# Residue bundling – a case study in Ireland

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## Abstract
Bundling residues from clearfell sites for use as a fuel is widely practiced internationally and more recently in Ireland. However, there is little information as to which bundling approach is most appropriate under Irish conditions. To this end, a clearfelling operation that included residue harvesting was evaluated in a 45-year-old stand of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in mixture with 5% grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.). The objectives of the study were to determine if arranging the brash for bundling during timber harvesting would impact on the supply chain costs, quantity and quality of the fuel. This included operations of a cut to length harvester, a forwarder, a residue bundling machine, a forwarder extracting residue bundles, and a shredder processing bundles into hogfuel. The fuel quantity mobilised was estimated, and the fuel quality was assessed. Three treatments (which were not replicated) were applied. Roundwood harvesting and extraction cost to the roadside ranged between treatments from €6.58 to €7.66 per $m^3$. In total, 589 bundles were produced, costing €4.80 to €6.43 per bundle between treatments (including forwarding). Shredding bundles into hogfuel cost €2.31 per bundle. The biomass removed ranged between 17.0 odt $ha^{-1}$ and 28.7 odt $ha^{-1}$. It was found that residues were most available for harvest and with highest energy content, when not used as a brash mat prior to bundling, and conversely were least available, with lowest energy content, when used as a brash mat and driven over.

**Keywords:** *Logging residues, residue bundling, wood fuel quality, roundwood harvesting, machine productivity.*

## Introduction
During cut to length harvesting, tree stems are usually delimbed and cross-cut into specified assortment dimensions. The branches and un-merchantable stem (top portion e.g. < 7 cm diameter over bark, defective stem sections, breakage, undersized trees, and any logs missed by the forwarder) are left behind. This material is termed as logging residues (Hakkila 1989). Machines have been developed to gather these residues off the forest floor, and compact them into cylindrical bales to make the process of forwarding, stacking, road haulage and storing more cost effective. These machines, called residue bundlers, are relatively new. They were developed commercially in Sweden in the late 1990s. The bales they produce are referred to as residue bundles, brash bales, or compact residue logs (CRL) (Spinelli and Magagnotti 2009). Two companies, Wood Pac and Fibrepac, began developing residue bundlers

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around the same time, and both were still testing their prototypes as recently as 1998 (Andersson and Nordén). At this time, residue bundling was still considered as only a concept. By 2000 the method had been adopted, and both companies had started to export machines outside of Sweden. In 2002, Timberjack bought the product patents from Fibrepac, and shortly afterwards the Wood Pac patents were bought by Valmet (Karha and Vartiamaki 2006).

Currently, residue bundling systems are widespread in the Nordic countries. For example, residues were recovered on 41% of the clearfell area in Sweden in 2011 (79,097 ha of a total clearfell area of 192,000 ha) representing 1.9 TWh of energy (National Board of Forestry 2011). A prototype residue bundler was constructed in the mid 1990's in Ireland but was not commercialised (Hoyne and Thomas 2001). A European-wide review of residue harvesting in 2006 reported that no logging residues were being harvested in Ireland (Kuiper and Oldenburger 2006). Recently, a study of a residue bundling supply chain in Northern Ireland found that the system was a viable source of wood fuel, with a relatively low production cost (Forbes et al. 2014).

The potential volume of residues on a site depends on tree species, age, silvicultural treatment over the rotation, and the assortment specifications to be cut from the main stem during timber harvesting (Hakkila 1989). In particular, the specifications and demand for small-diameter logs that constitute the upper-most portion of the stem will have a large impact on the amount of material available for energy. Tree size is also an important factor that determines the volume of residues available. Although larger trees have more total biomass, the proportion of residual biomass to merchantable stem biomass changes with tree height (Levy et al. 2004). Therefore, it may be difficult to predict the residual biomass available on any site, and the amount of residue available may vary greatly between sites. In a recent study, an indicative figure of 25 oven dry tonnes (odt) per hectare were baled on six clearfellerd Sitka spruce (*Picea sitchensis* (Bong.) Carr.) sites in Ireland (Coates and Kent 2013). Bales were produced on an average of 58% of the clearfelled area, so the biomass removed was 42 odt $ha^{-1}$ for the net area where bales were produced. Van den Broek et al. (2001) recognised that harvesting residues could constitute a substantial biomass resource in Ireland, estimating that residues from clearfell and thinning operations might provide an energy potential of 3.4 PJ (Lower Heating Value). This was based on 30% residue biomass per roundwood harvest for clearfells, 60% for thinning, 50% of the sites being suitable for residue harvesting, and 70% of the residues being recoverable on any site. However, these predictions may have been over estimated as residue harvesting is restricted mainly to clearfelled forest sites (Hakkila 1989). Phillips (2011) recently identified that 1,453,000 $m^3$ of forest biomass may be available in Ireland for the bioenergy market by 2020, but this supply falls short of demand, which is projected to reach 3,084,000 $m^3$ (CRDG 2011). However, Phillips' forecasts did not include logging residues. Phillips accounted for tree stem tops but not logging residues, so this resource could be used to partially fill the gap between supply and demand.

