) and plurality (more participants selected one answer than the remaining answers) for most questions after two rounds of deliberation (Table 5-1).

Table 5-1: Overall measurement of consensus from the 103 questions that offered the opportunity for the declaration of a majority vote.

Simple Majority	Plurality	No consensus (no general agreement)
35%	58%	7%

MANAGING RESIDUES ON THE CUTOVER

These questions were designed to investigate the fundamental causes for harvest residue issues in steepland cutovers, some of the economics for their removal, and what aspects of harvesting operations can lead to lower residue loading on cutovers.

Under the presumption that uncontrolled residue movement from the cutover is most often a result of erosion processes, Question 2 asked: What are the indicators of a 'high-risk' landform? Participants agreed that 'historic slip scars', 'weak parent material when weathered' and 'steep areas with wetness on the surface' were indicators of high risk. Things that were not necessarily indicators of high-risk terrain were 'occasional butt-sweep' (referring to bent plantation trees) and 'early colonising vegetation'.

On regulation and its role in guiding harvesting activities, responses varied with no simple majority, except for Question 3 as to whether Regional Councils are offering guidance for reducing residue mobilisation risk (13 responded no and 7 responded yes) with almost every region of New Zealand represented in the group (noting that some participants operate over several regions). Question 4 asked: In relation to cutover residues, whether the National Environmental Standards for Plantation Forestry (NES-PF) are clear and pragmatic guidance. Question 5 explored the usefulness of the Erosion Susceptibility Classification (ESC) map as a proxy for residue mobilisation risk. Results offered no clear agreement or significant movement away from the centre. There appears to be little interest for finer-scale ESC mapping, but comments did support aerial LiDAR coverage for improved planning.

Extreme weather, triggering erosion processes has led to incidents where harvest residues mobilise uncontrollably, and this has been an area of significant research focus (Cave *et al.* 2017; Dale 2019; Phillips *et al.* 1996). Question 6 showed that most participants (14 out of 20) are aware of significant residue mobilisation events every year or so. The participants agreed (15 of 20) that there is a linkage between annual rainfall and residue mobilisation risk (Question 7). However, several comments made note that annual rainfall is *not* the major contributor to risk, but it is instead the infrequent 'weather-bombs' that put sites most at risk of mobilisation; with some respondents adding that 'low-rainfall' areas can be just as risky as 'high-rainfall' areas. Soils play a critical role in how sites respond to rainfall also. While the formal answer to Question 7 indicated agreement on annual rainfall being a risk indicator, the comments reveal that it is actually more a function of a site's exposure and response to *extreme* rainfall.

Soils, rainfall, and existing slope instability are agreed indicators of high-risk cutovers, but Question 8 explored: At what slope should mobilisation risk mitigation measures be triggered, above-and-beyond usual best practice? The interpretation of the question is important and may have led to the wide range of responses from as low as 15 degrees slope to 'would not consider reducing risk'. A plurality was reached for introducing risk-reducing measures at 30 degrees (6 out of 19 responses), followed by 35 degrees (4 of 19). With respect to interpretation, a landform that is identified as 'high risk' would/should have some mitigation measures applied as a function of normal harvesting practice (NZFOA 2007). 'High risk of mobilisation' may also be a measure generated internally (therefore not standardised across NZ) as the indication is that the NES-PF ESC map may not be regarded as a useful proxy (from responses to Question 5) at the finer scale at which harvest planning is generally completed.

Five specific risk scenarios were presented to the group to establish thresholds for intervention to lower the risk posed by windblown trees (e.g. also known as 'windthrow'). Responses to Question 9: "Under what circumstances should a forest owner/manager intervene to lower residue mobilisation risk posed by windthrown production trees during harvest?" showed general agreement. The group agreed that 'one or a few windblown trees in a waterway or within the floodplain' is not cause for intervention. However, 'many windblown trees in a waterway or within the floodplain' and 'many windblown trees on a high-risk slope' would require intervention. There was no clear preference 'where the windblown tree(s) are straddling a waterway, but above the 5% AEP flood level' or for 'a handful of windblown trees on a high-risk slope'. Some agreement on specific windblow scenarios is a good result as there is currently little formal guidance to establish a threshold for intervention. Even with a lack of formal guidance, the experts did have some common understanding on what that those thresholds for intervention should be.

Participants were asked to provide an indication of what aspects of terrain or harvesting do or do not contribute to high residue volumes on a steepland cutover (Question 10). Twenty separate scenarios were proposed with the group also given opportunity to add and rate their submitted scenarios. Of the initial 20 scenarios, three achieved simple majority, and 15 achieved a plurality. A summary of the questions where there was strong opinion of a factor being a significant contributor (maximum value of 5), or not a contributor (minimum value of 1) is included in Table 5-2.

Table 5-2: Contributors and non-contributors to high harvest residue volumes on the cutover.

Scenario	Majority/Plurality (Mode)	Group Average (Scale 1-5)	
Windthrow	Majority (5/5)	4.5	**Contributors**
Broken terrain	Plurality (5/5)	4.4	
Poor deflection or blind areas in the harvest area (cable harvesting)	Plurality (5/5)	4.2	
Negative returns on pulp grades (pulp left off cutting instructions).	Plurality (5/5)	4.1	
Production pressure on harvesting crews (incl. low margin on harvest rates, inclement weather or breakdowns - limiting production)	Plurality (5/5)	3.9	
Untidy stem set-out for extraction	None (4/5 == 5/5)	3.8	
High total recoverable volume of the stand (t/ha)	Plurality (1/5)	1.8	**Non-contributors**
Ground-based whole tree extraction	Plurality (2/5)	1.8	
Shovelling/bunching stems on the cutover	Plurality (2/5)	2.1	

The participants were asked additionally what scenarios contribute to low residue volumes on the cutover (Question 11). Again, the results where there was a significant departure from the centre are shown in Table 5-3. Of the 18 scenarios provided, eight achieved a simple majority and nine achieved plurality, indicating high levels of agreement. A positive return from harvesting pulp logs is a clear driver for extraction from the cutover. With negative pulp log returns a frequent occurrence where pulp value is accounted for in its own right (i.e., as opposed to averaging across all grades), the participants agreed that this is a significant contributor to residue volumes on the cutover.

With increasing local demand for biomass, increasing prices should help to ensure extraction of biomass suitable for pulp. Two new scenarios stand out in Table 5-3: with the group agreeing that company/forest owner cutover residue standards and fixed felling heads have a role to play in reducing cutover residue volumes.

Table 5-3: Contributors and non-contributors to low harvest residue volumes on the cutover.

	Scenario	Majority/Plurality (Mode)	Group Average (Scale 1-5)[1]
Contributors	Positive returns on pulp grades (pulp on the cutting instructions).	Majority (5/5)	4.6
	Clear company/forest owner standard(s) for permissible harvest residues	Plurality (4/5)	4.1
	Tidy set-out for extraction	None (4/5 == 5/5)	4.1
	Controlled tree falling (fixed-head mechanised)	Majority (4/5)	4.1
	High deflection over cable yarding corridors	Plurality (4/5)	3.9
Non-contributors	No significant departure from the centre on any scenario.		

