# A comparison of biomass production and machine system productivity using three harvesting methods in a conifer first thinning

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## Abstract

A thinning trial took place in a 19-year-old Sitka spruce (*Picea sitchensis* (Bong.) Carr) plantation in the south east of Ireland where three methods of harvesting were performed using the same harvester and forwarder machine system: cut to length harvesting (CTL), integrated harvesting (INT), and whole tree harvesting (WT). The objectives of the trial were to evaluate the log volume and biomass mobilised using each method, the productivity of the machines, and quality parameters of the biomass as a fuel. Using the CTL method, 56.5 $m^3$ $ha^{-1}$ of pulpwood and 6.4 $m^3$ $ha^{-1}$ of small sawlog were harvested. This equated to 23.6 odt $ha^{-1}$ of roundwood material. A greater amount of biomass was mobilised using the INT and WT harvesting methods than the CTL method. On average, compared to the CTL method, 81.8% more biomass was mobilised by the INT method and 93.6% more biomass was removed by the WT method. Wood fuel supply chain (harvesting, forwarding, and chipping) cost to the forest roadside was highest for CTL, and was 23% lower for INT, and 33% lower for WT. The results suggest that the potential biomass mobilisation from first thinnings may be greater than current estimates suggest, while harvesting costs may be further reduced by employing specialised methods. However, the trial was confined to one site, and therefore as the results are site specific they need to be interpreted with caution.

**Keywords**: *Thinning, biomass, whole tree, integrated harvesting, cut to length.*

## Introduction

In Ireland, the latest National Forest Inventory (Forest Service 2015) shows forest cover is currently at 10.5%, of which 53% is publicly owned, with 47% in private ownership. Privately-owned forest comprises c. 72% grant-aided, and 28% non-grant aided. Grant-aided forests are a direct outcome of the support structures put in place over the last 30 years by the Irish government with the aim of increasing forest cover. Reflecting these measures, there has been an increase in planting, such that 84% of grant-aided private forests in Ireland is less than 20 years of age. In total, Sitka spruce (*Picea sitchensis* (Bong.) Carr.) comprises 52.5% of the forest area in Ireland, and 60% of the private grant-aided forest area.

In Ireland, approx. 95% of harvesting employs a cut to length (CTL) method (Karjalainen et al. 2001), but in first thinning, with small tree sizes, these systems may not be cost-effective due to high machine costs and low value markets. Since many private

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landowners have had little prior experience in forestry, and few have forest plantations older than about 30 years, there is a need for thinning operations to be profitable in the short term to encourage owners to thin their forests. Mobilising biomass from such plantations, using cost-effective methods of thinning, is consequently a topical and active research area in Ireland.

It is estimated that due to EU Directives and national policies, the demand for forest based biomass for energy in Ireland will be 3,084,000 m$^3$ per annum by the year 2020 (CRDG 2011) However, it is estimated that only 1,453,000 m$^3$ of forest biomass will be available for the bioenergy market from current sources (Phillips 2011). This forecast of supply, while it includes stemwood to tip, does not include branch biomass. As such, there is potential for harvesting methods other than conventional cut-to-length systems to bridge the gap between the supply and potential demand for forest biomass.

The objectives of this study were to compare alternative methods of harvesting in a first thinning and to: 1) quantify the harvestable and mobilised roundwood (merchantable stem cross cut into lengths) and biomass material available (that can be mobilised for use as wood fuel); 2) estimate machine system productivity; 3) estimate the quality of the biomass wood fuel available; and 4) identify the supply chain variables affecting productivity. Harvestable roundwood volume is typically estimated from measurements of standing trees and a harvesting reduction factor is used to convert this to material that can be mobilised. Biomass harvesting implies that stemwood less than 7 cm top diameter and branchwood is also recovered.

The machine costs estimated in this study include only harvesting costs for the operations carried out on site, and exclude business overheads, fleet management costs, or site relocation costs.

## Materials and methods

### *Study layout and treatments*

The study area was 0.86 ha within a 19-year-old Sitka spruce monoculture, planted on mounds with six lines of trees between drains, at Dungarvan, Co. Kilkenny (52° 33’ 42” N, 7° 04’ 00” E). Stocking was 2,483 trees ha$^{-1}$, mean DBH was 15 cm, and mean top height was 12.8 m. The study area consisted of 54 tree rows divided into nine plots: three plots per harvesting method; where each 12 m wide plot was the working width for a machine pass, located between two drains and was approximately 80 m in length. The thinning prescribed for the site was a one line in six systematic thinning with selection in between, removing approximately 40% of the stems and 30% of the basal area.

The machine system used in the trial was a John Deere 1070D harvester fitted with a John Deere 752 CTL harvester head; a John Deere 810D forwarder, and; a Komptech Chippo 5010 Cd chipper mounted on a MAN truck and powered by its engine. Harvesting was carried out in October 2014 and forwarding in November 2014. Chipping took place in April and June 2015. The same experienced operators were used for all harvesting methods. The three harvesting methods trialled are detailed below.

