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Characterisation of harvest residues on New Zealand's steepland plantation cutovers

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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 2019/2020). 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 (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 (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.

Van Wagner's (1968) governing equation (1) for the volume per area on a flat surface 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.

$$V = \pi^2 \Sigma d^2 / 8L \tag{1}$$

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 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

TABLE 1: Harvesting site details.

Site Code	Region	Study Area (ha.)	No. 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

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 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.

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). Figure 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.

The distribution of the total volume showed positive skew due to a significant number of plots returning high residue volumes (Figure 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). 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).

The volume of potentially merchantable residues on the cutover yields similar distributions (Figure 3) to that of total residue volume (Figure 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 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.

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 4). Those meeting the $p<0.001$ significance

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

Parameter	Average (m^3/ha)	Median (m^3/ha)	Interquartile range (m^3/ha)	5th/95th Percentile (m^3/ha)	Min/Max (m^3/ha)
Total Volume	109	88	87	17 / 269	0 / 580
Merchantable Logs	17	11	23	0 / 63	0 / 144
Binwood	27	19	32	0 / 88	0 / 160
Dead wood	25	7	24	0 / 93	0 / 539

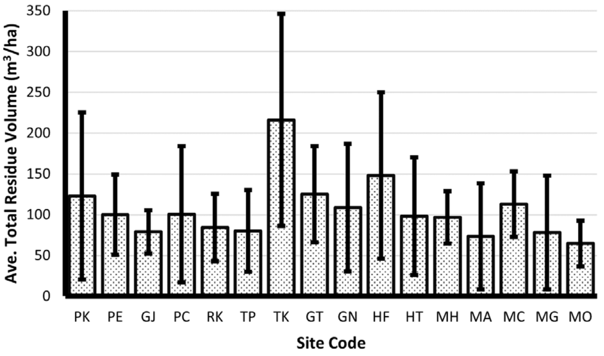

FIGURE 1: Average total volume of woody residues on each cutover site, including the standard deviation.

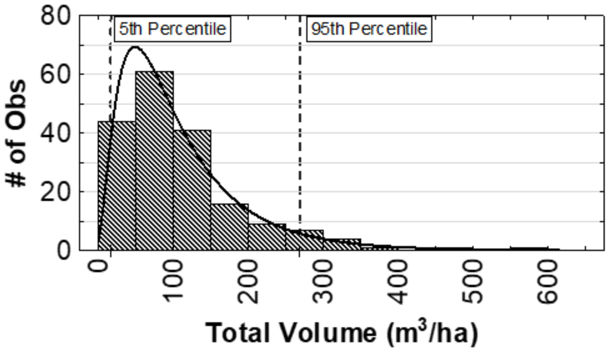

FIGURE 2: Distribution of total volume of residues >25 mm in diameter as measured across the 17 sites and 185 LIS plots.

level as predictors of the Box-Cox transformed total residue volume (λ = 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 (x 10) – 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.

Isolating the 118 cable-harvested LIS plots and applying general linear regression to the Box-Cox transformed total residue volume dataset (λ = 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 (see Fig. 4), satisfying the minimised Mallow's C_p criteria (see Table 5). Likelihood of multicollinearity is low, with variance inflation factors <10 for all contributing variables.

TABLE 3: Summary statistics of potentially merchantable residues measured on the 17 sites.

Parameter		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

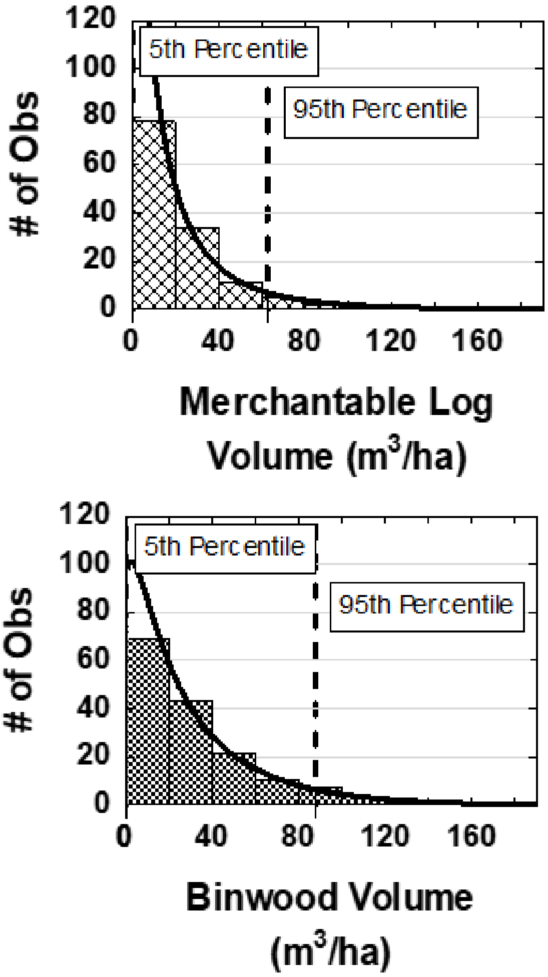

FIGURE 3: Distributions of residue volumes with merchantable potential across the 17 sites and 185 LIS plots.

TABLE 4: Effect of significant variables on the Box-Cox transformed volume of residues remaining on the cutover (λ = 0.297) post-harvest (Adjusted R^2 = 0.32 from 17 sites and N = 185 LIS plots).

