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COFORD

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Front cover: *Silvatec* terrain chipper, operating on band tracks at Toormakeady, Co Mayo.

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EXECUTIVE SUMMARY

The main objective of the ForestEnergy 2007 & 2008 Technology Transfer Programme was to demonstrate cost-effective woodfuel supply chains for woodchip suitable in industrial, medium and small-scale applications and firewood supply chains in small-scale applications. The main forest resource targeted for these activities was private forest at the first thinning stage. Five conifer and four broadleaf thinning sites were identified based on geographic location, and their being representative of the normal range of site conditions, ground bearing capacity and slope found in Irish forest plantations. During the field trials, public demonstrations of the machinery and methods used were held in conjunction with Teagasc and the Forest Service. Five demonstrations were held during harvesting operations and a further three were carried out during the chipping operations.

The woodfuel production methods trialled on conifer sites were as follows:

1. 3 m shortwood[1] lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
2. 3 m to 4.5 m xenergy wood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
3. Whole trees harvested by chainsaw, chipped in the stand with a terrain chipper, extracted by chip forwarder.
4. Whole trees treated with herbicide, and killed chemically, felled and chipped in the stand by terrain chipper, extracted by chip forwarder.
5. Whole trees harvested by chainsaw, extracted by winch and chipped by a roadside chipper.
6. Variable shortwood lengths harvested by chainsaw, extracted by all-terrain vehicle (ATV) and processed into firewood.

Wholetree terrain chipping was the lowest cost method of woodchip production in conifer first thinning. The production costs for wholetree harvesting and terrain chipping ranged from €2.22/Gigajoule (GJ) to €4.36/GJ. This method had two advantages over the standard shortwood method and the experimental energy wood method: the harvesting cost was lower, as there was no processing of each tree other than felling; and the harvested biomass per felled tree was greater, on average almost twice (190%) the standard shortwood system. The whole tree assortment produced very acceptable woodchip for large industrial boilers and CHP plants after seasoning for one summer. Trees that were chemically thinned and left standing appeared to dry better than trees left on the ground in the extraction racks. Chemical thinning should be further investigated as the moisture content achieved was lower than other conifer methods. On sites that were chemically treated and the terrain chipper used to fell the trees, the production costs ranged from €4.36-5.86/GJ.

The potential disadvantage of the wholetree method is that no brash is left on the extraction racks for machines to operate on. This has led to the perception that, while the terrain chipping system may be suitable elsewhere, it will not work in Irish forest conditions. The evidence of the field trials carried out in this programme does not support this perception. Certainly some Irish forest sites, with low ground bearing capacity or steep slopes present a challenge to any machine activity. However, the terrain chipping method remained productive throughout and was more productive on all sites compared with other methods. The terrain chipper could always sacrifice some material for brash if required and the addition of band tracks to the wheels of the terrain chipper and the chips forwarder improved traction and reduced soil damage.

Woodchip from shortwood and energy wood assortments had similar production costs. Costs for shortwood harvesting, forwarder extraction and roadside chipping ranged from €5.65-8.64/GJ. Costs for energy wood harvesting, forwarder extraction and roadside chipping ranged from €5.05-7.52/GJ. The energy wood assortment resulted in slightly lower cost due to additional biomass yield per harvested tree, on average 26% more volume than with the shortwood method. Production costs for both assortments were significantly higher than the wholetree terrain chipping method. Shortwood or energy wood harvested for energy markets should be kept for one full summer in the forest, under secure top cover in order to reduce moisture content. While the moisture content is very unlikely (in the case of Sitka spruce) to fall to less than the 35% required by the commercial heating sector, the level achieved will be sufficient to significantly improve the economics of road transport, by reducing load weight and therefore increasing the volume capacity per truck load. On arrival at the wood processing facility logs can be further seasoned over a shorter time period prior to chipping.

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[1] Shortwood is 3 m or variable length delimbed conifer wood, to a top diameter of 7 cm (overbark).

The small-scale woodchip and firewood supply chains trialled were much more expensive than the commercial scale systems. The cost for wholetree harvesting, winch extraction and roadside chipping ranged from €6.47-10.20/GJ. The cost for firewood production using chainsaw harvesting, ATV extraction, and a firewood processor ranged from €17.35-33.72/GJ. Productivity was significantly lower than full-scale commercial operations due to the high manual input and small handling capacity of the machinery used. On the other hand, the production costs assumed that all work was carried out by contractors. These methods could provide forest owners with technically sound methods of producing good quality woodfuel for their own use and local markets at little capital investment other than the time input. These systems could be very attractive diversification enterprises, capable of supplementing the forest owner's income.

The following woodfuel production methods were trialled at broadleaf sites:

1. 3 m lengths harvested by chainsaw, extracted by forwarder, processed into firewood.
2. 3 m lengths harvested by chainsaw, extracted by skidding with quad and timber arch, processed into firewood.
3. 3 m lengths harvested by chainsaw, extracted by quad and trailer, processed into firewood.
4. 3 m lengths harvested by chainsaw, extracted by skidding with horse and timber arch, processed into firewood.
5. 3 m lengths harvested by chainsaw, extracted with horse and trailer, processed into firewood.
6. 3 m lengths harvested by chainsaw, bunched by horse and extracted by forwarder, processed into firewood.
7. 3 m lengths harvested by chainsaw, extracted by tractor and grapple, processed into firewood.
8. 3 m lengths harvested by mechanical harvester, extracted by forwarder, processed into firewood.
9. Whole trees harvested by chainsaw, chipped in the stand with terrain chipper and extracted by chip forwarder.

The total cost for woodchip production in broadleaves using chainsaw felling, *Silvatec* terrain chipping and chip forwarder extraction ranged from €50.75-71.72/m^3 or €4.52-6.49/GJ. Ash whole trees could be felled and chipped in the same operation if the thinning was carried out in the dormant season, as the moisture content of ash in winter is naturally low. If harvesting takes place during the growing season then the trees should be left in the stand to dry for one summer prior to terrain chipping.

The woodchip production cost was lower than the production cost of any of the firewood methods trialled. The lowest production cost method for broadleaf firewood was €101.71/m^3, or €8.67/GJ, using chainsaw harvesting, tractor and grapple extraction, and processing with the *Bilke* firewood processor. The system with the highest cost (€292.31/m^3, equating to €26.05/GJ) was chainsaw harvesting, ATV with timber arch extraction, and processing with the *Hakke Pilke Hawk* firewood processor. As in the conifer firewood production cost methodology, the assumption for broadleaves was that all activities were carried out at contractor pay rates. In broadleaves, due to the typically small plantation area and low harvested volume, there is a strong argument for stimulating forest owners to engage in the thinning work through targeted skills training. With little investment in equipment a forest owner could become self-sufficient in fuel for heating and develop a supplementary income stream from local firewood sales.

Both conifer and broadleaf firewood should be cut and split immediately to promote rapid drying. The most effective and consistent drying will be achieved by storing firewood under top cover in an exposed location with good air flow. Overly sheltered locations with little wind should be avoided. Top cover must be secured in order to be effective. Conifer firewood requires a minimum of 12 months seasoning in order to achieve a moisture content suitable for use; for hardwoods the period required is at least one summer seasoning.