Harvesting Method 1: Cut to length harvesting, CTL (See Figure 2)
The harvester processed two assortments of roundwood: small sawlog (3.1 m length, 14 cm minimum small-end diameter) and pulp logs (3 m length, 7 cm minimum small-end diameter). Roundwood was placed off the extraction rack in bunches while tree tops and branches were placed in the rack for use as a brash mat. Logs were forwarded to the forest roadside, with the sawlog and pulp being stacked separately. The pulp roundwood was retained for seven months to season and was then chipped at roadside for use as a fuel, while the small sawlog was removed to a sawmill shortly after harvesting.

Harvesting Method 2: Integrated harvesting, INT (See Figure 3)
The harvester processed small sawlogs only, which were placed in bunches off the rack. The remainder, including stem wood categorised as pulpwood category, was also set aside off the rack as a wood fuel. No brash mat was used, although some branches that were delimbed while processing the small sawlog remained in the rack. The small sawlog and wood fuel were forwarded to the roadside and stacked separately. Small sawlog was removed shortly after harvesting and the wood fuel was stored for nine months before being chipped at the roadside.

Harvesting Method 3: Whole tree harvesting, WT (See Figure 4)
The harvester did not process any roundwood; instead the whole tree was cut into two biomass lengths to facilitate forwarding and placed perpendicular to the extraction rack. No brash mat was used. These biomass tree sections were stacked at roadside for nine months and then chipped.

### *Data Collection*

Pre-thinning standing measurements
Prior to harvesting, plot areas were surveyed, and boundary trees were marked with paint at ground level so that stumps could be identified after harvesting. Location and DBH of every tree in each plot was recorded, as were all missing or dead trees.

Post-thinning standing measurements
Every thinned tree was identified and used to calculate the proportion, basal area, and volume of the trees removed, and to describe stocking and basal area per hectare of the maincrop remaining after thinning. The standing volumes were estimated using the full tariff procedure (Matthews and Mackie 2006). The stand tariff number was calculated using felled sample trees, as outlined below.

Sample tree measurements

Data used for the quantification of volume and biomass harvested were gathered from the measurement and weighing of 15 trees on the site, which were used to develop a site specific biomass equation and to estimate the basic density of the roundwood. Trees were selected to represent the range of the thinned DBH distribution and included the smallest and largest DBH harvested (9 and 21 cm, respectively) with at least one sample from each 2 cm diameter. The fifteen trees were felled by chainsaw, and DBH, stump height, total height (including stump height), height at 7 cm diameter of the stem (merchantable stem), and midpoint diameter of the merchantable stem were measured. Each tree was then partitioned into small sawlogs, pulp logs, branches, and tops. The mid diameter and length of each log was measured and the log weighed. Three discs were cut from each log (midpoint, and half way from the midpoint to each end of the log) for moisture content and density determination. The branches and tops were weighed, chipped on site with a Linddana TP200 chipper, and sampled for moisture content. Moisture content was determined by oven drying at 105 °C for 48 hours. Volume was determined by submersion in a water bath and density was calculated as dry mass divided by volume. The relationship between basal area and dry matter (biomass) was then determined.

### Quantification of harvested material

The biomass harvested, defined as the total harvested biomass contained in a thinned tree, was estimated by inputting the DBH for each tree in the plot into the biomass equation. For the woodfuel assortments, the total weight and moisture content of the stacks were used to estimate the dry weight of the stack. For roundwood assortments length and mid diameter of each log was measured. The total volume was converted to dry weight using the basic density as estimated from the sample trees. The biomass mobilised, defined as the biomass that was removed to roadside was estimated from the sum of the oven dry weights of the products from each method.

### Quantification of mobilised material and wood fuel quality

The underlying data for the quantification of mobilised biomass and wood fuel quality parameters were gathered from weights and samples taken during the chipping of each stack of wood. Each stack of wood was chipped separately into a walking floor truck and weighed on a weighbridge. Five random fifty litre samples of woodchip were taken from each wood fuel assortment during chipping operations. Moisture content, bulk density, particle size distribution, calorific value and ash content were determined from the woodchip samples. These quality parameters were assessed using European solid biofuel standards, as per Coates et al. (2014). Moisture content was determined using the oven dry method at 105 °C for 48 hours, according to EN 14774-3:2009, and expressed as a percentage of total weight. Bulk density, expressed in kilograms per cubic metre, was estimated according to EN 15103:2009. Particle size distribution was determined using an oscillating sieve method as per EN 15149-1:2010 and classified according to the new

ISO standard, ISO/DIS 17225-1. Ash content, expressed as percentage dry weight, was determined using a Carbolite muffle furnace at 550 °C, according to EN 14775:2009. Calorific value, expressed in Giga joules per tonne, was determined, using a Parr 5500 oxygen bomb calorimeter, according to EN 14918:2009.

Machine operations measurements

Time-and-motion studies were performed on the harvester, forwarder and chipper. The resolution of the harvester study was at the plot level. The forwarder was studied at the cycle level, where a cycle was defined as the extraction of one load to the roadside.