In terms of the supply chain productivity, a bundler can operate after standard harvesting and extraction of the roundwood products without any prior planning. However, bundler productivity and the quality of the fuel can be improved considerably if best practices are followed at the bundling and harvesting stage, which result in a reduction of soil contamination and drier logging residues (Vonk and Theunissen 2007).

The study was a collaboration between Waterford Institute of Technology (WIT) and Coillte, the Irish State forestry company. A previous trial conducted by Coillte and WIT satisfied the stakeholders that a residue bundling supply chain was technically and economically feasible in Ireland (Coates and Kent 2013). However, fuel contamination with soil and stones was identified as a barrier to using residues for energy, so the trial described in this paper was established. The objectives of the study were to determine if arranging the brash for bundling during timber harvesting would impact on the supply chain costs, quantity and quality of the fuel.

**Materials and methods**

The trial made use of a 45-year-old stand of Sitka spruce mixed with 5% grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.) on a free-draining, mineral soil, with a 7 to 15° slope, located near Inistioge, Co. Kilkenny (52°28'10" N, 7°4'23" W; 230 m asl). The stand was divided into three treatment plots. The treatments used were as follows:

**Figure 1:** *Residue bundler working on the study site in Co. Kilkenny.*

- **Treatment A:** ***All Residues Driven upon (ARD)***. Logging residues were used as a brash mat for all timber harvester and forwarder machine passes (see Figure 2);
- **Treatment B:** ***Driving on Residues Reduced (DRR).*** Logging residues were used as a brash mat, but the forwarder only travelled on alternative extraction racks, the harvester travelled on all extraction racks (see Figure 3);
- **Treatment C:** ***No Residues Driven on (NRD)***. No residues were used as a brash mat; instead they were piled to the side of the racks (see Figure 4).

An inventory was carried out on each plot prior to harvesting operations. A portable GPS was used to estimate the treatment areas, and the stand descriptions were estimated from four 400 $m^2$ subplots per treatment area. The total site area was 3.7 ha, the average stocking was 623 trees $ha^{-1}$, the mean top height was 26 m, the quadratic mean DBH was 24 cm, the mean tree volume was 0.52 $m^3$, and the stand volume was 325 $m^3$ $ha^{-1}$. The treatment plots had the following characteristics: treatment ARD: 0.91 ha, 619 trees $ha^{-1}$, 0.58 $m^3$ $tree^{-1}$, treatment DRR: 1.58 ha, 569 trees $ha^{-1}$, 0.53 $m^3$ $tree^{-1}$, treatment NRD: 1.21 ha, 681 trees $ha^{-1}$, 0.45 $m^3$ $tree^{-1}$. The treatment plots were not identical in size, mainly due to practical constraints (e.g. shape of site).

**Figure 2:** *All Residues Driven upon (Treatment A). Logging residues were used as a brash mat for all timber harvester and forwarder machine passes.*

**Figure 3:** *Driving on Residues Reduced (Treatment B). Logging residues were used as a brash mat, but the forwarder only travelled on alternative extraction racks; the harvester travelled on all extraction racks.*

**Figure 4:** *No Residues Driven on. Residues were not used as a brash mat, instead were piled to the side of the racks.*

Harvesting was carried out in March 2011 with a Ponsse Beaver harvester. The roundwood products were brought to the roadside with a Timberjack 810D forwarder. The brash was left in situ on the ground for seven months (March – November 2011), and then a John Deere residue bundler fitted to a John Deere 1490 base machine bundled the residues on each of the plots. The bundles were forwarded to the roadside with a John Deere 1110 forwarder, and transported to Medite (Europe) Ltd., a medium density fibreboard MDF producer in Clonmel, Co. Tipperary using self-loading timber haulage trucks. At Medite a Jenz AZ 660 shredder fed by an agricultural tractor, fitted with a grapple bucket, shredded the bundles into hogfuel, which was then used as fuel in the boiler for the MDF production process. During the operations, a work study of the machines took place using Husky data loggers running the SIWORKS 3 software program (Kofman 1995). Mean roundwood assortment volumes were estimated from sample log measurements of mid-diameter and length, and calculated using Huber's formula, and used to quantify harvester and forwarder output, as per Spinelli et al. (2002). The residue bundler, bundle forwarding and shredder output was quantified as the number of bundles produced / forwarded / shredded per hour. The number of bundles and weight of bundles transported to Medite were also recorded over a weighbridge. Operation costs per production unit were calculated from the time and production studies and machine costs for the machines. The machine costs were estimated using the method of Miyata et al. (1980) and the COST model developed by COST Action FP0902 (Ackerman et al. 2014). Miyata's method has been used in many productivity studies (LeDoux and Huyler 2001, Behjou et al. 2009), and very recently by Magagnotti and Spinelli (2011). The COST model has been developed as a harmonisation of the procedures for forest engineering and economic machine cost analysis. The estimated machine costs are detailed in Table 1. The results are expressed per scheduled machine hour (SMH) and productive machine hour (PMH). The following values were used in the machine cost calculations: Salvage value was set at 13% for all machines. An interest rate of 10% was used. Insurance cost was calculated as 3% of the average annual investment. Machine engine power was sourced from manufacturer's specifications. A fuel cost of €0.88 $l^{-1}$ was used for all machines. Fuel consumption was calculated as a function of engine size and engine loading, whereby a 25% engine load was used for all machines, except the shredder which was set at 50%. Lubrication cost was calculated as 15% of the fuel costs. The following consumables were included: brash bundler sawbar, chains and baling twine; harvester: saw bar and chains; shredder knives and hammers. The number of work days per year was assumed to be 250, with 1 ten-hour shift per day. Operator costs included benefits and operator insurance. An overhead cost of 5% was applied and a normal operating profit of 5% was used. Sources for the inputs are detailed in the footnotes of the Table 1.