Noteworthy, because its exclusion from Table 5-3 is the scenario 'minimised shovelling in the cutover' for which there was no significant departure from the centre by the group. Yet previously, it was established that 'shovelling/bunching stems on the cutover' did not contribute to high volumes. This may be a result of variable practice, or the various goals of shovelling and bunching operations. This practice may require more investigation into its impact on cutover residue volumes as mechanisation rates continue to increase amongst harvesting crews (Visser 2018). Overall, there was good agreement on what does contribute to lower cutover residue volumes, with common scenarios such as tidy set-out for extraction and adequate cable deflection, indicating relative consistency from the group.

Finally for cutover residues, insights were sought on the impact of large woody residue removals on harvesting operations. Woody residues are typically uneconomic to extract (McMahon *et al.* 1998) and well below the optimum piece size for New Zealand's mechanised and high productivity harvesting configurations. Mandating the extraction of residues from cutovers is expected to reduce harvesting system efficiency and therefore increase harvesting cost. There will only be an economic incentive for residue removal if the price paid for residues reflects the reduced efficiency of the harvesting system. Question 12 explored what that productivity drop (in tonnes per day) might be, and what the increase in logging rate (in dollars per tonne) would be expected to. Furthermore, Question 13 asked what price bin wood have to be (assuming a typical harvest setting in steep country and a 50 km cart to market) to make its extraction from the cutover financially attractive?

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[1] 1 = not a contributor, 5 = a significant contributor.

Figure 5-1 indicates the range of expected effects on productivity, incurred costs and prices that might incentivise extraction of residues from the cutover. For clarity, where a participant indicated a range of values, the mid-point was taken. The central 50% of results estimate that production rates will drop anywhere between 24 – 50 tonnes per day (11 responses) and increase the associated logging rate between $2.40 – 8.50 per tonne (10 responses).

The experts indicated they would be inclined to supply a market from a steepland forest at a 50-kilometre radius at a rate between $51 – 79 per tonne (16 responses). This includes additional harvesting cost, loading, bin wood transport and profit margin. For additional context on the markets at the time of the Delphi surveys, the diesel price was approximately NZ$1.50 per litre (MBIE 2021) and the weighted average A-grade export log was NZ$182 /JAS f.o.b. for the June 2021 quarter (MPI 2021). Regional differences in harvesting rates and biomass demand are evident, much like the variable log markets. However, these are useful starting points for assessing the effect of additional demand on harvesting resources and how that may contribute to market price equilibrium in the biomass market.

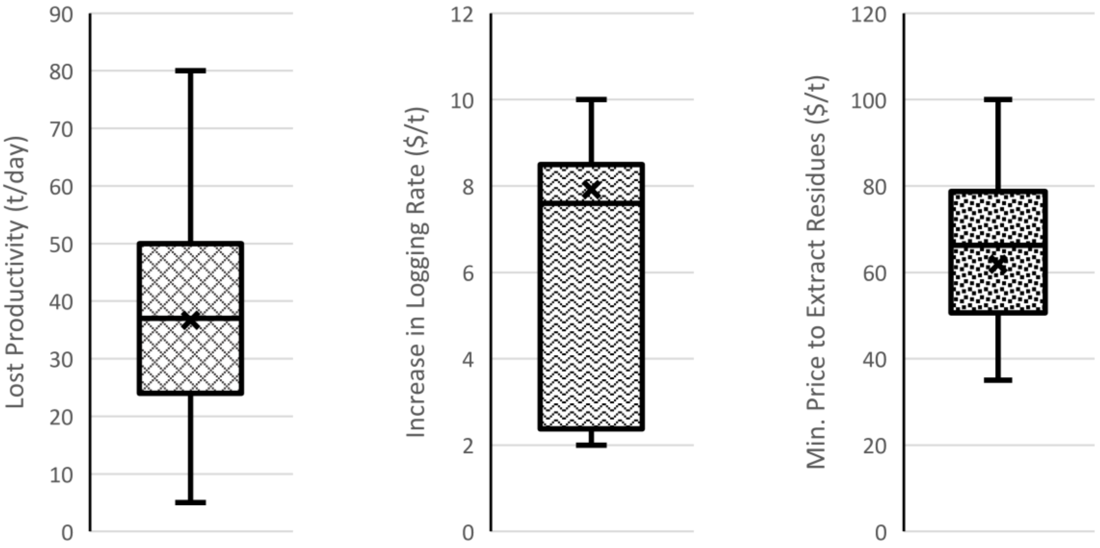

Figure 5-1: Left - Estimated lost productivity in tonnes per day by extracting residues from the cutover. Middle - Estimated increase in logging rate required to offset the reduced productivity of extracting residues from the cutover. Right - Estimated minimum residue value required to make extracting the material financially attractive.

MANAGING RESIDUES IN AND AROUND WATERWAYS

Residues located in waterways are arguably one of the more immediate and quantifiable risks for biomass mobilisation in many forests. Understanding the drivers of streamflow peaks during extreme rainfall events has progressively improved (Henderson *et al.* 2018), and this information increasingly underpins planning decisions. Forested terrain that is steep and broken, or simply extremely steep, has fundamental challenges associated with full suspension over the waterways, as well as system productivity for highly mechanised harvesting systems. For a logging contractor and forest owner, this can present profitability challenges while also protecting soils, waterways and worker safety.

The participants considered four questions on the management of residues around waterways.

Question 14 asked the group what mechanism typically delivered the most residues to waterways? Half the group selected ‘sweeping of felling debris during extraction’ (a plurality). This is a mechanism whereby the cable harvesting system will span over felled trees, pulling the stems from the cutover towards the yarder landing. For cable harvesting, to optimise tension in the wire rope cables and the payload on the cables, the stems are most often extracted under a ‘partial suspension’ condition, meaning cable tensions are reduced and that part of the stem drags over the ground. Partial suspension can result in a sweeping action when the stems move downhill, pulling debris (branches and broken tops) down with them, which can be exacerbated by side-hill conditions (i.e., where the direction of pull is parallel to the contour). A second consideration in cable harvesting is one of lower environmental impact. Cable harvesting is considered ‘best practice’ on steep slopes compared to tracking for ground-based harvesting due to the relative risks associated with soil disturbance (FITEC 2005). Winch-assisted ground-based operations also often ‘shovel-log’ felled stems downhill, which tends to accumulate woody residues along the path of the shovelled stems in a similar manner to partial suspension cable harvesting.

The second most frequent choice of mechanism that typically delivered the most residues to waterways was ‘slope failures (landslide)’. Of 20 respondents 5 selected this mechanism, reflecting the known fragility of steep terrain and its linkage with residue mobility.

The remaining three questions sought solutions from the participants.

Question 15 asked to what extent should a riparian buffer be relied on as a tool to mitigate the movement of cut-over residues to waterways?

A majority was reached on the question on using riparian strips as barriers to harvest residue movements to waterways. The group was neither strongly in favour nor opposed to the functional use of riparian strips (3 of 5, majority reached). In comments, several respondents noted that riparian strips are a last line of defence or that they cannot be relied upon, with one noting that riparian widening and structural reinforcement via planting of Redwoods (*Sequoiadendron*) is being trialled to improve the effectiveness of the riparian zone for the next harvest.

Question 16 related to managing legacy plantings right up to watercourses in erosion-prone, steepland forests. What is typically the most appropriate course of action at harvest? On managing legacy plantings right to the water's edge, two options were strongly favoured. Overall, the preference of the participants was to allow some form of flexible management approach – rather than a 'one size fits all' rule. The most favoured option (9 of 20 selected) was to: *"Apply mixed management. Fell and extract trees from riparian margins where operations can ensure minimal impact on streams. Abandon areas where harvesting impact on streams may be unacceptable"*. This approach allows some discretion by planners and fit-for-purpose management under the set of site-specific constraints.