RECOMMENDATIONS

- The level of biomass recovery from conifer first thinning may be increased by harvesting a wholetree or energy wood assortment instead of the conventional shortwood assortment. This leveraging of additional material will be essential to meet increasing demand for wood from the Irish forest resource. On average, the wholetree method and the energy wood assortment yielded 190% and 26% more biomass, respectively, compared with conventional shortwood harvesting.
- The adoption of whole tree first thinning in conifers would require a number of pre-conditions: the availability of a suitable terrain chipper and chips forwarder; the availability of a feller-buncher for selective thinning off the extraction racks; a container-based road transportation system; and, most importantly, an end-user that will accept whole tree woodchip. The *Silvatec* terrain chipping system has a maximum productivity per unit of approximately 30,000 m^3 solid volume per year. This matches the scale of demand for industrial-scale heat users and biomass CHP. The likely capital cost of the system, inclusive of road transportation and feller-buncher for selective thinning is approximately €1.5-2 million.
- Wholetree terrain chipping in broadleaf thinning is strongly recommended as this system produces more biomass and costs less than conventional thinning to produce roundwood.
- Woodfuel road transportation productivity was outside the scope of this project. However, the choice of road transport method had an impact on chipper productivity, in that the roadside chippers all required a truck or tractor and trailer to be present in order for the chipper to work. Maximising the productivity of the roadside chippers took precedence over the transport system, as the hourly rates of the chippers were higher than either the trucks or tractors. This resulted in the transportation component being idle with reduced productivity. Using a container-based system for transporting woodchip would eliminate the waiting time of trucks, as additional containers could always be left in the forest as full containers were transported. This disassociation of chipper and truck would allow for greater flexibility in using both elements.
- One short study of road transportation suggested that transportation using tractors and trailers may be as, or more, efficient as truck-based transportation in circumstances where the haulage route does not take in major public roads. Tractor operating costs are much lower than trucks and travel speeds are similar on forest roads and smaller public roads.
- Reducing the moisture content of wood increases energy content and reduces the transportation cost of woodfuels. Wood should be dried before chipping, as wet woodchip will decompose rapidly unless artificially dried at great expense. Wood may be dried at lowest cost in the forest prior to chipping and road transportation. Shortwood and energy wood assortments should be stored at roadside, in the most wind-exposed location for at least one summer period. Logs should be raised off the ground by placing two rows of logs underneath as bearers. A top cover of heavy gauge plastic should be used to maximise drying and avoid rewetting.
- Woodchip at less than 35% moisture content, required by small commercial boilers, cannot be consistently produced from logs stored in a forest at first thinning age, over one or even two summer seasoning periods due to the generally sheltered, moist microclimate. In this case, it is recommended that logs are stored for one summer in the forest, as this will reduce log haulage cost. Logs should complete drying in a depot at a wind-exposed location prior to chipping. Storage trials carried out at a depot revealed that logs will dry to below 30% moisture content in a 4-6 month period, depending on whether the storage starts in spring or autumn.
- Whole trees should be left to season in the stand for a minimum of one summer season in order for the moisture content to reduce and the leaves to fall off. Wholetree woodchip moisture content of 50% can be achieved in this way. Lower moisture content is achieved by chemically killing the whole tree, so that it is left standing while it dries.
- The natural moisture content of ash is far less than Sitka spruce, and is less than 40% during the dormant season. Thus it is recommended that ash whole trees be harvested during winter and chipped shortly after harvesting, if the market will accept woodchip of 40% moisture content.
- Small-scale harvesting and extraction methods were extensively trialled and found to be technically feasible in both conifers and broadleaves. In conifer shortwood-based thinning, the small-scale method was significantly more expensive than the conventional harvester/forwarder combination and can only

be recommended where conventional thinning is unsuitable. In broadleaf thinning, roundwood harvesting by chainsaw was found to be more productive than machine harvesting. However, extraction of roundwood by forwarder was found to be more productive than any small-scale extraction system trialled. Small-scale systems have greater potential in broadleaf sites, where the total harvested volume is small, the ground is level and even, and where the extraction distance is short.

- Firewood production from both conifer and broadleaf roundwood was examined. Firewood production was found to be labour-intensive; the production cost was largely determined by the time value put on labour. Four firewood processing systems were examined, each with advantages and disadvantages. Prior to purchasing a firewood processor the scale of firewood production and the availability of sufficient quantities of the roundwood size category suitable for the processor should be determined.
- Firewood processing should be carried out shortly after harvesting to minimise drying time. Firewood is market-ready at approximately 20% to 25% moisture content. This condition is achievable by air-drying in both conifers and broadleaves. Both conifer and broadleaf firewood should be stored in a ventilated area under a top cover to avoid rewetting by rainfall. Conifer firewood assessed in this project required two summer seasons to dry to an average moisture content of 20%. Broadleaf firewood could achieve 20% moisture content in four months, if harvested in February and stored until June. Little drying took place during winter and it was observed that moisture content could rise if the firewood was not stored under cover.
- Firewood was packaged in a number of ways in order to make it easier to handle, transport and store. Large 1 m^3 net bags placed on pallets were used initially. It was necessary to place firewood pieces individually into nets as they did not have the structural strength to contain loose firewood, and the entire bag was very unstable, particularly when moved. Small net bags of 30 and 50 litres were used without a problem, other than they were very time-consuming to fill. The best packaging option found was large, 1 m^3 woven-nylon bags that could be stored and moved without the need for pallets and were strong enough to contain loosely-filled firewood.

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INTRODUCTION

In 2006, the ForestEnergy Programme demonstrated several methods and machines for harvesting wood for energy that are commercially used in other countries but were not previously tried in Ireland. Most of the trials were carried out on sites selected to have good bearing capacity in order to demonstrate productive machine operation.

Nearly all the trees that were felled in early 2006 were chipped in the September of the same year after one summer's seasoning. The wholetree method of thinning, whereby trees were felled and left in situ to season in the extraction rack and subsequently processed by a terrain chipper and extracted to roadside, was shown to produce woodchip at the lowest production cost. Woodchip from standard shortwood harvesting was found to be most expensive. All woodchip produced in 2006 was suitable for industrial-scale applications only, as the fuel did not dry to a moisture content acceptable for commercial heating boilers. This indicated that a longer drying period was needed to achieve the required woodfuel quality for small and medium woodchip boilers operating in Ireland. Furthermore, road transportation was identified as the weak link in the supply chain, as most of the chip from the two terrain chippers had to be off-loaded to the ground and reloaded with a front loader into walking-floor trucks.

Furthermore, despite the high productivity of the terrain chipping method, doubts were raised about its ability to operate on ground with lower bearing capacity and on steep slopes.

Finally, the methods trialled in 2006 focused on large-scale woodchip production only. Many farm forest owners, with forests approaching the time for first thinning, identified a need for thinning methods at a scale suitable for small sites and for firewood production, in addition to woodchip. This was particularly true of broadleaf stands, where there was a perception that conifer thinning machinery and methods were uneconomic.

OBJECTIVES

To address these issues, the ForestEnergy Programme in 2007 and 2008 had the following objectives:

- Identify a minimum of four conifer thinning sites, with three located in the western half of Ireland, and three broadleaf thinning sites, and demonstrate cost-effective woodfuel supply chains for woodchip suitable in industrial, medium and small-scale applications and for firewood in small-scale applications;
- Document the productivity and costs of these systems;
- Harvest sufficient wood on each trial site, so that about half could be left in the forest for chipping in 2008, to allow two consecutive summer drying seasons;
- Document the drying rate of wood over one and two drying seasons in the forest and demonstrate efficient transport of woodchip from terrain chipping by container trucks.