The moisture content of the brash was determined at the time of timber harvesting, and again at the time of bundling. At the time of timber harvesting, one full forwarder load of brash was extracted from each treatment area. Each forwarder load was obtained by placing one grab of brash into the forwarder at 15 random intervals over the treatment area. The brash was unloaded at roadside into three separate piles. For each of these piles, the brash was progressively chipped using a TP200 disk chipper mounted on a double-axle trailer into 10 separate piles. Five samples of approximately 1 kg-size were taken from each of these piles to estimate moisture content. Moisture content was determined

**Table 1:** *Machine costs, based on productive machine hours (PMH) and scheduled machine hours (SMH), calculated for the harvesting, bundling, and shredding operations.*

| **Machine** | **Brash bundler** | **Forwarder 1110E** | **Harvester** | **Forwarder 810E** | **Shredder** | **Loader** |
|---|---|---|---|---|---|---|
| Fixed costs | | | | | | |
| Purchase price (€) | 425,000 [a] | 265,000 [a] | 332,000 [b] | 200,000 | 330,000 [c] | 72,000 [d] |
| Salvage value (€) | 55,250 | 34,450 | 43,160 | 26,000 | 42,900 | 9,360 |
| Economic life (PMH) | 18,000 [e] | 18,000 [e] | 18,000 [e] | 18,000 [e] | 7,000 [f] | 18,000 [e] |
| Annual depreciation [g] (€) | 36,153 | 22,543 | 27,681 | 17,013 | 72,185 | 6,125 |
| Insurance cost [g] (€) | 7,746 | 4,830 | 6,061 | 3,645 | 6,676 | 1,312 |
| Machine power (kW) | 134 | 135 | 129 | 95 | 375 | 74 |
| Utilisation (%) | 65 | 65 | 65 | 65 | 75 | 65 |
| **Total fixed costs** (€ $h^{-1}$) | **41.11** | **25.21** | **31.24** | **20.08** | **56.57** | **6.96** |
| Variable costs | | | | | | |
| Fuel use [h] (L $h^{-1}_{PMH}$) | 10.40 | 10.40 | 10.00 | 7.40 | 58.13 | 5.80 |
| Fuel cost (€ $h^{-1}$) | 9.13 | 9.18 | 8.80 | 6.48 | 51.15 | 5.07 |
| Maintenance & repair [i] (%) | 100 | 80 | 100 | 80 | 100 | 80 |
| No. additional track sets | 1 | 2 | 1 | 2 | - | - |
| Cost per track set [f] (€) | 5,500 | 5,500 | 5,500 | 5,500 | - | - |
| Track set lifespan [f] ($h^{-1}_{PMH}$) | 18,000 | 6,000 | 18,000 | 6,000 | - | - |
| Consumables (€ $h^{-1}_{PMH}$) | 21.00 [a] | - | 1.30 [J] | - | 24.06 [c] | - |
| **Total variable costs** (€ $h^{-1}$) | **55.41** | **23.94** | **31.03** | **21.28** | **131.03** | **8.78** |
| Operator costs (€ $h^{-1}_{PMH}$) | 23.82 | 23.82 | 22.43 | 23.82 | 20.64 | - |
| **Total costs (€) per:** | | | | | | |
| **PMH** | **131.42** | **79.20** | **92.02** | **70.60** | **228.50** | **17.35** |
| **SMH** | **85.42** | **51.48** | **63.49** | **45.89** | **171.38** | **11.23** |