The second most popular choice (7 of 20 selected) was to: *"Harvest all trees from riparian margins; leaving high stumps strategically and managing impacts on the stream and area covered by a 5% AEP flood".* Those respondents who selected the second option may hold the belief that any abandonment of standing trees in the riparian margin carries unacceptable risk. Isolated standing trees, while being a high probability to windthrow, are also a significant hazard during harvesting, aerial spraying operations, and other subsequent silvicultural operations. With clearly divided opinion, this presents an opportunity for further clarification through structured research.

The final opportunity to suggest a solution (Question 17) asked the participants to define a practical, robust, and defendable interpretation of a waterway from which slash should be removed? The NES-PF currently adopts the waterbody definition from the Resource Management Act 1991: '*water body means fresh water or geothermal water in a river, lake, stream, pond, wetland, or aquifer, or any part thereof, that is not located within the coastal marine area*' (RMA, 1991).

The definition of a 'river' is nested within 'waterbody' and includes *'intermittently flowing fresh water*' (RMA, 1991). Establishing the starting point for a waterbody, that would flow as a 'river' during an extreme rainfall event, is essential to the proper application of the standard. These definitions have the potential to cause issues for foresters, contractors, and regional councils alike as it is difficult to give practical, pragmatic direction to harvesting contractors when the extent of the rare, ephemeral waterbody is unknown.

Opinion was divided amongst the expert participants. The most support was for defining a minimum catchment size (e.g., 3 ha) to be the starting point of a waterway (5 selected of 18 – a plurality). The application of this would be a simple GIS analysis and re-mapping of waterways (for the purposes of debris clearance). Four opinions each were given to adhering to existing national spatial datasets: the Ministry for Environment (MfE) River Environment Classification, or the Land Information New Zealand (LINZ) New Zealand River Centrelines datasets. Both MfE and LINZ datasets are known to have their respective differences but are widely used, regardless of their limitations.

Some comments noted that little is known about the flow rate or flow speed that is required to mobilise woody material, and that should have some bearing on the start point of a flow path that requires clearing of debris. One respondent queried whether under extreme rainfall conditions (e.g., 5% AEP) even water table drains on roadways may be considered waterbodies, implying that some reasonable interpretation of the standard is necessary.

Overall, a standardised map-based solution was the preference of the participants that allows clear direction to planners, contractors, and councils.

MANAGING RESIDUES AT THE LANDING

Piles of woody residues, consisting of bark, branches and off-cuts continue to accumulate at forest landings and remain long after time of harvest. An increase in demand for biomass is expected in the coming decade due to the monetisation of greenhouse gas (GHG) emissions from burning non-renewable fuels such as coal and gas. Increased demand provides the opportunity to reduce the volume of residues stored at landings. However, there remains a need to effectively manage the material.

An open market for biomass will ensure that the lowest cost and most accessible material will be preferentially collected. It may be that under some market conditions, industrial-grade logs (such as pulp and bin wood) will be re-directed to biomass markets rather than to export and domestic fibre markets, in preference to lower-quality, lower-quantity (and higher cost) landing residues. This means there remains a need for forest managers to plan and manage residue piles, with current guidelines and standards remaining subject to continuous change.

Similar to the section on cutover residues, the group was given a list of 23 factors that may or may not contribute to high residue pile volumes at the landing. Question 18 asked respondents to rank each factor on a scale of 1 (no contribution) to 5 (significant contribution) on its contribution to high residue volumes at the landing. Majority agreement was reached on five factors, with pluralities established for the remaining factors. Table 5-4 summarises the four factors that resulted in a significant shift away from the centre. Failing to make positive returns on pulp logs featured again as a major contributor to high residue volumes, indicating that the group felt strongly that this drives residue accumulations.

Table 5-4: Contributors and non-contributors to high harvest residue volumes at the landing.

	Scenario	Majority/Plurality (Mode)	Group Average (Scale 1-5)
Contributors	Negative-returning pulp grades/pulp left off cutting instructions	Majority (5/5)	4.5
	Environmental crop damage (e.g. hockey-stick butts, snow damage)	Plurality (5/5)	3.9
Non-contributors	Bunching stems on the cutover	Plurality (2/5)	1.8
	Clearwood tending regime (low stocking and pruned)	Majority (2/5)	2.2

Crop damage from the environment (such as snow damage) fell into a similar category. Stem defects (such as excess sweep or large knots) are seldom allowable on sawlogs; therefore, pulp or chip grades are usually the only remaining avenue for sale. Bunching stems for extraction is a method used for increasing the efficiency of the extraction operation and the participants tend to agree that it also reduces landing residue volumes. Bunched stems tend to be better aligned for ‘breaking-out’, resulting in less breakage during extraction. Reduced breakage in turn reduces the need for cutting off waste sections for a ‘flush’ log-end; a typical specification of sawlog grades.

The final factor that does not contribute to landing residue volumes as indicated by the group (by majority) was a ‘clearwood’ tending regime, where the stand is pruned and thinned to a lower final crop stocking (i.e., fewer trees per hectare) than ‘structural’ regimes. Earlier research has established that larger diameter trees (as typical of the clearwood regime) tend to result in higher breakage rates on felling (Murphy 1982). However, the clearwood regime also results in fewer trees per hectare. The participants observed that this combination of factors does not result in increased landing pile volumes over the alternative ‘structural’ regime.

Solutions and clarification to known issues were asked of the participants, with most attaining either a majority, or improved clarity.

Question 19 asked whether the forest industry should continue to allow the incineration of residue piles? The group responded firmly yes, that burning needs to remain an available tool, but in the knowledge that it does carry risk.

The remaining seven questions in this set considered engineering controls and specific thresholds for residue storage.

Question 20 asked whether piled residues may be stored permanently on unmodified slopes, cuts or compacted fill slopes up to what maximum slope? On storing piles permanently on sloped ground, 12 of the 19 responses were divided between a maximum of 15 to 20-degree slopes. The preference (8 of 19 selected) was to store piles of residues permanently on slopes no greater than 15 degrees (Figure 5-2).

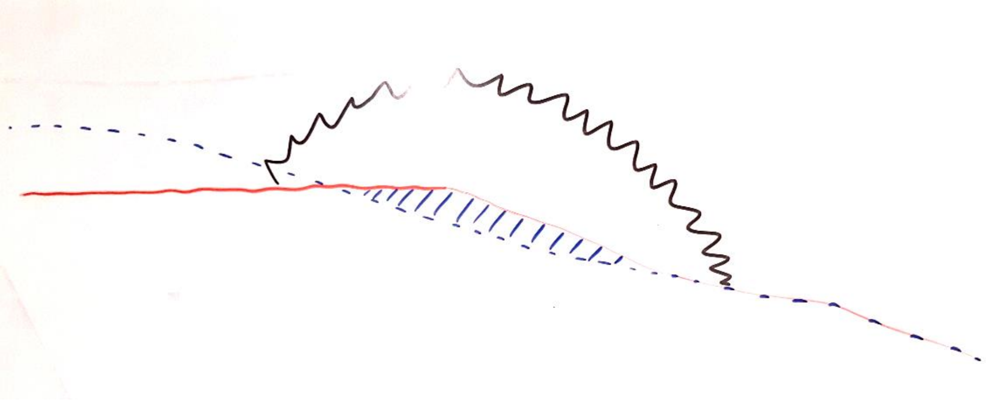

Figure 5-2: Residue pile stored on a fill slope, including over fill sections.