FORESTENERGY TRIAL SITES

Five conifer trial sites were identified for the ForestEnergy 2007 & 2008 programme, located in counties Cork, Limerick, Galway, Mayo and Donegal. Further trials were carried out in 2007 on two conifer sites used for the 2006 trials, at Kilbrin, Co Cork and Swan, Co Laois. Four broadleaf trial sites were identified: two in Co Tipperary, and one each in counties Laois and Kilkenny. The names of the sites and their geographical location are in Figure 1.

Figure 1: Location of the ForestEnergy trial sites.

Conifer sites:

1. Abbeyfeale, Co Limerick
2. Ballybofey, Co Donegal
3. Bweeng, Co Cork
4. Toormakeady, Co Mayo
5. Kilbrin, Co Cork
6. Swan, Co Laois
7. Woodberry, Co Galway

Broadleaf Sites:

8. Dovea, Co Tipperary
9. Greenane, Co Tipperary
10. Mullinavat, Co Kilkenny
11. Stradbally, Co Laois

REPORT STRUCTURE

The report presents the results of all studies carried out during the ForestEnergy harvesting operations in 2007 and 2008 and compares results to those published in the ForestEnergy 2006 report. The trial sites are characterised and inventoried, the machinery and methods employed to carry out harvesting, extraction and processing of woodfuel are described and productivity is quantified. The effect of one and two summer's storage on the moisture content of woodfuels is documented. The woodfuel production cost of each supply chain method is detailed.

The report is in four sections:

1. Description of the woodfuel supply chain trials carried out on eleven locations;
2. Methodology used in assessing productivity and costs;
3. Results of all the production trials and woodfuel assessments;
4. Conclusions that could be drawn from the work.

1. WOOD FUEL SUPPLY CHAIN TRIALS

1.1 CONIFER WOODFUEL SUPPLY CHAIN ASSESSMENTS

The first thinning of conifer plantations is a silvicultural operation to create access to the stand for further forest operations and improve growth and add value to the crop. Thinning should ideally be first carried out when the canopy closes and as the competition between the trees reduces increment. Early thinning promotes regular growth of good quality stems, removes poor quality trees and may afford some stability to exposed stands susceptible to windthrow. However, first thinning is sometimes delayed until the cost of the harvesting operations can be offset by the sale of merchantable timber. Such a short-term approach is less profitable overall, when compared with an early thinning intervention. Utilising energy assortments may facilitate earlier thinning as a greater volume of biomass is harvested per tree, compared to standard shortwood-based thinning.

The conifer thinning operations carried out had the objective of demonstrating marketable woodfuel supply chains which are commonly used in mainland Europe. The aim was to assess the cost-effectiveness of these methods under Irish conditions. The thinning trials focused on first thinning requirements in farm forestry conifer plantations; the thinning systems examined were therefore suitable for use on a small-scale, and for commercial scale woodfuel production systems.

Production systems for both woodchip and firewood were trialled at the conifer sites. Four different woodfuel assortments, with different characteristics and supply chains, were produced from the first thinning operations:

1. A standard 3 m shortwood assortment with a minimum top diameter of 7 cm for woodchip production.
2. An energy-wood assortment of crudely delimbed lengths between 3 m and 4.5 m, with no minimum top diameter for woodchip production.
3. A wholetree assortment containing all branches (but free of needles) for woodchip production.
4. A variable-length shortwood assortment for firewood production.

Harvesting was carried out in March–April 2007 at four of the five trial sites and in June 2007 at Toormakeady. At each site harvested assortments for woodchip production were partially chipped after one summer's seasoning in the autumn of 2007. The remainder of the material was left for another year and then chipped in autumn 2008 to investigate drying over two summers. This was the case at all sites, except for Bweeng and Toormakeady. At Bweeng there was insufficient material for a 2-year seasoning study, and so all the material was chipped the first year. As the Toormakeady material was harvested in June it had less seasoning time, and it was decided to chip all the material in the second year. Also, at Toormakeady no data from the shortwood chipping operations were collected, although the material was chipped, due to a public demonstration of machines operating onsite, and the chipper was starting and stopping for explanatory purposes. Two 2006 ForestEnergy trial sites: Kilbrin, Co Cork and Swan, Co Laois were revisited in 2007 in order to complete work on the chemical thinning trial plots. Further herbicide was applied to trees in spring 2007 and the trees were chipped in autumn 2007.

1.1.1 WOODCHIP SUPPLY FROM STANDARD THINNING

Conifer first thinning in Ireland is carried out using the shortwood harvesting system, where assortments are cut to specific dimensions by the harvester in the forest. The main assortment from this cut-to-length system is 3 m length shortwood which is termed pulp and normally is used in panelboard manufacture. Increasingly, this assortment is sold to woodfuel suppliers for chipping. This method may also produce sawlog and stakewood assortments, which are sold off as they have a higher value than shortwood for chipping. The stem is completely delimbed and branches and leaves, in addition to any stem material less than 7 cm in diameter and 3 m in length, are discarded. This material usually forms a brash mat on which the harvester and forwarder drive, improving traction and reducing soil disturbance.

1.1.1.1 HARVESTING

Delimbed shortwood was produced from a line-and-selection thinning, carried out by a *Silvatec* 856 harvester at all sites (Figure 2). The harvester was equipped with a *Silvatec* crane and a Logmax 5000 harvesting head. The crane had a reach of 7.5 m. Generally, one row in seven was removed for the line thinning, and the selection thinning carried out between the lines. The spacing of extraction racks was determined by the number of lines between the drains, so it ranged from one line in six to one line in eight. On average, thinning removed 40% of the stems, 14% being from the extraction rack, the remainder from the selection thinning. Stems were delimbed by harvester head, and cut into 3 m lengths. Sawlog and stakewood assortments were also cut, if present. The assortments were accumulated separately in small stacks perpendicular to the line. The tops and branch material were placed under the machine as a brash mat.

Figure 2: *Silvatec* C 856 harvester.

1.1.1.2 EXTRACTION

Shortly after harvesting, assortments were extracted to the forest roadside with a 90 kW *Valmet* 830 forwarder (Figure 3). The forwarder had a carrying capacity of 8,500 kg and was fitted with band tracks on the rear wheels to increase grip and flotation. The assortments were placed in large stacks along the roadside, and the stacks were raised off the ground by placing bundles of logs underneath, parallel to the road. Two different seasoning methods were trialled, whereby some shortwood stacks were covered across the top with plastic or paper, while others were left uncovered. The sawlog and stakewood assortments were sold off immediately.

Figure 3: *Valmet* 830 forwarder extracting shortwood at Bweeng, Co Cork.

1.1.1.3 CHIPPING

Shortwood chipping was carried out at the forest roadside in both years by Irish-owned and operated machines. The chippers were tractor- or truck-drawn machines, which operated while stationary on the forest road, and were fed by a crane fixed to the tractor or truck. In 2007, all the roadside chipping was done with a *MusMax* T8 drum chipper powered off the PTO of a *Valtra* 165 kW tractor (Figure 4). In 2008, two machines were used: a self-powered 275 kW *Starchl* drum chipper mounted on a truck and a self-powered 450 kW *Jenz* 700 drum chipper which was also truck-mounted.

In 2007, shortwood was chipped directly into Bord na Móna-supplied walking-floor trucks; in 2008 walking-floor trucks from a private company were used. In addition, tractors and trailers were used in 2008, which transported the woodchip to a nearby farmer's yard for short term storage, before being reloaded into walking-floor trailers for long haulage.