Sources:
[a] O' Dwyer, W. O'Dwyer Timber Contractors Ltd, personal communication, February 19th 2014;
[b] Väätäinen et al. 2006;
[c] Colman, R. CTO Environmental Solutions Ltd, personal communication, February 18th 2014;
[d] Egan, D. Finning (UK & Ireland) Ltd, personal communication, January 28th 2014;
[e] Spinelli 2011;
[f] Horgan, J. Horgan Brothers Timber Extraction Ltd, personal communication, January 29th 2014;
[g] Miyata 1980;
[h] Ackerman 2014;
[i] Calculated as a percentage of the machine replacement value, after Ackerman 2014;
[J] Kärhä 2004.

using the oven-dry method at 105°C. These samples were then homogenised and reduced for determination of calorific value and content of ash, carbon, hydrogen, nitrogen, chlorine and sulphur. Calorific value was determined using a Parr 6300 oxygen bomb calorimeter under constant volume according to EN 14918: 2010. Ash content was determined using a muffle furnace according to EN 14775: 2010. Carbon, hydrogen, and nitrogen were determined using an elemental analyser according to EN 15104: 2010, and sulphur and chlorine using titration according to EN 15289: 2010.

At the time of bundling (seven months later), 20 bundles per treatment area were sampled for moisture content. The bundles were dissected with a chainsaw and three subsamples (approx. 1 kg each) per bundle were taken to determine the values for moisture content and the other parameters, following the same method as previously described.

**Results**

*Cut-to-length roundwood harvesting*

The time study results and productivity calculations for operating the harvester in the three treatment areas are detailed in Table 2. The time taken to process trees was examined across the three treatments; 192 trees in ARD, 457 in DRR and 235 in NRD. The harvester productivity was identical for treatments ARD and NRD, processing 41 trees per productive machine hour ($hr^{-1}_{PMH}$) but was faster under treatment DRR with 46 trees $h^{-1}_{PMH}$. Volume harvested per scheduled machine hour ($hr^{-1}_{SMH}$) was estimated as 14.2 $m^3$ $h^{-1}_{SMH}$ under treatment NRD, 15 $m^3$ $h^{-1}_{SMH}$ under treatment DRR and 15.8 $m^3$ $h^{-1}_{SMH}$ under treatment ARD. Applying a machine cost of €63.49 $h^{-1}_{SMH}$, the harvester cost ranged from €4.02 per $m^3$ for ARD, €4.23 per $m^3$ for DRR and €4.47 per $m^3$ for NRD.

*Roundwood forwarding*

The time study results and productivity calculations for the forwarder operations on the three treatment areas can also be viewed in Table 2. The number of loads extracted per productive machine hour varied between treatments. An average of 3.1 loads $h^{-1}_{PMH}$ were extracted from treatment ARD, whereas only 2.2 loads $h^{-1}_{PMH}$ were extracted from DRR. The mean volume per load differed between treatments, with the average load volume of 7.7 $m^3$ under treatment ARD, and 10.3 $m^3$ under treatment NRD. Thus, even though extraction per load was faster under treatment ARD, a greater volume was carried per load under treatment NRD, resulting in similar hourly extraction costs of 17.9 $m^3$ $h^{-1}_{SMH}$ and 19.3 $m^3$ $h^{-1}_{SMH}$ respectively. Production was lower under treatment DRR, with 1.7 loads $h^{-1}_{SMH}$ extracted and an average load volume of 8.1 $m^3$ resulting in 13.4 $m^3$ $h^{-1}_{SMH}$ extracted. Using a machine cost of €45.89 $h^{-1}_{SMH}$, the timber forwarding costs under treatments ARD and NRD were €2.56 $m^{-3}$ and €2.38 $m^{-3}$, respectively, whereas under treatment DRR, the forwarding costs were higher at €3.42 $m^{-3}$.

*Residue bundling*

A total of 589 bundles were produced during the study. Mean bundle dimensions were 0.65 m diameter and 2.45 m length. Table 2 also displays the productivity and cost of the bundler and forwarding operations under the three different conditions. The residue bundler produced 18 bundles $h^{-1}_{SMH}$ under treatment ARD, 16 bundles $h^{-1}_{SMH}$ for DRR and 22 bundles $h^{-1}_{SMH}$ for NRD. The unit bundling cost was €4.75 under treatment ARD, €5.34 for DRR and lowest at €3.88 under NRD treatment conditions.

*Bundle forwarding and road transportation*

The forwarder extracted 43 bundles $h^{-1}_{SMH}$ in treatment NRD, 47 bundles $h^{-1}_{SMH}$ in treatment DRR and 56 bundles $h^{-1}_{SMH}$ in NRD. Bundle forwarding cost was highest for treatment ARD at €1.20 per bundle, while the lowest at €0.92 per bundle was calculated for treatment NRD. In total, 560 bundles, amounting to 160.4 t were transported in seven self-loading rigid and trailer timber trucks into Medite, which equated to an average of 80 bundles per truck. There was some loss of bundles from the supply chain. A total of 22 bundles were not forwarded from treatment DRR, as some were deemed inaccessible by the forwarder operator due to slope and several were used under the forwarder to aid traction. Seven bundles from treatment NRD were left at the forest roadside and were not transported to the end-user.