Question 21 asked whether the pile should be pulled back, clear of the fill-edge on slopes steeper than the limit given in Question 20. Results showed that the majority responded, ‘yes’ (18 of 20). Question 21 related to the respondent’s own selection of maximum slope, not the average of the group, however the message is clear that (a) if the rule is exceeded, then (b) pull all the residues back off the slope.

Question 22 asked if the response to Question 21 was ‘yes’, what minimum separation from the fill edge is appropriate for effective risk reduction? When piling residues on landing surfaces, the participants offered mixed opinions on separation from the landing edge. There was no majority answer from the group, however 15 of 18 responses replied between 2 – 4 metres of the fill edge, which is approximately the working corridor (i.e., track width) needed for an excavator.

In the comments there were some caveats. More than one respondent had little faith in the strength of earth fill with the added surcharge of residue piles, stating or inferring that it would be prudent to place residues on flat cut surfaces (commonly referred to as 'on the hard').

Installing benches below and around landings to hold residue piles and minimise their cumulative impacts on harvesting operations is common practice. How benches are designed and/or utilised is thought to divide opinion amongst forest practitioners. However, this Delphi process has established that there is a degree of commonality among expert opinions.

Question 23 asked whether benches should remain visible along their full length. The group agreed (16 of 19).

Question 24 asked which method is most appropriate for constructing slash benches in steep terrain? For construction of slash benches, a majority (11 of 20) agreed that the most appropriate geometry of a bench includes a surface sloped into the terrain, with cuts installed though the raised outer fill for drainage (Figure 5-3, left). Five additional responses agreed that the in-sloped method is valid, but also accepted an outward sloping bench (Figure 5-3, right).

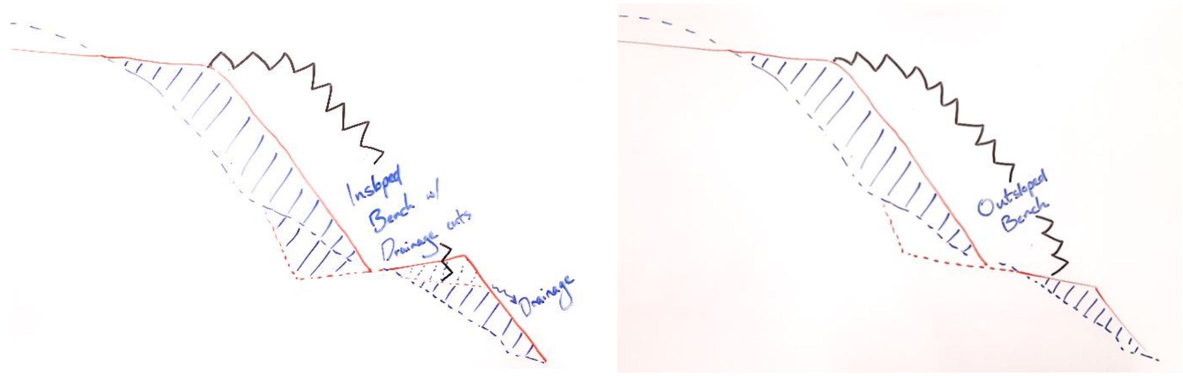

Figure 5-3: Example sketch of and in-sloped (left) and out-sloped (right) slash bench for the storage of residues adjacent to the landing.

Question 25 asked whether 'pocket benches' (Figure 5-4) are acceptable as an off-landing slash storage solution? A majority agreed that 'pocket benches' are an appropriate engineering control, although Question 26, relating to the conditions where a 'pocket bench' is inappropriate, found these were areas… “prone to sheet-slip type landslides” (13 responses), also “in locations prone to groundwater seepage through soil layers” (12 responses) and “where the pocket (‘trench’) is dug into weathered parent material” (5 selected). In the steepland forestry context, land that exhibits one or more of these attributes is very common (to almost ubiquitous) therefore the use of the ‘pocket bench’ may be limited to isolated scenarios only.

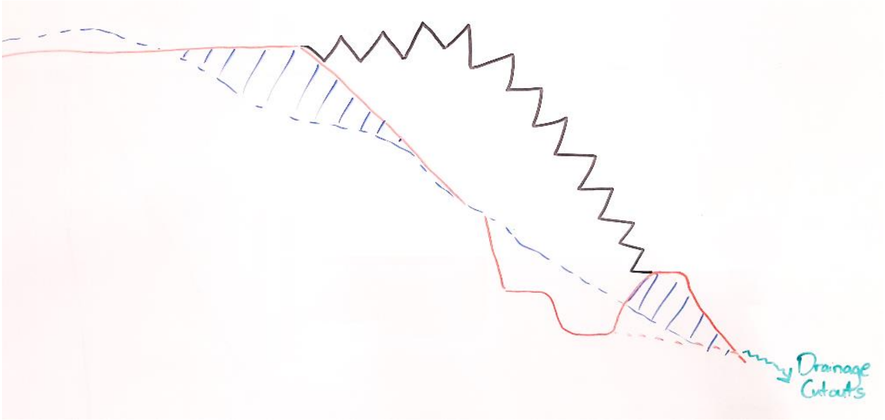

Figure 5-4: Pocket bench supporting a residue pile, with cut-out drains.

By aggregating responses to the questions from this section, the group view was to retrieve the residue piles from the benches shown in Figure 5-3 and Figure 5-4 post-harvest, due to slopes being steeper than the threshold of 15-20 degrees. If stored permanently, those retrieved residues would be located a minimum of 2 and 4 metres from the fill edge – or beyond the fill/virgin ground boundary. The merits of incinerating the pile(s) should also be considered versus the risks (fire, emissions, impact on the public etc.).

ALTERNATIVE FOREST MANAGEMENT OPTIONS

The final section requested the group to consider ‘big-picture’ solutions as plantation forestry moves forward into the future.

Question 27 explored how effective respondents believed an industry-wide transition to alternative, coppicing tree species on ‘high risk’ sites could be for reducing (but not eliminating) the frequency of post-harvest landslips? A move to coppicing species on steep slopes for erosion control was not strongly favoured or opposed by the group with an average rating of 3.2 (of 5). Comments included some concern about the market risk of such a change. With forestry being a long-term investment the risk of ‘going it alone’ at medium-to-large scale in any one region is significant. The worst-case-scenario is to pass on a stranded asset to the following generation. Radiata pine is a proven performer as a plantation species and as timber, with typically acceptable return on investment, well-developed markets and existing domestic milling infrastructure. Large scale conversion from plantation management carries significant risk for any forest owner without an industry-wide move (e.g., combined direction from other large forestry entities).

Question 28 explored the options of New Zealand harvesting practices trending toward smaller harvest coupes and boundary or adjacency constraints (such as waiting to harvest the adjacent coupe for some years). The New Zealand plantation forest industry could put logical limits on harvesting coupe size in alignment with standards elsewhere in the world (Visser *et al.* 2018). This aims to limit the exposure of a large, forested catchment to the 'window of vulnerability' between harvest and adequate re-establishment of the next crop (Phillips *et al.* 1996).

One real concern with this proposal from industry has been about the increased windthrow on the boundaries of the harvest coupe. It is conceivable that increased windthrow could lower productivity from forests, exacerbate safety issues, increase residue generation, and impact slope stability negatively due to the weight of windthrown trees on fragile soils.