Figure 4: *MusMax* T8 drum chipper & *Valtra* tractor chipping shortwood into a walking-floor truck.

1.1.2 WOODCHIP SUPPLY FROM INTEGRATED ENERGY WOOD THINNING

An integrated thinning system may be used where it is known that some or all of the harvested material will go to a woodfuel market. The energy wood assortment was trialled because shortwood cutting-to-length discards the entire stem under 7 cm diameter, which may contain a substantial proportion of the biomass. Also, some thinned trees may not produce any shortwood length and are typically discarded. Woodchip does not require a minimum top diameter log, and therefore cutting-to-length to a minimum top diameter is unnecessary. Producing the energy wood assortment utilised the same machines as the shortwood method, but any stem that was not processed for sawlog or stakewood was cut into lengths between 3 and 4.5 m, regardless of top diameter or quality. A brash mat was formed from the delimbed branches to aid machine travel. The brash mat may be augmented with larger material as required by the harvester. In this way, the removal of additional biomass does not necessarily impact negatively on the site.

1.1.2.1 HARVESTING

The energy wood assortment was harvested in a similar manner to the standard thinning method. A line-and-selection thinning was carried out in all cases with a 120 kW *Gremo* 958HPV harvester (Figure 5). The *Gremo* came with a Loglift parallel crane with 10 m reach and an SP551 harvesting head that could handle trees up to 43 cm in diameter. On average, the thinning removed 40% of the stems, 14% being from the extraction rack, the remainder from the selection thinning. The trees were felled and any sawlog or stakewood assortments were cut to length. The remaining stem was cut into variable lengths of between 3 and 4.5 m. The delimbing knives were set loose on the harvesting head, so that the energy wood assortment was crudely delimbed, retaining branch stubs but removing green needles. The roller pressure on the head was also increased, in order to facilitate drying by breaking the bark along the stem. The assortments were then bunched separately into small stacks perpendicular to the rack. Any branch material was placed under the harvester as a brash mat for increased bearing capacity. This thinning method should yield a greater quantity of biomass compared with the standard cut-to-length method, as the stem top and woody branch stubs are retained. Also, smaller and crooked stems that would normally be discarded are captured using this method.

Figure 5: *Gremo* 958HPV harvester.

1.1.2.2 EXTRACTION

Extraction was done in the same manner as the standard thinning method, using the same 90 kW *Valmet* forwarder. The forwarder extracted the assortments, stacking them along the roadside. Stacks were raised off the ground by placing bundles of logs underneath, parallel to the road. Again some energy wood stacks were covered on top, while others were left uncovered during the seasoning period. The sawlog and stakewood assortments were sold off immediately. Figure 6 shows the energy wood assortment being harvested at Bweeng.

Figure 6: Energy wood assortment with branch stubs and a minimum top diameter.

1.1.2.3 CHIPPING

Chipping was done in the same manner as the shortwood assortment: roadside chippers chipped into walking-floor trailers or tractor and trailers. The same chippers were used to chip the energy wood as the shortwood: in 2007 a *MusMax* T8 drum chipper powered off the PTO of a *Valtra* 165 kW tractor was used; in 2008 a self-powered 275 kW *Starchl* drum chipper mounted on a truck (Figure 7) and a self-powered 450 kW *Jenz* HEM 700 drum chipper were used. A problem arose in the chipping operation at the Toormakeady site: the gradient of a section of the forest road was too steep for the truck pulling the *Jenz* HEM 700 chipper and the truck lost traction, preventing the chipper from locating at the stacks. Luckily the chipping contractor also had a *Jenz* HEM 420 crawler-based machine with off-road driving capability which was brought in to chip the material. This chipper was transported on a low loader to the entrance of the site and was driven under its own power to the stacks. It also chipped under its own power, being fed with a separate small excavator with a grab.

Figure 7: *Starchl* drum chipper outputting to a tipping truck at Ballybofey, Co Donegal.

1.1.3 WOODCHIP SUPPLY FROM WHOLETREE THINNING

The wholetree harvesting method has the potential for complete above-ground biomass removal (apart from needles and leaves). By felling the trees without delimbing or crosscutting, and using a terrain chipper to chip the whole tree, the maximum biomass available from the thinning is processed into woodchip. This system involves a minimum of one summer season between harvesting and chipping, in order for leaves/needles to desiccate and fall off, and for the tree to dry out in the stand. There is no brash mat created during harvesting. However, machines are only used at the chipping phase, and trees or tops may be used as a brash mat at the discretion of the chipper operator.

1.1.3.1 HARVESTING

The wholetree harvesting system differs significantly from the previous two methods, in that initial harvesting is carried out by a chainsaw operator. Trees are felled only, with no delimbing or cross-cutting. Also, the wholetree operation was line thinning only, with no selection between lines. This method was adopted from the Danish thinning system, whereby line thinning is followed by a selective wholetree thinning the following year. The method was previously trialled in 2006 at three sites, selected for good ground bearing capacity. Both parts of the thinning operation were trialled, whereby a feller-buncher was used to carry out selection thinning. The wholetree method was trialled in this series in 2007, on a further five sites in order to assess it on a range of sites, representative of Irish ground conditions, in the West, South and Midlands.

Trees were felled by different chainsaw operators at each site. Felling was in the same direction onto the extraction rack, so that all butts were facing the same way. Butts were totally removed from the stump to prevent any subsequent uptake of moisture from the root system (Figure 8). No cross-cutting or delimbing took place; the whole tree was left intact to season on the forest floor.

Figure 8: Wholetree felling by chainsaw onto the extraction rack.

1.1.3.2 CHIPPING

At the time of the trials, no machines were available in Ireland which could chip whole trees in the forest, so machines were brought in from Denmark to do the work. The wholetree terrain chipping system consisted of a 205 kW *Silvatec* 878CH terrain chipper (Figure 9) and a 125 kW *Silvatec* chip forwarder. The *Silvatec* chipper was designed especially for chipping whole trees felled in thinning. The machine is narrow and articulated in order to be manoeuvrable in extraction racks. In Denmark, under normal conditions, 500 mm wide tyres are fitted. For the 2007 demonstrations, wider 800 mm tyres were used in order to provide additional flotation. The *Silvatec* has a disc chipper and can handle trees up to a diameter of 35 cm. Trees are lifted into the chipper with a Cranab 290HL parallel crane. The grapple was fitted with a chainsaw, so it could double as a felling head to fell occasional trees that were in the way. For the 2008 trials, the machine was equipped with band tracks on all wheels to increase flotation and traction.

The terrain chipper drove down the felled line, using a grapple arm to feed whole trees (butt end first) into a front-mounted disc chipper. By chipping while driving, the chipper was in constant production while it moved down the line. The container of the terrain chipper had a capacity of 15 m^3 in 2007, and 17 m^3 in 2008. When full, the container was unloaded by lifting the entire container to 3.5 m, and then tipping over the rear hinge so that the chips fell from a height into the loading bay of the chip forwarder. The chip container can be levelled hydraulically to compensate for side slopes up to 10 degrees.

Figure 9: *Silvatec* terrain chipper, operating on band tracks at Toormakeady, Co Mayo.