**Table 1:** *Machine rate calculations for the machines used in the trial.*

|  |  | **Harvester:** | **Forwarder:** | **Chipper:** |
|---|---|---|---|---|
| **Rate** | **Unit** | **John Deere 1070D** | **John Deere 810D** | **Komptech Chippo 5010 CD** |
| Machine price: | € | 365,000[a] | 235,000[a] | 610,000[b] |
| Machine power: | kW | 136 | 86 | 397 |
| Salvage value: | € | 73,000[c] | 47,000[c] | 122,000[c] |
| Economic life: | yrs | 8[d] | 7[e] | 8[f] |
| Annual scheduled machine hours (SMH): | h a$^{-1}$ | 2,000 | 2,000 | 2,000 |
| Utilisation percentage: | % | 65[g] | 65[g] | 40[g] |
| Annual productive machine hours (PMH): | h yr$^{-1}$ | 1,300 | 1,300 | 800 |
| Depreciation: | € yr$^{-1}$ | 37,922 | 27,246 | 61,000 |
| Interest: | € yr$^{-1}$ | 20,227[h] | 13,143[h] | 33,703[h] |
| Insurance: | € yr$^{-1}$ | 9,518[h] | 6,185[h] | 15,860[h] |
| Maintenance and repair: | € PMH$^{-1}$ | 29.2[i] | 16.8[i] | 76.3[i] |
| Fuel: | € PMH$^{-1}$ | 8.6[j] | 5.6[j] | 26.0[j] |
| Lubrication: | € PMH$^{-1}$ | 3.0[k] | 2.0[k] | 9.1[k] |
| Labour incl. benefits: | € PMH$^{-1}$ | 32.2[l] | 32.2[l] | 52.3[l] |
| Overheads per SMH: | € SMH$^{-1}$ | 4.1[m] | 3.0[m] | 6.0[m] |
| Profit per SMH: | € SMH$^{-1}$ | 7.7[n] | 5.7[n] | 11.4[n] |
| Total rate per SMH: | € SMH$^{-1}$ | 93.0 | 68.7 | 138.2 |
| Total rate per PMH: | € PMH$^{-1}$ | 143.1 | 105.7 | 345.5 |

[a]John Deere agent for Ireland: John Deere Forestry Ire Ltd, personal communication 18th August 2015. Note: the prices quoted are for the equivalent new series of John Deere machine, i.e. 1070E and 810E, as the D line is now superseded. [b]Komptech agent for Ireland: Environmental Technology Resources Ltd, personal communication 19th August 2015. [c]Salvage value set as 20% of the purchase price at the end of economic life. ([d]Weise et al. 2009. [e]Lyons 2015). [f]Prada et al. (2015). [g]Coates et al. (2014). [h]Interest rate set at 8.5 %, Insurance rate set at 4 %. [i]Repair and maintenance set as a percentage of depreciation per year as per Ackerman 2014: (Harvester 100 %, Forwarder 80 %, Chipper 100 %). [j]Fuel consumption calculated as a function of engine size as per Ackerman 2014, and fuel cost per litre as per IFA (2015). [k]Estimated as 35% of the fuel cost, as per Murphy (2010). [l]Labour cost set at €15.5 per SMH, and benefits set at 35 %. Labour rate for the chipper appears higher per PMH as the utilisation percentage for the chipper is lower than the other machines. [m]Overheads set as 5 %. Profit was set at 9%.

Chipping operations were recorded as the productive time required processing each stack.

Only productive time recorded in the field was used for machine productivity calculations, as defined by Magagnotti and Spinelli (2012). The cost of running each machine per hour was estimated per productive machine hour (PMH) using the method set out by Miyata (1980) and Ackerman (2014).

*Influence of moisture content on fuel quantification (by volume, weight and energy)*
Moisture content affects the net energy content of woodfuel, and therefore should be reduced through air drying in order to optimise the supply chain (Hakkila 2004). Moisture content also affects weight, and so presents difficulties when trying to quantify and trade wood fuels. The following equations were used to quantify the wood fuel products on-site according to a range of moisture contents in terms of weight, volume, and energy:

$$Weight\ (t) = 100\times\left(\frac{odt}{100 - MC}\right) \qquad [1]$$

$$Volume\ (m^3) = \frac{Weight\ (t)\times(1 - \left(\frac{MC}{100}\right)}{Basic\ density\ (t\ m^{-3})} \qquad [2]$$

$$NCV_{db} = GCV_{db} - 212.2\times H - 0.8\times O + N \qquad \text{(EN ISO 17225-1: 2014)} \quad [3]$$

$$NCV_{ar} = NCV_{db}\times\left(\frac{100 - MC}{100}\right) - 0.02443\times MC \qquad \text{(EN ISO 17225-1: 2014)} \quad [4]$$

$$GJ\ ha^{-1} = NCV_{ar}\times Weight\ ha^{-1}(t) \qquad [5]$$

where:
$MC$ = moisture content expressed as a percentage of total weight;
$GCV_{db}$ = gross calorific value for dry matter at a constant pressure in joules per gram;
$NCV_{db}$ = net calorific value for dry matter at a constant pressure in joules per gram;
$H$ = is the hydrogen content, in percentage by mass, of the moisture-free (dry) wood fuel, given as 6.3% for a raw material of roundwood, and 6.0% for a raw material that includes branches and needles (EN ISO 17225-1: 2014);
$O$ = the oxygen content, in percentage by mass, of the moisture-free wood fuel, given as 42% for a raw material of roundwood, and 40% for a raw material that includes branches and needles (EN ISO 17225-1: 2014);
$N$ = the nitrogen content, in percentage by mass, of the moisture-free wood fuel, given as 0.1% for a raw material of roundwood, and 0.5% for a raw material that includes branches and needles (EN ISO 17225-1: 2014).