Question 28 asked respondents to suggest possible solutions for reducing the incidence of stand-edge windthrow in steep terrain? The results are given in Table 5-5.

Table 5-5: Possible solutions to the issue of stand-edge windthrow by reducing harvest coup size in steep terrain. Participants were encouraged to select all that may apply.

Possible Solution	Number of Selections
Plan coup boundaries with the prevailing wind in mind.	16
Coup boundaries on the gully-bottom where possible.	7
Alternative silviculture on planned coup boundaries, i.e. retain higher (or lower…) stocking where future exposed boundaries will be.	6
Plant the borders of coups with more wind-firm alternative species.	4
Full transition to alternative, more wind-firm species.	3
Monocultural coups but differing species in adjacent coups.	2
Mixed species coups.	1
Participant Submission: **Harvest plan whole catchment area and take out full settings at higher altitudes and leave the lower areas for X years.**	1
Participant Submission: **Almost any of the options may help at the margin.**	1

Consistent with the suggestions about alternative species, there is preference for a variation of current practice, without changing species. Planning to locate coupe boundaries along 'lower risk' edges and improving the wind resistance of the new coupe boundaries through differential silviculture were the clear recommendations from the group.

Finally Question 29 asked respondents what is best for the forest industry as-a-whole in terms of an individual owner's or a company's freedom to assess, manage and be accountable for the slash mobilisation risk, on a scale from 1 to 5. A rating of 1 corresponded to: The assessment of risk and setting of operational restrictions should be at the governance level. A rating of 5 corresponded to: The management of and accountability for slash mobilisation risks should be held at the individual or company level.

The majority (11 of 20) selected a 4 out of 5. This result has been interpreted as meaning that the group of experts felt that the skills and experience required to manage residues along with other aspects of the forestry business lies within forest companies (i.e., the forest industry) rather than with the regulator (territorial authorities such as Regional and District Councils). However, this response also recognises the key role of oversight by the regulator as the majority was not ranked 5 out of 5. Comments from respondents confirmed this. It was recognised that both groups (the industry and the regulators) coexist and need to bear their own responsibilities to mitigate environmental and safety risks effectively.

Chapter 5

DISCUSSION

This Delphi survey is a useful benchmark that establishes a sample of the forest industry's collective consciousness for many of the challenges that harvest residues present currently as the biomass market develops. It has not been completed in isolation. Significant work has been completed by the University of Canterbury (UC), Energy Efficiency and Conservation Authority (EECA), Bioenergy Association of New Zealand (BANZ), Scion, and individual biomass suppliers and processors at various parts of the forest biomass supply chain. Some large forest owners have also formed direct partnerships with early adopters of biomass utilisation for process heat, and with intermediaries such as large fuel suppliers.

This research recognises that demand from the developing biomass market is unlikely to perfectly match the forest industry's ability to supply forest residues. Harvesting volumes will continue to respond to the log markets, regional age-class distribution, and contractor availability. Demand for woody biomass will show seasonal variation and respond to relevant market conditions (i.e., for commodity log products). With the dynamics of an open market, there will likely be forests where the costs (at the time of harvest) to extract, collect, process, load, and transport forest residues to end users will be too high to meet the market price (based on the energy content of the residues). This is evident already with the participants of this Delphi process indicating that the returns on chip and pulp logs directly influence residue volumes available on the cutover and at the landing. Log export market demand for logs of lower specification will play a key role in establishing the price ceiling for landing or cutover residues.

Another factor that has been the focus of much study overseas, and with some case studies in New Zealand, is system efficiency for extracting, processing, loading, and transporting forest residues. With low margins for the product (typically), system efficiency is critical to ensure economic viability. What has not been the focus of any significant local study in New Zealand is the indicative cost of retrieving residues from the cutover. In order of economical preference for sources of residual woody biomass this is the last option however, with the preferred order being:

1) Billet wood, made during log processing
2) Landing residue piles (bin wood)
3) Large diameter/long length cutover residues

With diesel prices around $1.50 /litre during the study (MBIE 2021), the survey participants indicated that a harvesting rate increase would be required (Figure 5-5) to justify the reduced harvesting productivity from extracting residues down to 0.8 m in length and 10 cm small end diameter (SED).

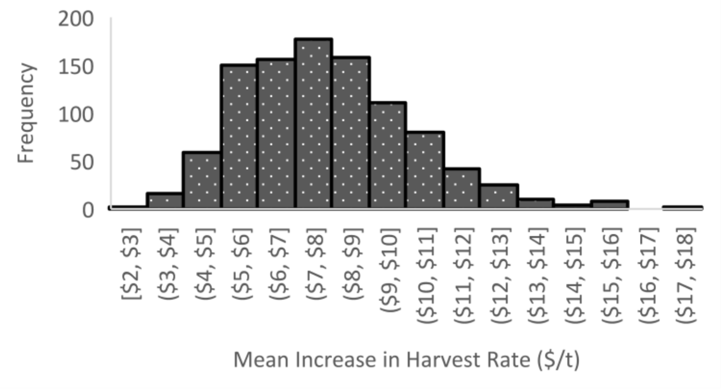

Figure 5-5: Bootstrapped mean harvesting rate increase in dollars per tonne as indicated by the group.

Figure 5-6 relates this increase in mean harvesting rate to the increase on the price of diesel, as diesel fuel makes up approximately 15% of a harvesting crew's daily cost (inferred from Forme 2019). It is anticipated that a 'fair' price for woody residue material from the cutover will reflect the original harvesting rate, plus the increase in harvest rate (Figure 5-5), plus the costs of comminution and distribution (plus profit margin). The relative cost price ceiling for low-grade export logs should be a function of the market price of the export logs (At Wharf Gate), plus the cost of comminution. A factor should be added for the gain in recovery rates (allowing for lower specifications), plus any additional distribution and handling costs (for the extra processes in the supply chain). Consumers' willingness to pay export log price equivalent and overall process efficiency remain the most critical elements to drive the utilisation of any woody residues. The most controllable element for any forest owner and contractor remains process efficiency.

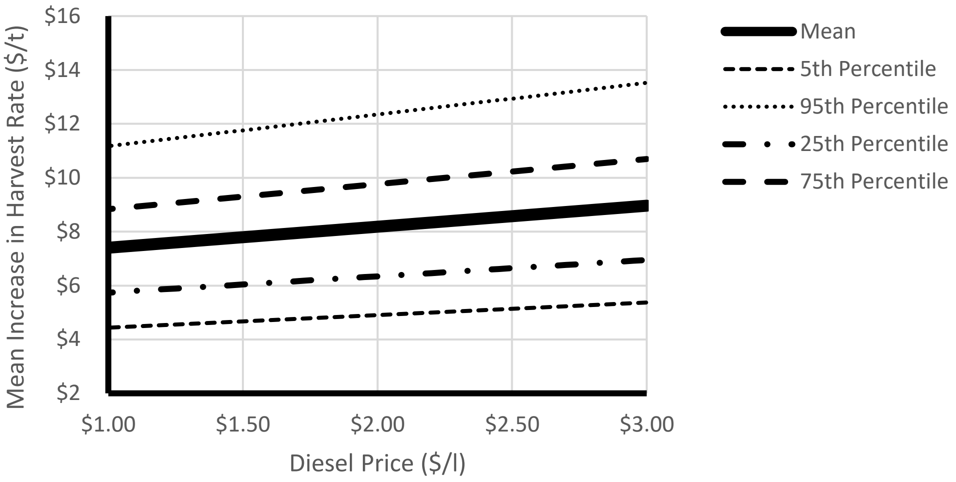

Figure 5-6: Sensitivity analysis on the mean increase in harvest rate required (as indicated) to extract residues from the cutover against diesel price at a typical rate of 15% of daily system cost.