The *Silvatec* chip forwarder (Figure 10) had a container with a capacity equal to that of the container attached to the chipper. The top boards and the front board could be opened hydraulically. When reversing towards the chipper, the driver could see through the chip forwarder, because the head and rear board were open. Just before receiving the load, these boards were closed. After receiving the loads, the side boards were closed to compress the load slightly and to avoid spillage. After driving to the road, the chips were unloaded from a height of 3.2 m. The entire container is lifted on a scissors-like mechanism and then tipped sideways. The lower side board was opened and the chips fell out. The lower side board can also be used to flip the chips further into the container. Ideally, the chip forwarder should return to the terrain chipper before the container was full again, that way the chipper would not have to wait to unload and production could be constant. The forwarder used in 2008 did not have band tracks fitted at first, but after a few days they were fitted.

In 2007, to demonstrate the entire wholetree woodchip supply chain, two lorries were contracted from Denmark to carry out haulage. Each lorry and trailer had two roll-on roll-off containers. The containers were left on the forest road for loading by the chip forwarder. In Denmark, several containers would be distributed on the forest road in order to optimize the chip forwarder turnaround time. Similarly, lorry and trailer haulage productivity could be optimized as long as there were full containers in the forest. In 2008, these lorries were not employed, so the chip forwarder unloaded the woodchip at the landing for reloading by excavator onto walking-floor lorries for haulage to Edenderry Power.

Figure 10: *Silvatec* chip forwarder on band tracks.

1.1.4 WHOLE TREE WOODCHIP FROM CHEMICAL THINNING

Chemical thinning, whereby the line trees to be removed are treated with herbicide and left to die standing, was trialled on three sites in 2006. This method was investigated to find out if the trees would die, and if it was possible to harvest them with the felling head on the *Silvatec* terrain chipper. The trial stands were in Cork (Kilbrin), Laois (Swan) and Roscommon (Frenchpark). Chemical thinning has two advantages: stands that may be susceptible to windthrow may be thinned in this way because the canopy is not opened to the wind, as thinned trees are not immediately removed; and, the treated trees may dry better when left standing, as they are more exposed. Several of the 2006 sites were revisited in 2007 to finish work in the chemically-thinned plots that had not completely died. Some lines of trees from the wholetree row thinning at Swan, which had been left in 2006, were chipped. The Frenchpark site was not included as the site had proven inaccessible due to water logging in 2006.

1.1.4.1 CHEMICAL TREATMENT

In this method, trees in the rows to be removed were crudely brashed to improve access to the stem. The stems were then cut so that the cambium was exposed in at least two places for each 10 cm diameter of the stem (a tree under 10 cm should have two cuts, trees over 10 cm should have three to four cuts). Undiluted *Glyphosate* was applied to the wounds with a brush or a spray gun, as used for stump treatment with urea (Figure 11). The spray gun did not drip as much as the brush.

Figure 11: Treating trees with *Glyphosate* from a knapsack sprayer following wound-cutting by chainsaw.

1.1.4.2 FELLING, CHIPPING & EXTRACTION

Since the soil was not disturbed during the initial chemical thinning treatment, bearing capacity was maintained. This method is thus suitable for stands with a low bearing capacity and especially those vulnerable to windthrow. Since the trees remained standing, they died off slowly, allowing the remaining trees to gradually take over. When the trees were dead and the needles and the small twigs had fallen off, they were felled and chipped in one operation by the terrain chipper (Figure 12). Very small trees, under 5-6 cm diameter, were neither brashed nor chemically treated, but simply cut free of the stump and left standing. Because of their small size and weight, they were not hazardous even while standing. The advantage was that the *Silvatec* chipper did not have to spend time felling such small trees but could subsequently chip them easily. The woodchip was transferred to the chip forwarder and extracted to roadside.

Figure 12: *Silvatec* terrain chipper with felling head removing a chemically-thinned line.

1.1.5 SMALL-SCALE WOODCHIP PRODUCTION FROM WHOLE TREES

A farm forest owner may consider woodchip for domestic consumption or to supply to a small number of local consumers. This small-scale trial sought to demonstrate the opportunity for a forest owner to produce woodfuel chips by simple means. The method could be viewed as a pre-thinning as only already suppressed trees that no longer compete with the standing crop are removed and chipped. Subsequently, thinning that stand would be faster and the mean log size would be of larger diameter.

1.1.5.1 HARVESTING

Small working plots of less than 0.5 ha were defined on each site to trial a selective whole tree thinning system that could be suitable on small sites for local or domestic woodchip production. A chainsaw operator walked through the plot identifying smaller, weaker trees and cut these at the base. The harvested trees typically remained upright, as the tree became hung-up in the surrounding crowns. These trees were then left to season in-situ.

1.1.5.2 CHIPPING

The *TP*230 Greenline disc chipper (Figure 13), mounted on the drawbar of a small high tipping trailer, drawn by a small farm tractor was used to chip small whole trees arising from the selection thinning. This manually-fed chipper was powered off the PTO of the tractor. To assist the operator, a small, remotely-controlled hydraulic winch was mounted on an arch above the chipper. The chipper was set up at the roadside outside the stand. To chip a tree, the operator had to walk through the stand pulling the cable to the tree, grapple the butt end with the cable, which was then winched to the chipper. Generally it was possible to grapple several trees strung along the winch cable. At the chipper, the tree was then manually released from the cable and fed by hand into the chipper. Movement of the cable winch was radio controlled by a handheld device, so that the operator could control the winch from within the stand. The tipping trailer had a capacity of 7 m^3, and was unloaded into transport containers when full.

Figure 13: Winching whole trees to the *TP*230 Greenline chipper with tipper trailer.

1.1.6 FIREWOOD SUPPLY CHAIN

The firewood supply chain was trialled as an alternative to woodchip production. A forest owner could produce firewood without the requirement for expensive equipment or specialised training, and the fuel is easily marketable for domestic stoves or wood gasifiers (conifers are not suitable for open fireplaces as they have a tendency to spark). A forest owner could replace or supplement their own use of fossil fuels, and also sell to local customers by producing firewood from a portion or all of their thinnings.

1.1.6.1 HARVESTING

A combined line-and-selection thinning was carried out by chainsaw in all cases. The number of trees felled selectively was fewer than in the machine thinning plots as the selected trees would frequently get hung-up and were difficult and time-consuming to fell. Cross racks were cut between the main racks in order to facilitate extraction. The trees were felled, delimbed and cross cut into random lengths that could be handled manually. The logs were placed in piles of five to six lengths, parallel to the rack. Residues and some logs were also used to fill in drains that had to be crossed. The remaining branches and other harvesting residues were cleared from the extraction racks.

1.1.6.2 EXTRACTION

Logs were skidded to the roadside by an all-terrain-vehicle (ATV) pulling a small timber arch (Figure 14). The timber arch was loaded manually by the operator. To load it, the operator positioned the ATV at one end of a stack, and ran a choke chain under the logs. A hand-cranked winch on the timber arch pulled the ends of the logs upwards off the ground, thus reducing friction of the logs during extraction. Ideally the small stacks of five to six logs that were made during harvesting were the size of one timber arch load. The extraction worked on a one way circuit using the cross racks made at harvesting, to reduce time delays reversing the ATV and timber arch.

Figure 14: ATV fitted with timber arch for log extraction.

1.1.6.3 PROCESSING

At the roadside logs were cut and split into firewood using a *Hakke Pilke Hawk* firewood processor (Figure 15). This unit was used as it was a self-powered machine with a small Honda engine, and was towable for transport between sites. Logs were manually fed into the machine, and cut into standard 25 cm lengths with the machine's hydraulic chainsaw, controlled manually by a lever arm. Once a length was cut, it dropped down into a hydraulic splitter which split the length into either two or four pieces, depending on the desired setting. The pieces were then pushed onto a conveyer belt by the following length, and conveyed into large 1 m^3 net bags on pallets. The pallets were shifted with a front-end loader or telescopic loader, or by tractor with prongs. The bags were then left to season in different environments: exposed at the forest roadside, covered at the forest roadside, or in shed storage, as part of the drying trials.