*Bundle shredding*

The time study results of the residue bundle shredding are also detailed in Table 2. The mean number of bundles processed per scheduled machine hour was 79 bundles, with an estimated cost of €2.31 per bundle (using an estimated cost per scheduled machine hour of €182.61 for the shredder and a loader to feed the shredder).

*Fuel quality*

At the time of harvesting, treatment mean moisture content values differed by less than 2% (Table 3). The moisture content of the loose residues increased from 44% to 61% under treatment ARD, from 42% to 52% for DRR and from 42% to 46% for NRD. Ash content, expressed on a dry weight basis, increased in treatments ARD and NRD between harvesting and bundling (Table 6). Gross and net calorific values, expressed as the energy content on a dry-weight basis ($GCV_{db}$ and $NCV_{db}$, respectively), remained relatively unchanged between harvesting and bundling, meaning that the energy potential due to the chemical composition did not change. Net calorific value, at the time of delivery, ($NCV_{ar}$) which is the term used to describe the energy content available accounting for the moisture content, reduced in all treatments between harvesting and bundling, as the moisture content increased in all treatments. The loss of useful energy content was greatest from the ARD treatment and least from NRD.

**Table 2:** *Productivity and cost results covering machine operations for harvesting and bundling across the three different treatments.*

| | ARD treatment | DRR treatment | NRD treatment |
|---|---|---|---|
| **Roundwood harvesting** | | | |
| Total no. of trees | 192 | 457 | 235 |
| Harvesting rate (trees $h^{-1}_{SMH}$) | 28 | 32 | 28 |
| Harvesting cost (€ $m^{-3}$) | 4.02 | 4.23 | 4.47 |
| **Roundwood forwarding** | | | |
| Total no. of loads | 16 | 31 | 26 |
| Average extraction distance (m) | 127 | 166 | 152 |
| Volume extracted ($m^3$ $h^{-1}_{SMH}$) | 17.9 | 13.4 | 19.3 |
| Extraction (€ $m^{-3}$) | 2.56 | 3.42 | 2.38 |
| Roadside roundwood cost (€ $m^{-3}$) | 6.58 | 7.66 | 6.85 |
| **Residue bundling** | | | |
| Total no. of bundles | 74 | 270 | 230 |
| Bundles ($h^{-1}_{SMH}$) | 18 | 16 | 22 |
| Cost per bundle (€) | 4.75 | 5.34 | 3.88 |
| **Bundle forwarding** | | | |
| Total no. of loads | 6 | 7 | 10 |
| Mean extraction distance (m) | 193 | 197 | 138 |
| Bundles ($h^{-1}_{SMH}$) | 43 | 47 | 56 |
| Forwarding cost per bundle (€) | 1.20 | 1.10 | 0.92 |
| Cost per bundle at roadside (€) | 5.94 | 6.43 | 4.80 |
| **Bundle shredding** | | | |
| Bundles ($h^{-1}_{SMH}$) | 79 | 79 | 79 |
| Shredding cost per bundle[a] (€) | 2.31 | 2.31 | 2.31 |

[a] Shredding cost was an average for all treatments, n = 78 bundles.

The industry reference for woodfuels across Europe, the EN standards document EN ISO 17225-1: 2014, Solid biofuels – Fuel specifications and classes – Part 1: General requirements, published by the NSAI (2014), gives typical values for coniferous wood, sourced throughout Europe, including virgin harvesting residues. These values are displayed in the final column of Table 3 for comparison. The energy content delivered was highest under treatment NRD, which was estimated as 501 GJ $ha^{-1}$ (Table 4). The lowest energy content was observed under treatment ARD, which was estimated at 240 GJ $ha^{-1}$.

**Table 3:** *Quality parameters of the residues were tested at time of harvesting and at time of bundling (seven months later). Mean values are presented with a standard deviation from the mean in brackets. Parameters were calculated on a dry-weight basis (db) where indicated. Typical values presented are taken from EN 14961-1: 2010, Solid biofuels – Fuel specifications and classes – Part 1: General requirements (NSAI 2014) and describe what can generally be expected of conifer logging residues in Europe.*