The opportunities that the expanding domestic biomass market offers the forest industry are many and varied. Not only can biomass potentially add to the profitability of forestry, but it has the potential to reduce the risks of storing the material on site post-harvest and add to regional employment throughout the value chain. For most steepland forests there appears to be few drawbacks to extracting residual biomass to meet the country's energy needs (with a decarbonisation focus) and remain competitive.

A healthy, functioning biomass supply chain and strong market demand for residues however is unlikely to eliminate harvest residue accumulations across all harvesting sites or regions in New Zealand. Because of the dynamics of log and residue markets and anticipating the need to retain harvest residues on many cutover sites (as is the status-quo), the current focus on continuous improvement for onsite residue management should continue.

In 2019 the NZFOA reported on many of the immediate issues resulting from storm events in a workshop with industry representatives (Dale 2019) which resulted in several priorities for further action. This Delphi survey has approached the key issues differently to the 2019 NZFOA report with specific cases and thresholds for intervention put forward to assess whether industry experts form collective agreement on certain regular occurrences and practice.

The Delphi technique tends to be effective because of its anonymous nature. Participants can equally give reasoned opinions, in their own time, free of influence or fear of causing offence, whereas those opinions may not be possible in a face-to-face workshop setting. Anonymity in the process also eliminates concern of reprisal for putting forward personal opinions; however, this does require confidence in the administration of the Delphi process. The results presented in this report do remain subjective, formed of the opinions and experience of the participating forest operations experts.

The Delphi results and the NZFOA report share several commonalities, showing consistency of industry opinion over time and under different circumstances. Market options for biomass extraction remain a priority with the potential to provide tangible and intangible benefits all along the value chain. Smaller harvesting coupe sizes for Radiata pine, whilst being a proposed solution for hydrological variations over a rotation in a large catchment, and also reducing risk for catchment-wide disasters, remain unpopular due to commonly observed windthrow on exposed stand boundaries (and associated safety/soil stability issues).

Tree falling with mechanised felling heads has been an area for investigation with both the 2019 NZFOA report and the experts during this Delphi process identifying felling head technology as having potential for reducing cutover residues. Two published studies have verified informal accounts of the benefits and drawbacks of fixed felling head trials in steepland plantations (Prebble & Scott 2019, Prebble 2021).

Cutover residue accumulations in and around watercourses have been a significant challenge with planting across watercourses without setbacks affecting today’s harvests. Best practice has established methodologies for minimising impacts; however, some conflict inevitably results with other best practices (such as minimising earthworks), and the need to accommodate heavy machinery. Continual reassessment of best practice is required due to the adoption of new, mechanised harvesting methods. The group’s responses reflect the progressive nature of best practice, indicating a clear, collective preference to manage as considered lowest impact for the specific individual site.

In 1999, a survey was circulated amongst eleven forestry companies on the management of logging slash in streams and also debris flows (Baillie 1999). The survey gathered 19 responses, covering the management of approximately 60% of New Zealand’s plantation estate at the time. Most respondents used stream size or flow type (ephemeral/perennial) to determine the slash management practices applied for a given reach. To minimise slash entry into a stream, cable yarding systems used skylines, carriages, gully to ridge extraction, full (or partial suspension) & directional felling. One further development as a result of this study is that respondents have identified log ‘sweeping’ during cable extraction as a key driver for high residue volumes in gullies – indicating that partial suspension may be beginning to fall out of favour in key scenarios.

Landing residues represent the most convenient and readily available material to supply a biomass market. It is clear however, that not all sites will have the ability or economic viability to supply the new market. The Delphi process has both highlighted differences in opinion and also broad consensus on managing piles of material at the landing where it cannot be marketed. Of particular note is the experts' opinions of the temporary nature of off-landing residue containment structures such as benches and pocket-benches, in steep terrain. The results of this study infer that terrain steeper than 15-20 degrees is unsuitable for the permanent storage of residue piles. The result is significant and consistent with the NZFOA report by Dale (2019) as steepland forest land regularly exceeds 20 degrees slope in New Zealand and benching for residue piles is a regular part of steepland harvest management. The inevitable result is that many or most residue piles would require retrieval onto the flat landing platform post-harvest.

The Delphi technique did not seek consensus on new ways of work to improve the extraction of woody biomass. With the experts generally expecting the same or increasing demand for forest residues, and industrial energy users issuing similar signals (Fonterra Co-operative Group Limited 2019; Pooch 2021) optimisation of biomass recovery at the landing is expected in future. Should demand for woody biomass increase, it may become a regular part of logging across New Zealand's steepland forest estate. Loading 'hook-bins' for uplift during harvest, sorting and piling to load onto 'bin-trucks' and retrieving piles post-harvest are currently methods being used in the pursuit of improved harvest efficiency.

Woody biomass quality (i.e., contamination with bark, rock, sediment, and other impurities) and the moisture content of biomass are key foci for current bioenergy customers, in addition to volume and supply security. Therefore, the problem posed is, how does a forest owner and logging contractor provide a biomass product to agreed specifications for acceptable profit (or minimised cost) while ensuring adherence to the core business of producing quality roundwood products? Further (or more widespread) demand for the product may initiate a step-change in harvesting systems to handle log and residue products more efficiently. Centralised and automated processing and sorting facilities are one such proposal (FGR 2020). While biomass extraction process improvements remained outside the scope of this Delphi process, investigating a variety of options will be critical to ensuring that the more remote plantation forests are accessible for woody biomass utilisation, thereby improving the industry’s ability to supply increasing demands from the existing forest estate.

Chapter 5

CONCLUSION

Using the Delphi questionnaire approach in this study has been effective in discussing a series of complex challenges for managing harvest residues with experts of varying professional experiences. The system of inquiry has enabled the participants to interact in a structured way, allowing clear justifications in response to the questions.

A significant proportion of the experts shared optimism for the evolving biomass market. Several hurdles necessitate market, engineering, and harvest system solutions to enable biomass products to be marketed from more remote steepland plantation forests.

The operations experts tended to prefer a continuous improvement approach to changing the management of harvest residues. Tools such as the NES-PF ESC map provide coarse risk identification, and it was the opinion of the group that aerial LiDAR is more useful for operational planning, with its finer resolution.

Wind-firmness of plantation trees remains a widespread concern that informs many harvest and forest management decisions. Careful stand boundary planning (for prevailing wind) or differential silviculture to protect exposed edges has been recommended by the group. Aside the known limitations of Radiata pine, it has been a successful plantation tree species. Therefore, suggestions of planting alternative species at scale has drawn little support from the group. Developing current harvesting standards is a more favourable approach.

Where landing residues cannot be marketed, retrieval of piles is recommended for slopes over 15-20 degrees, regardless of engineered controls such as benches. Incineration of residues as a method of disposal where there are no economic solutions should remain an option where appropriate.

Riparian buffers are supported as a partial solution to reduce the occurrence of woody debris entering waterways but are recognised as being a partial barrier only used in conjunction with other best practice methods, such as reducing generation of residues, and maximising extraction and utilisation of woody biomass. The Delphi process has confirmed that best practice for residue management comprises a suite of management options which allows foresters to cater to the individual risks and needs of the specific site.