## Results

### *Sample tree measurements*

The sample tree dry weight ranged from 8.1 kg (0.0072 $m^2$ BA) to 137.3 kg (0.0366 $m^2$ BA). A straight line equation was found to give a good model fit for dry matter versus basal area (Figure 1). The fit had an R-squared value of 94.2% (R-squared adjusted was 93.7%). Basic density of roundwood products was measured as being 382 kg $m^{-3}$. The equation to predict total aboveground biomass from basal area on the site was:

$$\textit{Total above ground dry matter per tree}\ (\text{kg}) = -10.28 + (3633 \times \textit{Basal area})\ (\text{m}^2) \qquad [6]$$

### *Silvicultural treatment*

It was important to demonstrate that differences in the quantities of biomass being mobilised could be attributed to harvesting method rather than differences in the number or size of trees thinned between plots. Table 2 details the silvicultural treatment using each of the methods. The percentages of trees removed per $ha^{-1}$ was: CTL, 44%; INT, 46%; and WT, 44%. The percentages of basal area removed $ha^{-1}$ was: CTL: 36% (15 $m^2$), INT: 36% (16 $m^2$), and WT: 35% (15 $m^2$). The quadratic mean DBH (QMDBH) before thinning was 15 cm for all treatments, mean DBH of the trees removed was 13 cm for all treatments, and the mean DBH of the main crop was 16 cm for all treatments.

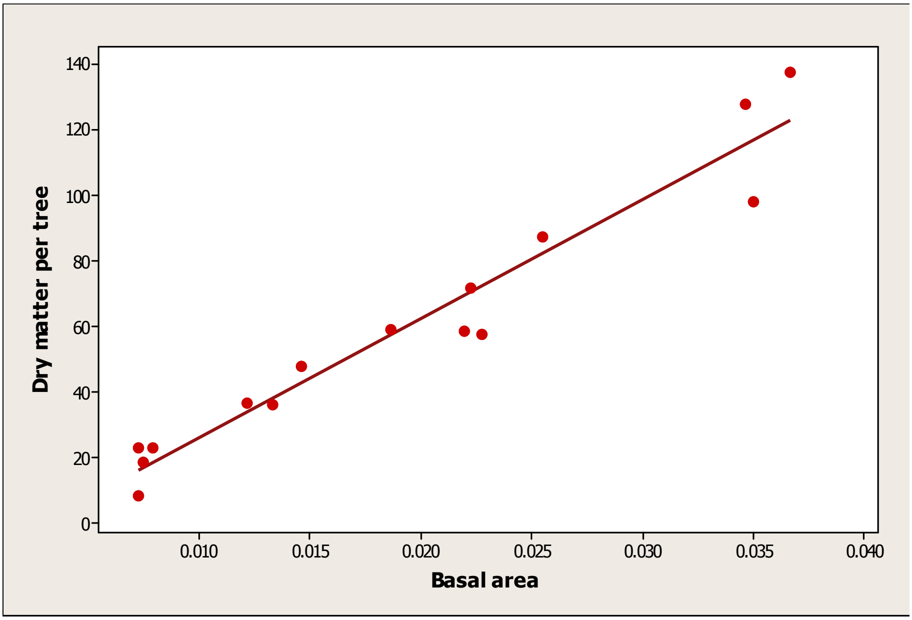

**Figure 1:** *Scatterplot of aboveground biomass per tree (kg) vs. basal area ($m^2$).*

**Table 2:** *Stocking, DBH, basal area and volume assessment of the harvesting methods, expressed per net productive hectare.*

| **Method** | **Pre thin** | | | | **Thinning** | | | | | | **Main crop** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Trees ha$^{-1}$** | **QMDBH** (cm) | **Basal area** (m$^2$) | **Merch. vol.** (m$^3$) | **Trees ha$^{-1}$** | **% trees removed** | **QMDBH** (cm) | **Basal area** (m$^2$) | **% basal area removed** | **Merch. vol.** (m$^3$) | **Trees ha$^{-1}$** | **QMDBH** (cm) | **Basal area** (m$^2$) | **Merch. vol.** (m$^3$) |
| **CTL** | 2,466 | 15 | 42 | 192 | 1,085 | 44 | 13 | 15 | 36 | 65 | 1,381 | 16 | 27 | 137 |
| **INT** | 2,517 | 15 | 44 | 204 | 1,148 | 46 | 13 | 16 | 36 | 69 | 1,370 | 16 | 28 | 135 |
| **WT** | 2,507 | 15 | 42 | 197 | 1,097 | 44 | 13 | 15 | 35 | 64 | 1,409 | 16 | 28 | 133 |