| Treatment operation | ARD Harvest | ARD Bundling | DRR Harvest | DRR Bundling | NRD Harvest | NRD Bundling | Typical values |
|---|---|---|---|---|---|---|---|
| MC (%) | 44.0 (3.7) | 60.7 (8.2) | 42.0 (2.3) | 51.7 (10.1) | 42.3 (4.9) | 45.8 (9.1) | <10->55 |
| % ash (db) | 3.7 (2.0) | 6.5 (2.6) | 3.2 (1.3) | 3.2 (0.5) | 2.9 (1.8) | 5.8 (2.7) | <1-10 |
| % C (db) | 52.7 | 50.4 | 52.3 | 51.1 | 53.6 | 50.7 | 48-52 |
| % H (db) | 5.14 | 4.74 | 5.31 | 4.65 | 4.98 | 4.81 | 5.7-6.2 |
| % N (db) | 0.98 | 0.86 | 0.58 | 0.47 | 1.02 | 0.64 | 0.3-0.8 |
| % S (db) | <0.1 | 0.0 | <0.1 | <0.1 | 0.0 | <0.1 | 0.02-0.06 |
| % Cl (db) | 0.03 | 0.02 | 0.03 | 0.01 | 0.04 | 0.01 | <0.01-0.04 |
| $GCV_{db}$ (MJ $kg^{-1}$) | 21.0 (0.2) | 20.1 (0.1) | 20.8 (0.2) | 20.8 (0.2) | 20.8 (0.3) | 20.8 (0.7) | 19.5-21.5 |
| $NCV_{db}$ (MJ $kg^{-1}$)[a] | 19.8 | 19.0 | 19.6 | 19.7 | 19.7 | 19.8 | 18.5-20.5 |
| $NCV_{ar}$ (MJ $kg^{-1}$)[a] | 10.0 | 6.0 | 10.4 | 8.4 | 10.3 | 9.6 | - |

[a] *$NCV_{db}$ and $NCV_{ar}$ are calculated according to EN 14918. An oxygen value of 40% db for logging residues was used for the calculations, as per ISO 17225-1. $NCV_{ar}$ used the MC% observed in the field to estimate the net energy value at field MC%.*

**Table 4:** *Energy content per hectare from residue bundles as delivered by the fuel from across the three treatments.*

| | ARD treatment | | DRR treatment | | NRD treatment | |
|---|---|---|---|---|---|---|
| | total | $ha^{-1}$ | total | $ha^{-1}$ | total | $ha^{-1}$ |
| No. bundles | 108 | 119 | 207 | 131 | 245 | 202 |
| Delivered weight (t) | 36.4 | 40.0 | 60.7 | 38.4 | 63.2 | 52.2 |
| Dry matter weight (odt) | 15.5 | 17.0 | 30.5 | 19.3 | 34.8 | 28.7 |
| Delivered energy (GJ) | 218 | 240 | 502 | 318 | 606 | 501 |
| **Energy per bundle (MWh)** | **0.56** | | **0.67** | | **0.69** | |

## Discussion

The treatments represented scenarios with different levels of preparation for bundling. Brash that was driven over, particularly with multiple passes by the forwarder, may become contaminated with soil and stones that can cause wear and damage to the bundler and chipper/shredder. The driven-on brash may also become compacted and sodden if allowed to stand in water, perhaps delaying needle shedding. Soil and stone contamination of delivered fuel will increase the ash content of the fuel, reducing energy output and increasing ash disposal and boiler maintenance costs. The higher moisture content of the wood from the ARD treatment (60.7%), than in DRR (51.7%) and NRD (45.8%) treatments, suggests that the preparation of the brash facilitated drying of the bundles to a lower moisture content. This was most likely due to less brash being compacted in treatment DRR, and in treatment NRD being loosely piled to facilitate drying. It must be also noted that even though the moisture content may rise during the seasoning period, seasoning is still necessary, as green needles should be allowed to desiccate and fall off as they are not appropriate boiler fuel.

As expected, ash content after roundwood harvesting was highest from treatment ARD due to soil and stone contamination in residues. Values were lowest in treatment NRD, where residues were not driven on. Ash content increased after bundling, suggesting that soil contamination occurred during bundling as a result of the gathering of loose residues in the grapple.

The results of this study suggest that fuel characteristics of Irish logging residues are comparable to the European normal standard for conifer logging residues. The ash values observed in the study ranged from 3.2% to 6.5%, which is higher than the normative values of 1 to 4%. Hydrogen values were slightly lower than the normative of 5.7 to 6.2% at both harvesting and bundling. All the sulphur values were low, so much so that there was difficulty in detecting them, consequently a result of <0.1 is presented for values in this study. Chlorine content is an important component of woodfuel to evaluate, as high chlorine content corrodes boilers during combustion at temperatures above 480 °C (Alakangas 2005). The normative figures for chlorine in Europe are given as between <0.01 to 0.04%, corresponding to values tested here. In Finland, the energy content of a residue bundle is approximately 1 MWh (Laitila 2005). In this study it was found that the energy content per bundle was in the region of 0.6 – 0.7 MWh. In Finland, bundles are produced to a length of 3 m, whereas in this study the bundles were made to approximately 2.5 m in length, in order to maintain the structural integrity of the bundles (longer bundles fell apart). The reason the 3 m-length bundles are practical in Finland may be related to a larger top diameter specification for pulp logs (8 cm), which allows longer lengths of roundwood to be included in the bundles providing greater stiffness and rigidity.