The New Zealand forest industry has extensive research, comprising operational knowledge and experience for the management of Radiata pine plantations on steepland sites. The experts polled in this study should continue to build on the findings of this survey, to increase supply of woody biomass for new markets and continue to meet the challenges posed by steepland forest sites.

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Chapter 6 – THESIS CONCLUSIONS.

This thesis aims to provide information and tools to help improve the management of harvest residues in New Zealand's steepland plantation forests. Harvest residues are a prominent example of a resource with competing interests – not simply the traditional form of multiple end users demanding resource (which is increasingly the case), but competition also comes from biological systems (soil and freshwater) for nutrients and nutrient cycling, forest management (e.g., replanting and releasing impedance), erosion control and harvesting efficiency (and safety). Finding balance between these competing interests on each harvest site is intrinsic to the sustainability of plantation forestry as a land use and will continue to be the subject of ongoing research.

The objectives of this project are practical and pragmatic, intended to give the research relevance to harvesting professionals and academics alike. In fulfilling the objectives of the thesis, results and methodologies may be utilised and/or improved-on by industry, ensuring continual progress in the field of harvest residue management.

Objective 1

Objective 1 set out to establish a methodology for accurately and economically sampling the volume of large woody residues remaining on steepland sites, then use that to understand the distribution of volumes on steepland sites across New Zealand. The methodology was developed to satisfy some key constraints. With the minimum large woody debris (residue) diameter of 25 mm and the tendency for residues to form piles in the cutover, manual LIS was appropriate, with modifications to reduce orientation bias (bias from residues being pulled into alignment, typically in the direction of pull), and improve efficiency. Orientation bias was reduced by introducing a 'trigonal-planar' shaped plot. To improve data collection efficiency and owing to the relative abundance of residue material <50 mm in diameter, only material >50 mm in diameter was measured beyond 5 m horizontally along each transect, starting from the central point.

The theory for the Line Intersect Sampling methodology is underpinned by research use, inside and outside the field of forestry. It is practical and can realistically be used by foresters to collect data on the residues produced in any forest, physically or remotely. Refinements can be made to suit specific objectives such as investigating for recoverable woody residues only.

This research revealed that the median volume of large woody residues distributed across the selection of cutovers studied is 88 m^3/ha. Residue loading on cutovers also varies substantially. That residue distribution is right leaning with areas represented from a minimum of 0 m^3/ha (bare of large woody residues) to maximum of 580 m^3/ha (indicative of un-salvaged windthrow). Investigating the abundance of woody residues that are 'potentially merchantable' but not recovered to the landing shows that large material that could have been a log (pulp or higher specification) accounted for a median of 11 m^3/ha, with the recoverable pieces being a median of 6.4 m long and 180 mm diameter at mid-length. Shorter pieces of binwood with lengths ranging from 0.8 to 4 m accounted for a median of 19 m^3/ha. These results show that a quantum of large woody residues are available for harvest from steepland cutovers. The results do not interpret their current economic or technical feasibility for harvest.

Objective 2

Objective 2 was to improve upon past methods for measuring landing residue piles and use that to investigate a series of piles in steepland harvest settings across New Zealand.

Modern photogrammetry technology, utilising UAV-captured aerial photography and GCPs allowed modelling of the visible surface of landing residue piles – providing the ability to calculate the total bulk volume of residues, with interpolation of the obscured terrain profile. This methodology provided economic and safety advantages over past methods – allowing the capture of dimensional data without excavation, foot access onto piles or pile surface approximations.

At landings, residue piles were found to vary markedly in size, relative to the area (or volume) of the associated harvest coup(s). Across 16 sites, the average bulk volume of residues piled was 170 m^3 per hectare harvested, ranging from 40 to 350 m^3 per hectare harvested. Where crop yield information is known, the studied sites show that each tonne of timber harvested contributes on average 0.23 m^3 of bulk volume to the landing residue pile(s). These numbers can form the basis of analyses of landing residue production for storage planning or for possible uplift of residues for biomass markets.

The variation between harvest sites underlines the importance of understanding local residue production rates. The refined measurement method in Chapter 4 shares how to gather that information in a format appropriate for operational foresters. Accuracy is improved on also (from that used in Chapter 3) by additionally modelling the landing as built, prior to harvest. This requires an additional site visit and further photogrammetric modelling time. In Chapter 4's case study, a map of pile depth was produced, demonstrating that 99% of the pile area was less than 3 m in depth. This forms an accurate picture of the pile's volume, but also helps to find (without intervention with heavy machinery) where targeted rehabilitation may be required to meet the BPG for pile depth. This methodology provides the opportunity for not only understanding the bulk volume of residue piles in a particular harvesting operation or estate, but also to make active use of the data in post-harvest decision-making.

Objective 3

Harvest residue management is led by BPGs in New Zealand to achieve operational and environmental goals. Objective 3 investigated how harvesting experts respond to the high-level guidelines with steepland operations, the various drivers for residue matters and opportunities for improvement.

The Delphi revealed that there is considerable agreement amongst the operations experts on the various aspects of harvest residue management, despite the experts' diverse affiliations and geographic spread. It also confirmed that a suite of management options need to remain available to foresters, enabling the most appropriate solution to be found for each harvest site.

Fragile soils, exposure to extreme rainfall and existing instability indicators increase the expert panel's assessed risk of residue movements from the cutover. A series of factors add to the volume of residues available to mobilise, most notably: windthrow, broken terrain and poor deflection/blind areas in the harvest area (cable harvesting). However, things that can reduce the residue loading are; favourable economics for extracting the timber, clearly conveyed company expectations for removals and tidy stem set-out for extraction. In response to favourable economics, the expert panel suggests that (in mid-2021) binwood with a 50-kilometre delivery radius would need to be worth around $51 – 79 per tonne to make the product economically viable to extract from steepland cutovers. Its extraction however would be met with a decline in harvesting productivity, and therefore result in a proportional increase in harvesting rates.

The experts considered how harvest residues are managed around watercourses and prefer to retain several management options – particularly with plantings to the waters-edge. Streamside riparian strips - favoured for their ability to buffer activities from waterways - are not regarded a 'last line of defence', but part one of a wider set of applied best practices. Finally, it is conclusive that the expert panel prefers a map-based approach to defining the extents of watercourses (where residues should be excluded from), where New Zealand law currently adopts a generic definition of a waterbody and a river.

The experts agreed that economic viability of supplying low-grade timber (e.g., pulp) to market significantly influences the volume of residues that accumulate at steepland landings, in addition to volumes on the cutover. A conclusion is therefore that effective market solutions for the material could have a significant role to play in reducing steepland residue accumulations.

Consideration of options for managing residue piles on steepland landings uncovered that the group of experts widely agrees that piled residues should not be stored permanently on slopes exceeding 15-20°, and if stored on a landing surface, should be set back 2-4 m from the fill edge. Both results are significant for Best Practice, showing a common understanding amongst the experts where the published expectations for operational practice remain effects-based, or rely on an interpretation of site risk.

Alternative forest management strategies such as smaller harvest coups and alternative species selection are not strongly favoured. The expert panel predicted an increase in windthrow as a result of more exposed stand boundaries, which (if accurate) could have a perverse impact on residue volumes on cutovers. Alternative species also raise some concern regarding market potential if grown at scale.