Figure 15: *Hakke Pilke Hawk* firewood processor.

1.1.7 ROAD TRANSPORTATION

The transportation of woodfuel from the production site to the end-user is a significant cost in the woodfuel supply chain. This project focused primarily on the supply chain elements from the standing tree to the forest roadside. Obviously, the integration of road vehicles with the chipping operations was an important consideration in demonstrating the productivity of chipping operations in the forest. While the detailed study of road transportation was outside the scope of this project, some studies were made of road transportation of woodchip in both 2007 and 2008. Woodchip transported to Edenderry Power was generally transported using walking floor trucks (Figure 16).

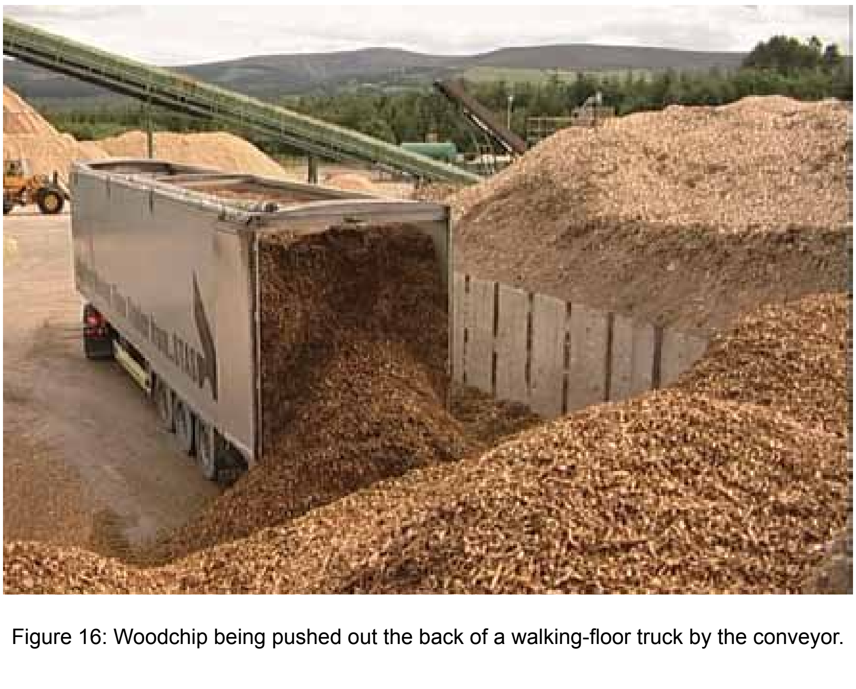

Figure 16: Woodchip being pushed out the back of a walking-floor truck by the conveyor.

1.1.7.1 CONTAINER TRUCKS

In the 2007 programme, a limited number of studies were performed on the transportation of chips from the forest to several consumers by container truck (Figure 17). The trucks were brought over from Denmark to show the complete integration of the wholetree terrain chipping system. This system, as operated on most first thinning sites in Denmark, is highly integrated, whereby the trucks deliver sufficient empty containers to the forest site in order to ensure that the *Silvatec* chipper is constantly productive. The containers are distributed along the forest road to minimize the extraction distance and time. The studies carried out in this project were not comprehensive, and concentrated on the actual road transport productivity and not the unloading and loading of the boxes in the forest.

Figure 17: Woodchip container truck at Woodberry, Co Galway.

1.1.7.2 TRACTORS AND TRAILERS

Tractors and trailers are widespread in Ireland and are generally available, apart from small periods during the year. While the carrying capacity and road speed of tractors and trailers is low compared with truck transportation, the lower operating cost and greater flexibility may mean that tractors and trailers can be cost-effective in certain conditions. In the 2008 studies chips from the *Jenz* 700 truck chipper were blown into tractor & trailer combinations (Figure 18) and transported over 10.7 km to a sawmill yard, where the chips were temporarily stored and then reloaded onto walking-floor trucks. Transportation with tractors was studied for some loads.

Figure 18: *Jenz* 700 chipping shortwood into tractor & trailer.

1.1.8 SUMMARY OF CONIFER WOODFUEL SUPPLY CHAINS

1. 3 m shortwood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
2. 3 to 4.5 m energy-wood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
3. Whole trees harvested by chainsaw, chipped in the stand with a terrain chipper, extracted by chip forwarder.
4. Whole trees chemically thinned, felled and chipped in the stand by terrain chipper, extracted by chip forwarder.
5. Whole trees harvested by chainsaw, extracted by winch and chipped by roadside chipper.
6. Variable shortwood lengths, harvested by chainsaw, extracted by ATV and processed into firewood.

1.2 BROADLEAF WOODFUEL SUPPLY CHAINS

The broadleaf thinning operations had the objective of demonstrating cost-effective supply chains of marketable firewood and woodchip. Therefore the product specification was an important consideration: firewood should be roundwood only, of a reasonable diameter; while woodchip may come from any part of the tree excluding of course the leaves. Thus, two woodfuel assortments were identified as products of the harvesting operation: a standard length roundwood assortment for processing into firewood; and a wholetree assortment containing all branch wood but free of leaves.

The need to season the woodfuel was an important consideration in describing the supply chain. Firewood should be processed fresh, as moisture content reduction is accelerated by cross-cutting and splitting. Therefore harvesting, extraction to roadside, firewood processing and packaging should take place prior to storage. On the other hand, woodchip should only be produced after seasoning, as wet woodchip will decompose quickly and is expensive to dry. Thus, the wholetree assortment was left to season at the stump and chipped after seasoning for at least one summer.

The production study plots were marked for thinning in accordance with Teagasc thinning guidelines*. Lines of trees were marked for removal to create extraction racks at between six rows and ten rows apart, depending on the site. At Stradbally and Mullinavat drains were present at intervals of six tree rows. No deep drains were present at Mullinavat or Dovea. The presence of drains was a major constraint to utilising a standard extraction rack spacing of seven rows apart; as this would mean the extraction rack would be located on the drain in some cases. A total of 350-400 potential final crop trees/ha were identified and marked clearly with a band of paint at breast height. One or two trees competing with the potential final crop trees were selected and marked, with paint or a scribe, for removal. At Mullinavat, there were a high proportion of trees with ash canker which were preferentially removed.

1.2.1 FIREWOOD SUPPLY CHAINS

1.2.1.1 HARVESTING

Harvesting was carried out by chainsaw primarily, with mechanical harvesting trialled in one plot on the Mullinavat site for comparison (Figure 19). Marked trees were felled, delimbed and crosscut into standard 3 m lengths generally. The operators were also responsible for the presentation of the logs for extraction and the piling of brash. The top diameter for this assortment was to a minimum of 7 cm. The method of presenting logs for extraction was dependent on the extraction system employed. Also, the location of the remaining brash and tops was different for each extraction method.

Figure 19: Harvester operating in an ash stand at Mullinavat.

1.2.1.2 EXTRACTION

A number of extraction methods were examined. In addition to determining how the logs were presented and brash dealt with, the method of extraction affected the storage space required at roadside, as the forwarder was capable of making stacks up to 3 m high, whereas the other methods were all limited to a height of c. 1.5 m. In conifers, the forwarder would be capable of stacking much higher, but the crookedness of the broadleaf logs meant that the stacks were kept low for stability.