The forwarder cost under treatment DRR was high due to the reduction in space for stacking the logs along the extraction racks. In this treatment, the logs were stacked only on alternate extraction racks, so less space was available for machine movement. This caused the assortments to be stacked less precisely, so the forwarder had to spend more time sorting logs while loading.

Unfortunately, because of budget and logistic limitations, the trial could not be replicated on more sites. For this reason, site interaction effects could not be controlled, which meant an in-depth statistical analysis could not be carried out. Nevertheless, the results of the inventory carried out prior to treatment indicated that tree volume and other tree characteristics differed little between plots, suggesting that within site variation was unlikely to have confounded the results. The plots were located adjacent to one another so that the plot characteristics were as similar as possible. There are also other considerations to residue harvesting which were outside the scope of the trial, such as impacts on soil structure due to the non-use of a brash mat under treatment NRD, as well as the potential nutrient loss resulting from the removal of the brash. The UK forest standards (UKFS) (Forestry Commission 2011) recommend that the harvesting of forest residues should be avoided on soils that are at risk of increased soil and water acidification. The UKFS also identifies that the removal of brash could potentially contribute to a reduction of the net fertility of a site, especially on sites with naturally low fertility and with shallow soils subject to high rainfall. The UKFS recommend that a risk assessment prior to residue harvesting on a site is needed to insure that long-term fertility is not compromised. For these reasons, residue harvesting will not be suitable at all forest sites. The impacts of residue harvesting and the criteria for site selection will be topics for future research.

**Conclusions**

Preparation of brash where suitable, by minimising its use as a brash mat, significantly improved the quality of the bundles. The quality parameters of the fuel all fell within the European normative figures. Seventeen odt ha$^{-1}$ were recovered from the treatment with no brash preparation. Over 60% more, 28 odt ha$^{-1}$, was recovered from the treatment where all brash had been piled to one side, and no machines had driven on the brash. The brash that was not driven over also had a lower moisture content which resulted in a higher energy content: 9.59 MJ kg$^{-1}$ in comparison to 5.99 MJ kg$^{-1}$ for the brash recovered without any preparation. This resulted in a delivered energy content of 501 GJ ha$^{-1}$ where all the brash had been prepared, compared to 240 GJ ha$^{-1}$ in the treatment without any preparation. The cost of roundwood production (at forest roadside) varied between treatments, from €6.58 m$^{-3}$ to €7.66 m$^{-3}$. The main cause of higher roundwood harvesting costs in treatments where the residues were partially driven over was the additional time the forwarder spent loading. The bundler productivity was higher (34 bundles h$^{-1}_{SMH}$) on the treatment where all the brash had been prepared, where as a result the cost of production was lower. The cost of bundling and bundle forwarding was €4.80 per bundle under this treatment, compared to €5.94 where no preparation was involved.

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**References**

Ackerman, P., Belbo, H., Eliasson, L., De Jong, A., Lazdins, A. and Lyons, J. 2014. The COST model for calculation of forest operations costs. *International Journal of Forest Engineering* 25: 75-81.

Alakangas, E. 2005. *Properties of Wood Fuels Used in Finland-Biosouth Project*. VTT Processes, Technical Research Centre of Finland. Jyvaskyla. pp 58.

Asikainen, A. 2001. Design of supply chains for forest fuels. *Supply Chain Management for Paper and Timber Industry*. pp 90-179.

Andersson, G. and Nordén, B. 1998. Composite residue logs: a new concept in bioenergy fuel. *Skogsforsk News*.

Behjou, F.K., Majnounian, B., Dvorak, J., Namiranian, M., Saeed, A. and Feghhi, J. 2009. Productivity and cost of manual felling with a chainsaw in Caspian forests. *Journal of Forest Science* 55: 96-100.

Brinker, R.W., Miller, D., Stokes, B.J. and Lanford, B.J. 2002. *Machine Rates for Selected Forest Harvesting Machines*. Circular-Alabama Agricultural Experiment Station (USA).

Coates, E. and Kent, T. 2013. Biomass estimates for mobilising wood for energy using compact residue logs on harvested conifer plantations in Ireland. *Proceedings of BIOENERGY 2013 – A Boost for Entire Industry*. Jyvaskyla, Finland.

CRDG: Coford Roundwood Demand Group (2011) *All Ireland Roundwood Demand Forecast 2011-2020,* Dublin, Ireland, COFORD.

Forbes, E.G.A., Easson, D.L., Fairgrieve, M., Wilson, B.P. and Love, R.J. 2014. Brash bale production on a clear-felled farm forest and comminution of bales to a biomass energy fuel. *Biomass and Bioenergy* 64: 124-132.