**Table 3:** *Harvested and mobilised biomass, and assortments produced from each harvesting method. Standard deviations in parenthesis. Merchantable volume/odt refers to volume to 7 cm top diameter. Harvested biomass refers to the total aboveground biomass contained in the harvested trees. Mobilised biomass refers to the biomass that was removed from the site.*

| **Treatment** | **Thinned merchantable vol.** | **Thinned merchantable vol.** | **Harvested biomass** | **Mobilised biomass** | **Assortments** | | |
|---|---|---|---|---|---|---|---|
| | | | | | **Small sawlog** | **Pulp logs** | **Wood fuel** |
| | (m$^3$ ha$^{-1}$) | (odt ha$^{-1}$) | (odt ha$^{-1}$) | (odt ha$^{-1}$) | (m$^3$ ha $^{-1}$) | (m$^3$ ha$^{-1}$) | (odt ha$^{-1}$) |
| **CTL** | 65 (7.6) | 25 (2.9) | 46 (2.1) | 24 | 6 (1.8) | 57 (3.7) | |
| **INT** | 69 (0.9) | 26 (0.3) | 49 (0.5) | 43 | 7 (1.7) | - | 41 |
| **WT** | 64 (1.8) | 25 (0.7) | 46 (1.3) | 46 | - | - | 46 |

**Figure 2:** *Thinning method 1: Cut to length (CTL) harvesting. Note the brash mat remaining in the rack and the roundwood on the left hand side. The stack displays the products harvested (small sawlog on the left, pulp logs on the right) from 0.30 ha using this method.*

**Figure 3:** *Thinning method 2: Integrated (INT) harvesting. Note that there is little brash left in the rack. The small sawlog and woodfuels assortments can be seen placed to each side. The stack displays the products harvested (woodfuel on the left, small sawlog on the right) from 0.28 ha using this method***.**

**Figure 4:** *Thinning method 3: Whole tree (WT) harvesting. Note the absence of a brash mat in the rack. The wood fuel assortment can be seen bunched to the side. The stack displays the wood fuel harvested from 0.28 ha using this method.*

*Quantification of biomass and assortment classes*

The estimated quantity of biomass mobilised in the trial is shown in Table 3. In the CTL plots, an average 57 m$^3$ ha$^{-1}$ of pulpwood and 6 m$^3$ per ha of small sawlog was mobilised. This equates to 24 odt ha$^{-1}$ of roundwood material: the mean roundwood basic density was 382 kg m$^{-3}$. A greater amount of biomass was mobilised using the INT and WT harvesting methods. On average, a total of 43 odt ha$^{-1}$ (41 odt of biomass, 7 m$^3$ of small sawlog) was harvested using the INT method, and 46 odt ha$^{-1}$ using the WT method.

If the WT method indicated the potential maximum removal of biomass then the INT method removed 6% less harvested biomass due to delimbing and cutting of small sawlog to length, while the CTL method left behind 48% of harvested biomass, due to delimbing, cutting to length and discarding the stem above 7 cm diameter.

A point to note is that the small sawlog volume mobilised from both the CTL and INT plots was very similar (6.5 m$^3$ in the INT, 6.4 m$^3$ in the CTL), indicating that placed the novel INT method did not affect the operator's ability to identify small sawlog in the trees.

*Wood fuel quality*

The wood fuel quality parameters for products from each harvesting methods are listed in Table 4. At harvesting, CTL roundwood moisture content was 62% and the wood fuel assortments were 59%. Woodfuel moisture contents at time of chipping (seven months later for the CTL assortment, nine months later for the INT and WT wood fuel) was 56% for the CTL roundwood, 59% for the INT wood fuel, and 55% for the WT wood fuel, indicating that there was little natural drying of the material on site over the storage period (October to April/June). Ash content values, expressed as a percentage of dry weight, were as expected, with the CTL roundwood chip having a 0.5% mean ash content with low variation, and the WT and INT

**Table 4:** *Quality parameters of the wood fuel assortments. Standard deviation in parenthesis.*

| **Treatment** | **CTL** | **INT** | **WT** |
|---|---|---|---|
| **Raw material of wood chip** | Roundwood, free of branchwood | Small diameter stemwood with branches | Whole stem and branches |
| **Quality Parameters** | | | |
| Woodchip bulk density, db (kg m$^{-3}$) | 159 (8) | 171 (6) | 164 (4) |
| Moisture content,% total wt. | 55.9 (2.6) | 58.8 (1.6) | 55.1 (2.7) |
| Ash content,% db | 0.50 (0.11) | 2.37 (1.65) | 1.37 (0.76) |
| GCV db (MJ kg$^{-1}$) | 19.8 (0.02) | 19.7 (0.09) | 19.8 (0.12) |
| NCV ar (GJ tonne$^{-1}$) | 6.8 | 6.1 | 7.0 |
| Particle size classification: ISO F | F06 | F20 | F20 |
| Particle size classification: ISO P | P31 medium | P31 medium | 45 large |