Extraction by forwarder was trialled in plots on four study sites, where the logs were stacked off the extraction rack and at right angles to it (Figure 20). All the brash was placed in the extraction rack in order to minimize the impact of the forwarder on the forest floor. At the Mullinavat site, forwarder extraction was trialled in two plots: one harvested by chainsaw; the other by mechanical harvester. In both plots the assortment was the same: 3 m lengths. A trial was carried out in a plot on the Greenane site, where a horse and timber arch was used to bunch the logs, prior to extraction by forwarder. This was done in order to examine the impact of extraction distance and of larger stacks of logs on the productivity of the forwarder. Small-scale extraction methods were compared with forwarder extraction.

Figure 20: Presentation of logs and brash for the forwarder in the ash stand at Dovea.

An ATV towing a timber arch was used in plots on four sites. Logs were presented in small stacks on, and parallel to, the extraction rack (Figure 21). The logs were bunched and suspended on one end under the timber arch by a choke chain. All brash was placed off the extraction rack so that it would not interfere with the ATV or impede the skidding. The ATV skidded the logs to roadside on a one-way loop, in order to minimize reversing delays when towing. An ATV towing a small forwarding trailer was used on one site. The trailer was loaded by hand as it did not have a crane. The log presentation on the rack and the ATV one-way route was the same as for the timber arch, though the stacks were bigger in order to minimize the number of stops needed to fill the trailer. Again, the brash was placed off the rack. The main difference between the two ATV-based systems was the increased capacity of the trailer over the timber arch. The extracted logs were stacked at roadside by hand by the ATV operator.

Figure 21: Presentation of logs and brash for ATV for horse extraction in an ash stand at Greenane (yellow bands designate potential final crop trees).

One of the few horse extraction contractors in Ireland was used at two sites. Similarly to the ATV, a timber arch attached to the horse was used to skid logs to roadside and a forwarding trailer loaded by hand was also used (Figure 22). At the Dovea site the logs were cut, where possible, into 6 m lengths to increase the load capacity of each timber arch load. Logs were presented on and parallel to the rack, with the brash cleared off the rack. The horse operated on a one-way loop, again, to minimize delays in reversing when towing. The operator leading the horse loaded and unloaded the logs by hand. The horse and timber arch was also used in conjunction with the forwarder on a Greenane plot, as described above.

Figure 22: Horse and trailer extraction in an ash stand at Greenane.

A tractor fitted with a grapple on the three-point linkage (Figure 23) was utilized on the Mullinavat site to extract 3 m lengths. The logs were presented in the centre of, and parallel to, the extraction rack (Figure 24). The tractor reversed down the extraction rack to load. The brash was placed off the extraction rack, so as not to interfere with the extraction. The grapple gripped a number of logs and raised them completely off the ground before driving out to roadside. The tractor could stack to a height of about 1.5 m by reversing into the stack and unloading the logs.

Figure 23: Tractor and grapple used for extraction at Mullinavat.

Figure 24: Neat presentation of logs and brash for extraction by the tractor and grapple in an ash stand at Mullinavat.

1.2.1.3 FIREWOOD PROCESSING

The broadleaf roundwood lengths were processed into firewood using a number of different methods and types of processor. The simplest method was to cross-cut the lengths into firewood round logs of c. 25 cm length using a chainsaw, though the length was not consistent. A number of logs were placed in a saw bench and secured with a chain. The saw bench ensured that the logs were placed at good working height, and that there was sufficient space under the bench for firewood to drop from a number of loads before it was necessary to clear it away. Firewood produced in this manner was packaged in small net bags for storage. This method was employed at two sites. The saw bench was limited to logs up to 30 cm in diameter. One operator was employed on this system.

A petrol-driven *Hakke Pilke Hawk* firewood processor (Figure 25) was used at three sites. It was capable of processing logs up to 30 cm diameter. The log was loaded and fed by the operator. The machine was equipped to cross-cut with a chainsaw to an adjustable length and split with a hydraulic ram that forced the round log onto a knife, in two separate operations of the one lever. The speed of processing was determined by the speed of cross-cutting, added to the hydraulic ram speed, over which the operator had little control. The knife could be adjusted to split the log into two or four pieces. The firewood pieces fell onto a conveyor belt, which could be raised to an adjustable height of c. 2 m. In the trials carried out on site, this machine was used to fill 1 m^3 bulk bags on pallets. In addition to the operator, a second person was employed to help load logs onto the processor and ensure that the bulk bags were being filled effectively from the conveyor. Firewood of a standard 25 cm length was produced.

Figure 25: *Hakke Pilke Hawk* firewood processor.

A *Bilke* firewood processor (Figure 26), powered off a tractor PTO, was used at one site. It had a conveyor in-feed, which pulled the log into a circular chopper, where the log was cross-cut and split in one operation. A second conveyor extracted the split firewood for unloading into a trailer. The in-feed conveyor limited the capacity of the processor to a maximum log diameter of 20 cm. The firewood length was adjustable. Two production trials were carried out, producing firewood of 20 and 50 cm in length. Only one operator was required to use the machine.

Figure 26: The *Bilke* firewood processor in operation.

A Posch cross-cutter, powered by a tractor PTO, was trialled at one site. This machine required two people to operate it, one to load the logs and the second to cross-cut to an adjustable firewood length, using a circular saw. Firewood was not split, but was conveyed into a trailer. Firewood pieces of a standard length of 25 cm were produced. Logs up to 25 cm diameter could be processed.

1.2.2 WOODCHIP SUPPLY CHAIN

1.2.2.1 HARVESTING

Woodchip production does not require a minimum top diameter log, and due to the small mean tree volume in broadleaf first thinning, much of the above ground biomass is in the top and branches. Therefore harvesting whole trees allows for the maximum biomass to be extracted with little lost as brash. Harvesting was carried out by chainsaw, whereby the trees in the extraction racks were felled onto the rack with the butts facing the same direction. The trees marked for selection off the rack were felled and dragged by the chainsaw operator so that the butt end was placed in the rack at an acute angle (Figure 27).

Figure 27: Presentation of whole trees for terrain chipping at Dovea.

1.2.2.2 CHIPPING

The trees were left on the ground to season for one full summer's season when the *Silvatec* terrain chipper was used to chip the whole trees in the stand. It was equipped with a grapple to feed the trees into the front-mounted disk chipper (Figure 28). The *Silvatec* had a 17 m^3 capacity container and unloaded woodchip into a chip forwarder with an equal capacity container, which then extracted the woodchip to roadside (Figure 29). This ensured that the chipper was continuously productive, other than when waiting for the chip forwarder.

Figure 28: *Silvatec* terrain chipper working in an ash stand at Mullinavat.

Ideally, the chip forwarder would unload into containers located on the forest road for road transportation. However, at the Dovea broadleaf trial site, chips were unloaded into a pile on the forest roadside for reloading into tractors and trailers. At Mullinavat, the chips were unloaded in a nearby farmer's yard and reloaded afterwards into tractors and trailers (Figure 29).

Figure 29: *Silvatec* chip forwarder unloading in yard at Mullinavat.