Forestry Comission 2011. *UK Forestry Standard Guidelines*. Forestry Commission, Edinburgh.

Hakkila, P. 1989. *Utilization of Residual Forest Biomass*. 1st Ed. Springer Verlag, Helsinki, Finland.

Hoyne, S. and Thomas, A. 2001. *Forest residues: Harvesting, Storage and Fuel Value*. COFORD, Dublin, Ireland.

Johansson, J., Liss, J.E., Gullberg, T. and Bjorheden, R. 2006. Transport and handling of forest energy bundles – advantages and problems. *Biomass and Bioenergy* 30: 334-341.

Kärhä, K., Rönkkö, E. and Gums, S.I. 2004. Productivity and cutting costs of thinning harvesters. *International Journal of Forest Engineering* 15: 43-56.

Kofman, P. 1995. *Siwork 3: User Guide*. Danish Forest and Landscape Research Institute, Vejle, Denmark.

Laitila, J. Cost structure of supply chains in Finland. *Northern Woodheat Symposium 2005*. June 5th – 9th, Joensuu, Finland.

Ledoux, C. and Huyler, N.K. 2001. Comparison of two cut-to-length harvesting systems operating in eastern hardwoods. *International Journal of Forest Engineering* 12: 53-59.

Lehtikangas, P. and Jirjis, R. 1997. Storage of logging residues in bales. *Proceedings of the International Conference Biomass for Energy and Industry*. Wurzburg, June 1997. pp 1013–5.

Levy, P.E., Hale, S.E. and Nicoll, B.C. 2004 Biomass expansion factors and root: shoot ratios for coniferous tree species in Great Britain. *Forestry* 77: 421-430.

Liska, S., Klvac, R. and Skoupy, A. 2011. Evaluation of John Deere 1490D operation phase in typical conditions of the Czech Republic. *Journal of Forest Science* 57: 394-400.

Magagnotti, N. and Spinelli, R. 2011. Integrating Animal and Mechanical Operations in Protected Areas. *Croatian Journal of Forest Engineering* 32: 489-499.

Miyata, E. 1980. *Determining Fixed and Operating Costs of Logging Equipment*. North Central Forest Experiment Station, Forest Service, US Dept. of Agriculture.

Murphy, G. 2009. *Irish Logging Productivity and Costing Model*. (Version 1.10) [Computer software].

National Board of Forestry. 2008. *Statistical Yearbook of Forestry 2008*. Jönköping, Sweden.

NSAI. 2014. *EN ISO 17225-1: 2014, Solid biofuels – Fuel specifications and classes – Part 1: General requirements*.

Phillips, H. 2011. *All Ireland Roundwood Production Forecast 2011-2028*. COFORD, Department of Agriculture Fisheries and Food, *Dublin*.

Rummer, B., Len, D. and O'Brien, O. 2004. *New Technology for Residue Removal*. Forest operations research unit, Auburn, Alabama.

Spinelli, R., Owende, P.M. and Ward, S.M. 2002. Productivity and cost of CTL harvesting of *Eucalyptus globulus* stands using excavator-based harvesters. *Forest Products Journal* 52: 67-77.

Spinelli, R. 2011. *Supply of Wood Biomass for Energy Purpose: Global Trends and Perspectives*. Italy.

Spinelli, R. and Magagnotti, N. 2009. Logging residue bundling at the roadside in mountain operations. *Scandinavian Journal of Forest Research* 24: 173-181.

Spinelli, R., Magagnotti, N. and Picchi, G. 2011 Annual use, economic life and residual value of cut-to-length harvesting machines. *Journal of Forest Economics* 17: 378-387.

Spinelli, R., Magagnotti, N. and Picchi, G. 2012. A supply chain evaluation of slash bundling under conditions of mountain forestry. *Biomass and Bioenergy* 36: 339-345.

Steele, P., Mitchell, B., Cooper, J. and Arora, S. 2008. Bundled slash: a potential new biomass source for fuels and chemicals. *Applied Biochemistry and Biotechnology* 148: 1-13.

Väätäinen, K., Liiri, H. and Röser, D. 2006. Cost-competitiveness of harwarders in CTL-logging conditions in Finland — a discrete-event simulation study at the contractor level. In *Precision Forestry in Plantations, Semi-natural and Natural Forests*. Eds. Ackerman, P., Längin, D. and Antonides, M., Proceedings of the International Precision Forestry Symposium, Stellenbosch University, Stellenbosch, South Africa. pp 451–463.

Van den Broek, R.,Teeuwisse, S., Healion, K., Kent, T., Wijk, A van., Faaij, A. and Turkenburg, W. 2001. Potentials for electricity production from wood in Ireland. *Energy* 26: 991-1013.

Vonk, M. and Theunissen, M. 2007. *Harvest of logging residues in the Dutch forest and landscape*. Biomassa-upstream stuurgroep. Wageningen Netherlands.