Effect	**Regression Coefficient**	**F Value**	**p Value**	**Variance Inflation Factor**
Intercept	23.7	48	0.000	-
Large Structural Logs Proportion (0-100)	-0.252	11	0.001	1.9
Terrain Slope (degrees)	-0.0955	11	0.001	1.1
Planform Curvature (x10)	-0.117	8.9	0.003	1.4
Spur (1 = yes, 0 = no)	0.677	5.1	0.03	1.1
Pulp &/or Binwood on Cutting Instructions (1 = yes, 0 = no)	1.32	4.5	0.04	6.6
Motor-manual Falling (1 = yes, 0 = no)	0.886	2.7	0.1	5.1
Profile Curvature (x 10)	0.0891	2.7	0.1	1.3

Discussion

Hall (1999b) represents the most recent study on residue volumes on New Zealand's steepland cutovers. Two intensively surveyed hauler 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 hauler 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 decade (Raymond 2018), 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

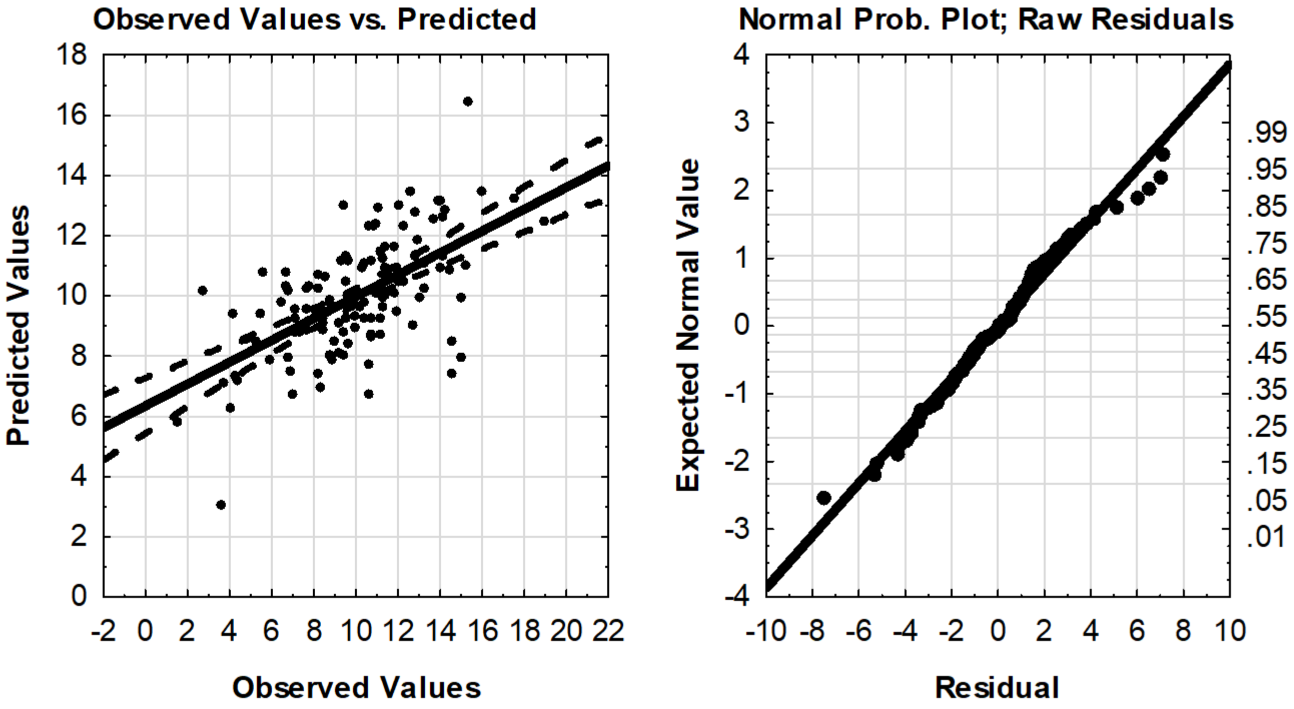

FIGURE 4: Results of multiple regression for the Box-Cox transformed total residue volume, including a 95% confidence interval.

TABLE 5: Effect of significant variables on the Box-Cox transformed volume of residues remaining on hauler-harvested cutovers ($\lambda = 0.324$) post-harvest (Adjusted $R^2 = 0.31$ from 11 sites and N = 118 LIS plots).

Effect	Regression Coefficient	F Value	p Value	Variance Inflation Factor
Intercept	25.8	43	0.000	-
Terrain Slope (degrees)	-0.104	10	0.002	1.1
Large Structural Proportion of TRV (0-100)	-0.274	9.9	0.002	1.9
Planform Curvature (x10)	-0.128	8.4	0.004	1.4
Pulp &/or Binwood on Cutting Instructions (1 = yes, 0 = no)	1.46	4.2	0.04	6.6
Spur (1 = yes, 0 = no)	0.692	4.0	0.05	1.1
Profile Curvature (x10)	0.106	2.9	0.09	1.4
Motor-manual Falling (1 = yes, 0 = no)	1.02	2.8	0.10	5.0

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 a strong biomass market 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).

Conclusions

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 innovations to harvest systems are promising to reduce the production/distribution of residue material.

Competing interests

The authors have no competing interests to declare.

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Authors' Contributions

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

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