Harvest residue management is multi-faceted. There are competing objectives and risks (sometimes significant) associated with each harvest site. The optimum management strategy for each site (within current understanding) reflects the available market opportunities and the array of risks that the site is exposed to. Objective 3 combines the knowledge and experience of 20 of New Zealand's forestry operations experts to clarify the key matters within four themes of residue management: on cutovers, near waterways, at landings and for strategic forest planning. The understanding of operational considerations from an operational perspective is now improved. This knowledge can inform the development of Best Practice, ensuring proper regard is given to operational experience and knowledge.

Research Contributions

Information and science can bolster efforts to find balance between the competing demands for harvest residues. This thesis details an investigation into the volumes of large woody residues that are distributed across steepland cutovers and some of the key drivers for their accumulation and spatial distribution. This information primarily indicates the volume of the material on the cutover and hence its availability for extraction. Importantly however, it also provides an opportunity to now question how much volume should be extracted in order to sustain biological systems while also managing catchment risk (such as debris flows).

Considering the feasibility of residue extraction from the cutover, this thesis gives insight into the distribution of residue piece sizes encountered through sampling. The presence of broken stems on the cutover reflects an opportunity to improve recovery of more valuable log grades (i.e., sawlogs) if stem breakages had not have occurred. This research can inform efforts to adapt harvest systems to more efficiently extract the material or otherwise provide impetus to reduce the production of those residues.

Accumulation of residues at steepland landings in the New Zealand context has not been a recent focus of forest industry research. This thesis provides two solutions to the challenge of measuring these accumulations in steep terrain. One is the demonstration and use of photogrammetry workflows, drawing on accessible technology to safely and efficiently capture dimensions of piles. The second is a compilation of pile measurements from steepland clear-fell sites, which provides empirical data for prediction of residue accumulations where pile measurement is not carried out. These are both developments that can assist decision-making in harvest management, and also inform the sector’s intentions to supply residues to developing biomass markets.

The industry experts that participated in this study are cautiously optimistic for increasing demand for harvest residues from the developing biomass markets. Through a Delphi inquiry, this thesis investigates and provides insight into how steepland forests may supply biomass to market, and some of the barriers, as perceived by those experts. The Delphi also highlighted common knowledge and agreement amongst the experts on specific residue management scenarios, where little explicit (New Zealand-based) guidance is available.

This thesis contributes to the body of knowledge supporting New Zealand’s plantation forest industry, helping to better understand harvest residues in steepland forests and guide improvements to the management of those residues as an asset or an obligation.

APPENDIX: DELPHI SURVEY QUESTIONS REFERRED TO IN TEXT

1. Over the next 5 years, do you anticipate the demand for forest residues in your region to Increase/Decrease/Stay the same?
2. What indicators show that a landform is 'high risk' for slash mobilisation?
3. Does your Regional Council provide additional (i.e., in addition to the NES-PF) guidance for how to manage residue mobilisation risk? This may be of any form: i.e., written guides, advice on site visits, workshops etc.
4. How clear/pragmatic is the guidance in the NES-PF and its supporting documentation for managing the risk of harvest residue mobilisation?
5. How reasonable is the NES-PF Erosion Susceptibility Classification map as a proxy for slash mobilisation risk? Red/Orange/Yellow = Very High/High/Moderate slash mobilisation risk respectively.
6. How common are significant harvest residue mobilisation events?
7. Should annual rainfall be given consideration in terms of its contribution to harvest residue mobilisation risk?
8. On a landform that is 'high risk' for slash mobilisation, above what slope would you consider applying techniques/practices to reduce harvest residue mobilisation risk?
9. Under what circumstances should a forest owner/manager intervene to lower residue mobilisation risk posed by windthrown production trees during harvest? Assume the windthrow material is 'sound enough' to withstand being picked up with a grapple.
10. Rate each factor / statement in terms of its contribution to a high residue volume on a steepland cutover:

Top selected contributors are detailed below:

- Windthrow
- Broken terrain
- Poor deflection or blind areas in the harvest area (cable harvesting)
- Negative returns on pulp grades (pulp left off cutting instructions).
- Production pressure on harvesting crews (incl. low margin on harvest rates, inclement weather or breakdowns - limiting production)
- Untidy stem set-out for extraction
- High total recoverable volume of the stand (t/ha)
- Ground-based whole tree extraction
- Shovelling/bunching stems on the cutover

11. Rate each factor / statement in terms of its contribution to a low residue volume on a steepland cutover:

Top selected non-contributors are detailed below:

- Positive returns on pulp grades (pulp on the cutting instructions)
- Clear company/forest owner standard(s) for permissible harvest residues
- Tidy set-out for extraction
- Controlled tree falling (fixed head mechanised)
- High deflection over cable yarding corridors.

12. Our research has indicated that a steepland cutover typically has 30 m3/ha of pulp and bin wood (i.e., all sound wood greater than 0.8m in length and 10 cm in SED) remaining post-harvest. If a harvesting crew was required to extract all/most of this material, what would be your best estimate of: a) lost productivity (t/day); &, b) increase in logging rate ($/t)?

13. Assuming a typical harvest setting in steep country in your region, what price would bin wood have to be ($/t delivered, freshly harvested) to make extracting it from the cutover financially attractive? Assume a distance to market of 50km.
14. Which mechanism typically delivers the most residues to waterways?
15. To what extent should a riparian buffer be relied on as a tool to mitigate the movement of cut-over residues to waterways?
16. In managing legacy plantings right up to watercourses in erosion-prone, steepland forests, what is typically the most appropriate course of action at harvest?
17. The NES-PF currently defines a river by its ability to move freshwater. Slash is to be removed from the floodplain of a 5% AEP event. What is a practical, robust and defendable interpretation of a waterway from which slash should be removed from the 5% AEP floodplain?
18. To what degree do each of the following factors contribute to high residue pile volumes at the landing?

Most significant contributors and non-contributors shown below:

- Negative-returning pulp grades/pulp left off cutting instructions
- Environmental crop damage (e.g. hockey-stick butts, snow damage)
- Bunching stems on the cutover
- Clearwood tending regime (low stocking and high pruning)

19. Burning residue piles on forest landings should continue to be an available tool (assuming proper management). Vote from 1 (total ban) – 5 (must always remain an option).
20. Piled residues may be stored permanently on unmodified slopes, cuts or compacted fill slopes up to a maximum slope of what?
21. Should residues piled on engineered fill surfaces in terrain that is steeper than your selection above, be pulled back clear of the fill edge?

22. If Yes to Q21, what minimum separation from the fill edge is appropriate for effective risk reduction?
23. Should benches that are constructed to retain slash remain visible along their full length?
24. Which method is most appropriate for constructing slash benches in steep terrain? (refer to Figure 5-3).
25. Are ‘pocket benches’ (ref. to Figure 5-4) acceptable as an off-landing slash storage solution?
26. If yes to Question 25, under what conditions is a pocket bench not appropriate for slash storage?
27. How effective do you believe an industry-wide transition to alternative, coppicing tree species on ‘high risk’ sites be for reducing (not eliminating) the frequency of post-harvest landslips?
28. If NZ harvesting practices trend toward smaller coups and boundary constraints (wait to harvest the adjacent coup(s) for X years), what possible solutions are there for reducing the incidence of stand-edge windthrow in steep terrain?
29. What is best for the forest industry as-a-whole on the following spectrum in terms of an individual’s / a company’s freedom to assess, manage and be accountable for slash mobilisation risk?