wood fuel having a higher mean ash content of 1.4% to 2.4% and a much higher variability probably related to the higher bark and needle content. Gross calorific value, dry basis, (GCV, db) was the same across all treatments at 19.8 GJ tonne$^{-1}$. The Net Calorific Value, as received (NCV, ar) describes the energy content net of that energy lost evaporating the moisture contained in the wood fuel at the time of measurement. Therefore, this varied due to different moisture contents between woodchip produced by the three methods. Particle size was classified according to ISO 17225 and notably all treatments failed to classify to the older EN 15149-1 or EN 15149-4 standards. CTL roundwood chip had fewest fine particles (passing through a sieve with 3.15 mm apertures) contributing less than 6% of the total mass (F06). The fines fractions of the INT and WT wood chip were both F20, meaning that 20% by mass was less than 3.15 mm. The CTL and INT wood chip classified as P 31 medium, meaning that over 60% by mass of woodchip was between 3.15 mm and 31.5 mm in length, that less than 6% of the material is over 45 mm, less than 3% of the material is over 100 mm, and that all particles are less than 200 mm. The WT wood chip classified as P45 large due to presence of particles longer than 200 mm.

*Machine productivity and cost*

The machine productivity and cost for the system operating under each of the harvesting methods is shown in Table 5. The harvester operation times for the CTL and INT methods were similar: at 9.2 and 9.5 PMH ha$^{-1}$ respectively, and less for the WT method, at 8.1 PMH ha$^{-1}$. The longer time needed to carry out the CTL and INT operations was mostly as a result of the extra time required to identify small sawlog. The one-way extraction distance during the trial was an average of 371 m (min. 317 m, max. 425 m). The forwarder operation time was estimated as 8.9 PMH ha$^{-1}$ for the WT, and 9.3 PMH ha$^{-1}$ for the INT method. The forwarder time was substantially less in the CTL method, at 5.7 PMH ha$^{-1}$, due mainly to the lower amount of material mobilised. The harvester cost was estimated as €1,321 ha$^{-1}$ using the CTL method, €1,355 ha$^{-1}$ using the INT method, and €1,159 ha$^{-1}$ using the WT method. Forwarding costs were estimated as €602 ha$^{-1}$ using the CTL method, €944 ha$^{-1}$ using the INT method, and €987 ha$^{-1}$ using the WT method.

Table 5 also shows the productivity of the chipper in oven dry tonnes per productive machine hour. The results are similar for all assortments. The CTL roundwood was chipped at a rate of 23.3 odt PMH$^{-1}$. The INT wood fuel and WT wood fuel assortments were chipped at a rate of 20 odt PMH$^{-1}$. Consequently, the estimated cost of chipping increased from €15 odt$^{-1}$ for the CTL roundwood to €17 odt$^{-1}$ in the wood fuel assortments. The overall cost of harvesting and forwarding of roundwood was estimated at €30.50 m$^{-3}$. As the INT method

**Table 5:** *Productivity and cost of the machine system using the harvesting methods. Standard deviation in parenthesis.*

| Treatment | CTL | INT | WT |
|---|---|---|---|
| **Machine Productivities** | | | |
| **Harvester** | | | |
| Harvester time (PMH $ha^{-1}$) | 9.2 (1.2) | 9.5 (1.2) | 8.1 (0.1) |
| Harvester cost (€ $PMH^{-1}$) | 143.1 | 143.1 | 143.1 |
| Harvesting cost (€ $ha^{-1}$) | 1321 | 1355 | 1159 |
| Harvesting cost of roundwood (€ $m^{-3}$) | 21.0 | - | - |
| **Forwarder** | | | |
| Forwarder time (PMH $ha^{-1}$) | 5.7 (0.4) | 8.9 (0.5) | 9.3 (0.8) |
| Forwarder cost (€ $PMH^{-1}$) | 105.7 | 105.7 | 105.7 |
| Forwarding cost (€ $ha^{-1}$) | 602 | 944 | 987 |
| Forwarding cost of roundwood (€ $m^{-3}$) | 9.6 | - | - |
| **Chipper** | | | |
| Chipping productivity (odt $PMH^{-1}$) | 23.3 | 19.8 | 20.1 |
| Chipper cost (€ $PMH^{-1}$) | 345.5 | 345.5 | 345.5 |
| Chipping cost (€ $odt^{-1}$) | 14.8 | 17.4 | 17.2 |
| **Machine system cost** | | | |
| Cost of roundwood at roadside (€ $m^{-3}$) | 30.5 | 30.5 | - |
| Cost of wood fuel at roadside (€ $GJ^{-1}$) | 6.2 | 4.6 | 4.1 |

resulted in the production of both roundwood and wood fuel at the same time, it was not possible to identify the time associated with each assortment separately. To overcome this, the roundwood cost of €30.50 $m^{-3}$ (as estimated for the CTL method) was assigned to the small sawlog produced using the INT method, and the remaining cost was spread over the remaining biomass. The machine system cost for wood fuel was estimated as follows: €6.20 $GJ^{-1}$ using the CTL method, €4.60 $GJ^{-1}$ using the INT method, and €4.1 $GJ^{-1}$ using the WT method.

*Influence of moisture content on quantification of biomass by volume, weight, and energy*

Moisture content is highly variable in wood fuel, and is strongly influenced by length of storage time and time of year (Hakkila 2004). Results were analysed to investigate the influence of moisture on energy value of the wood fuel assortments. Small sawlog was excluded from the CTL and INT methods.

Figure 5 shows the estimated volume of the wood per hectare and also the estimated range of the total weight per hectare according to moisture content. As volume is largely unaffected by moisture content, the volumes per hectare remain constant over a range of moisture contents. The total weight of the CTL wood fuel changes from 53 t $ha^{-1}$ at 60%, to 30 t $ha^{-1}$ at 30%. Likewise, the range of the total weight of the INT wood fuel is estimated at 101 t $ha^{-1}$ at 60% to 58 t $ha^{-1}$ at 30%, and the WT wood fuel is estimated at 114 t $ha^{-1}$ at 60%, and 65 t $ha^{-1}$ at 30%.

Figure 6 illustrates the estimated energy content in Mega Watt hours (MWh) per hectare at a range of moisture contents and again the total weight of the wood fuel per hectare. The energy content per hectare using the CTL method was estimated to range between 87 MWh at 60% MC, to 102 MWh at 30% MC. The INT and WT methods have a much higher energy content, as more biomass was mobilised using these methods. The energy content ha$^{-1}$ using the INT method was estimated to range from 166 MWh at 60% MC, to 195 MWH at 30% MC, and using the WT method the

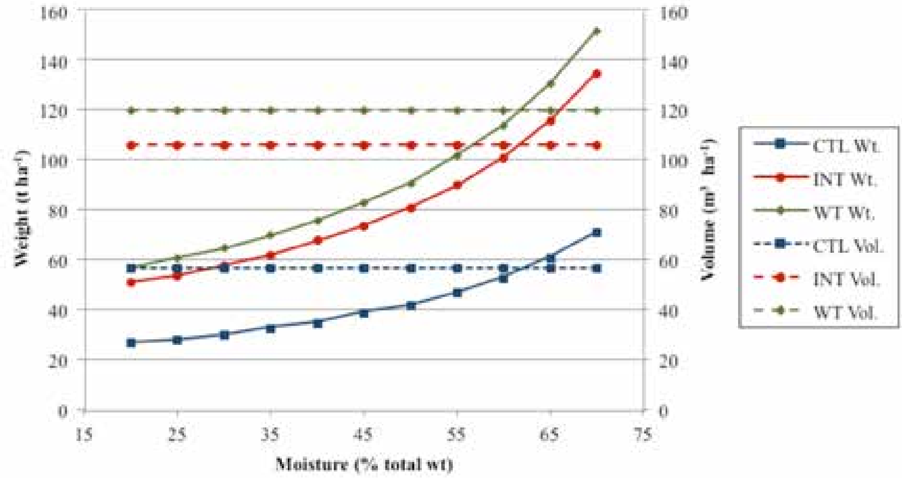

**Figure 5:** *Comparison between methods of the influence of moisture content on variation between mobilised wood fuel volume (m$^3$ ha$^{-1}$) and weight (t ha$^{-1}$).*

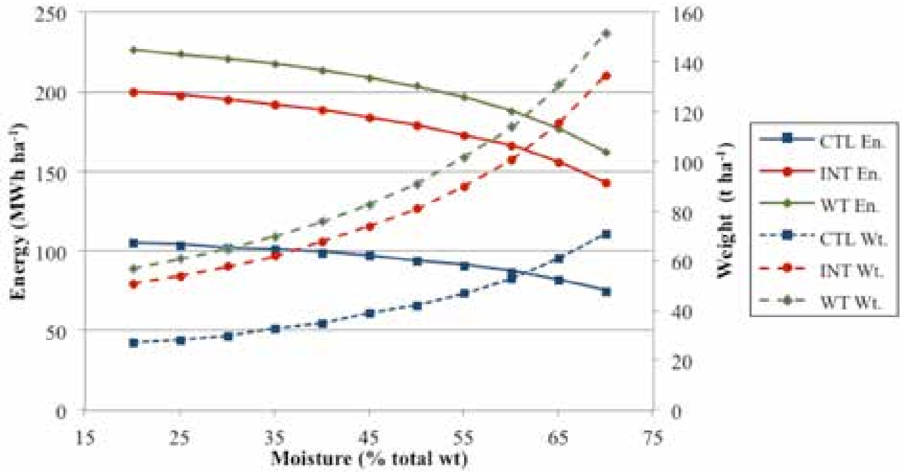

**Figure 6:** *Comparison between methods of the influence of moisture content on variation between mobilised wood fuel energy content (MWh ha$^{-1}$) and weight (t ha$^{-1}$).*

energy content per hectare was estimated to range between 188 MWh at 60% MC, to 221 MWh at 30% MC.

## Discussion

The additional biomass mobilised using the INT and WT methods arises largely from the inclusion of branches and tree tops at the time of felling, and not from harvesting additional trees. The harvester cost per hectare was slightly lower for WT harvesting than the INT or CTL methods. CTL and INT harvester costs were the same, and importantly, the same volume of small sawlog was realized from each of these methods. The forwarding costs $ha^{-1}$ were higher for extracting wood fuel, as a direct result of more biomass being brought to the roadside. The chipping cost was similar for all products. The data showed the cost to be slightly less when chipping roundwood, but this information is based on a single plot per treatment so these results should be interpreted cautiously.

The costs estimated are similar to previous research carried out in Ireland Kent et al. (2011) ran a series of wood energy supply chain studies in Ireland and found that WT harvesting was the most cost effective, ranging from €2.22 $GJ^{-1}$ to €4.36 $GJ^{-1}$. The WT system trialled by Kent et al. in 2007 and 2008 was a terrain chipping system, which was purpose specific to produce wood fuel. In this study, it was found that WT harvesting costs with a harvester, forwarder and a road side chipper were €4.1 $GJ^{-1}$, which is at the upper end of the Kent et al. results, but the system also had the flexibility of producing roundwood when required. The same authors also reported costs using the CTL method of €5.65-8.64 $GJ^{-1}$, and costs using the INT method of €5.05-7.52 $GJ^{-1}$. In this study, costs using the INT method were lower, at €4.60 $GJ^{-1}$.

The natural drying of wood fuel was poor during the trial period. Further investigation needs to be carried out to determine if the material can be dried more effectively in the forest before forwarding. It is in the interest of wood fuel suppliers to reduce the moisture content of wood fuel to maximise the energy content and reduce transportation costs of the material. It can be seen from the data that as moisture content declines, the weight decreases and the energy content increases. Quantification by weight is the simplest and often the preferred method for trade purposes, but conflict may arise if the forest owner is unable to obtain a premium for selling seasoned wood with a low moisture content. Wood destined for chipping needs to be monitored during storage so that it is at acceptable moisture content before chipping. It is therefore important that all parties in the management of the supply chain are incentivised to reduce for moisture content to optimise the energy potential of this resource.

The impacts of making branch and tree top material unavailable as a brash mat were not evaluated in this study, but it is important to note that soil damage is a possibility, especially on sites with low carrying capacity, particularly if the operation is carried out during wet weather. INT or WT harvesting should therefore only be prescribed for sites where the risks of soil damage are considered low. One of the benefits of using the INT or WT methods, with a machine system that is capable of performing a CTL harvesting, is that the machines can use a brash mat on sites where it is needed, or on parts of a site where numerous machine passes are required. It should also be noted that the indicative figures taken from EN ISO 17225-1: 2014 for the nitrogen content of wood fuel with significant amounts of needles is five times higher than that of the wood fuel from roundwood. This may have implications for forest nutrient cycles. Investigation of these impacts was outside the scope of the study, but they should be evaluated in an Irish context, given that the demand for wood fuel is likely to increase in the future. A practical mitigation approach to limit nutrient loss may be to leave the biomass within the forest during the seasoning period, so that the needles fall off in the stand, and then forward the material to the roadside, as outlined by Kent et al. (2011). This may, or may not, facilitate biomass drying and so should be investigated. It should also be noted that wood fuels with needles or leaves included are not suitable for combustion as they can lead to boiler corrosion.

The ash content of the INT and WT wood fuel chip were higher than the CTL chip. There was also more fine material in the chips derived from biomass containing branch material, and the size of the chips fell into a lower quality classification. The woodchip produced in this trial was accepted for co-firing at a peat and biomass electricity generation plant. The chip made from the CTL roundwood could be used in smaller commercial boilers and these users may be willing to pay a higher price for wood fuel. It should be noted that the marketability of the lower quality chip may be limited to a few large scale industrial users in the country that have large boilers and robust infeed systems that can handle large wood particles containing higher moisture and ash contents. Conversely, there may be more market opportunities at a local level for higher quality material, thus also reducing haulage costs. However the ability to produce this higher quality chip is a function of the raw material, seasoning conditions, and chipping technology, but a large proportion of the biomass is not usable. Another aspect of biomass supply is the efficiency of the boilers for which the wood is destined, an important aspect in the context of carbon accounting. This may be an important consideration in the choice of supply chain, as the combustion technology to either generate electrical power at a large scale, or heat at a smaller scale, may have different efficiencies.

The INT and WT methods described in this paper are still not commonly used in Ireland. The results of the study revealed that these methods show promise, perhaps allowing more wood than previously estimated to be supplied from the emerging private sector resource. This new source of wood may help bridge the gap between supply and demand of biomass in Ireland and may also encourage more private sector owners to thin their stands, especially given that these operations may be economically viable.

## Conclusions

Whole tree (WT) and integrated (INT) harvesting methods of thinning a Sitka spruce can mobilise a larger amount of biomass from the forest compared to cut to length (CTL) harvesting, while still delivering the same silvicultural stand benefits.

The machine system costs are lower for the WT and INT methods than for the CTL method.

The costs presented in this paper applied only to the operational costs and did not take into account business and management costs or other returns to the landowners. In addition, the biomass fuel may require extended drying periods at the roadside, so payment may be delayed, thus adding more cost.

Cost-benefit financial analysis, using market prices for the products, should be undertaken to determine the optimal method of harvesting wood to maximise the return from thinning.

The conversion from volume to weight to energy is affected by moisture content changes over time. The price paid for wood fuel should reflect the positive impact of seasoning, so the moisture content of the wood should be considered at the time of sale.

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