1.2.3 SUMMARY OF BROADLEAF WOODFUEL SUPPLY CHAIN TRIALS

1. 3 m lengths harvested by chainsaw, extracted by forwarder, processed into firewood.
2. 3 m lengths harvested by chainsaw, skidded by quad and timber arch, processed into firewood.
3. 3 m lengths harvested by chainsaw, extracted by quad and trailer, processed into firewood.
4. 3 m lengths harvested by chainsaw, skidded by horse and timber arch, processed into firewood.
5. 3 m lengths harvested by chainsaw, extracted by horse and trailer, processed into firewood.
6. 3 m lengths harvested by chainsaw, bunched by horse, extracted by forwarder, processed into firewood.
7. 3 m lengths harvested by chainsaw, extracted by tractor and grapple, processed into firewood.
8. 3 m lengths harvested by mechanical harvester, extracted by forwarder, processed into firewood.
9. Whole trees harvested by chainsaw, left to season and subsequently chipped in the stand by terrain chipper and extracted by chip forwarder.

1.3 ASSESSMENT OF WOODFUEL MOISTURE CONTENT AND BULK DENSITY

The woodfuel supply chains investigated in the ForestEnergy Programme were scheduled to include a storage period in the forest to allow seasoning to take place. The aim of the seasoning was to improve the quality of the fuel produced by reducing moisture content. Moisture content reduction increases the energy content and reduces the weight for road transportation. Each assortment had a particular seasoning rate and this was an important consideration in determining the productivity of the supply chain.

Woodfuel supply chain productivity was quantified in terms of the wood energy content in addition to the harvested wood volume. Therefore it was necessary to measure moisture content and bulk density in order to convert harvested volume to energy content.

Moisture content assessment has been outlined for the woodfuel supply chains used at each site, and during harvesting all assortments at all sites were sampled to determine moisture content at the time of felling. Subsequently, changes in moisture content during in-forest seasoning were assessed over two summers. The first assessment was during the chipping operations in autumn 2007, approximately 21 weeks after harvesting. The second assessment was during chipping in autumn 2008, between 63 and 72 weeks after harvesting. The purpose was to determine how long woodfuel should be stored in the forest to get to acceptable moisture content and what circumstances are required to achieve this.

Assessment of bulk density of woodfuels was carried out in order to determine the energy content of woodfuels based on the harvested volume and the moisture content after seasoning. Bulk density assessment also facilitated the conversion of bulk to solid volume and vice versa, which was required to estimate the solid volume of whole trees and the solid volume of loosely packed firewood.

1.3.1 MOISTURE CONTENT OF WOODFUELS

1.3.1.1 SEASONING CONIFER SHORTWOOD AND ENERGY WOOD ASSORTMENTS

Wood that is to be used for energy should be seasoned before it is chipped. The energy content of woodchips is directly related to the moisture content. Reducing the moisture content of shortwood before chipping by natural drying in the forest is the simplest and cheapest method; alternatives add cost. Transporting freshly felled shortwood will generally increase transport cost, as the weight limit is likely to be exceeded before the truck is full. Chip produced from freshly felled shortwood will decompose very quickly, so it must be dried using blown air in dedicated storage; an expensive option which this low value bulk product cannot bear. Seasoning the timber at the forest roadside, before transportation or chipping utilizes the ambient climate to remove moisture and does not require investment in dedicated storage.

In the conifer harvesting trials, two assortments were stored at the forest roadside: 3 m cleanly delimbed pulpwood with a top diameter of 7 cm, and variable length crudely delimbed energy wood without a specified top diameter. The assortments were stacked separately so drying rate could be compared. A number of stacks in each assortment were covered on top to prevent rainwater lodging in the stack, while other stacks were left uncovered for comparison. A paper cover, commonly used for the same purpose in Scandinavia called *Energywrap*, was used as covering (Figure 30). It was supplied in 3 m-wide rolls for the shortwood (Figure 31) and in 4 m rolls for the energy wood.

Figure 30: Covering an energy wood stack with special-purpose *Energywrap* paper.

Figure 31: Covered Sitka spruce shortwood stack at Woodberry.

Trials were carried out at all five conifer first thinning sites, harvested between April and June 2007. At three sites, Abbeyfeale, Ballybofey and Woodberry half the stacks were chipped in September 2007 and the remainder were stored further until chipping in August 2008. All of the stacks at Bweeng were chipped in September 2007, and similarly at Toormakeady in August 2008. All these stacks were covered, apart from one of the shortwood stacks at Woodberry.

1.3.1.2 SEASONING CONIFER AND BROADLEAF WHOLE TREES

The purpose of this trial was to determine how whole trees seasoned in the stand. Seasoning whole trees on extraction racks before chipping relied on ambient climate conditions to remove moisture rather than using dedicated storage. As the felled conifers dried, the needles desiccated, turned brown and dropped off (Figure 32). This had the added advantage that the nutrients, mainly concentrated in the needles, stayed in the forest. The broadleaves were felled during the summer and quickly became bare of leaves as the trees dried.

Figure 32: Sitka spruce whole trees seasoning in the extraction rack at Bweeng.

Wholetree thinning by chainsaw was trialled at five conifer sites in April–June 2007. At three sites, Abbeyfeale, Ballybofey and Woodberry half the felled trees were chipped in September 2007 and the remainder were left to season for a second year until chipping in August 2008. Trees at Bweeng site were entirely chipped in September 2007 and similarly, at Toormakeady all trees were chipped in August 2008. At Woodberry, Ballybofey and Bweeng another small trial was carried out in spring 2007. In a narrow strip along the road, small trees were cut free from the stump and left standing. In September 2007, after one summer seasoning, the trees were winched to the roadside and chipped for energy, by a small tractor-mounted chipper with a winch attachment over the in-feed. Two conifer chemical thinning trials carried out at Swan and Kilbrin in 2006 (Figure 33), were revisited in spring 2007 and received a second chemical treatment as the first had not been completely effective. These two trials were felled and chipped in autumn 2007 using the *Silvatec* terrain chipper.

Figure 33: Chemically-thinned line of Sitka spruce at Swan.

Broadleaf wholetree thinning trials were carried out at three sites: Dovea, Greenane and Mullinavat. Wholetree thinning plots were laid down at Dovea in July 2007, at Greenane in February 2008 and at Mullinavat in April 2008. Trees in the Dovea and Mullinavat trials were chipped in September 2008. Ground conditions were not suitable for terrain chipping at Greenane during that period.

1.3.1.3 SEASONING CONIFER AND BROADLEAF FIREWOOD

Firewood should be well seasoned and dried to less than 25% moisture content before it is used. If it is too wet, there is likely to be poor combustion, leading to the emission of smoke and fine particles and the formation of soot in the chimney, which in turn may lead to a chimney fire. The energy content of firewood is directly related to the moisture content. Natural drying is the simplest and cheapest method. Natural drying can achieve a moisture content of about 18-20%. At this moisture content, the moisture between the wood cells and within the cells has evaporated and only the water chemically bound to the cell wall remains. Generally speaking it is not possible to dry wood below this level in the typical Irish climate. Artificial drying can reduce moisture content to 8-10%, for example sawn timber that is dried in a kiln. Long pieces of roundwood take a long time to dry. Most evaporation takes place from the exposed ends of the logs; and bark restricts moisture loss from the log. To speed up the drying process, firewood is usually cross cut into the required short lengths and split as soon as possible after harvesting. This increases the surface from which the water can evaporate and thus reduces drying time.

In the ForestEnergy trials, firewood was produced from both conifer and broadleaf roundwood. The firewood was produced using a small mobile firewood processor that cross-cut and split the logs and conveyed the logs into large (1 m^3) net bags stored on pallets (Figure 34).

Figure 34: Large net bags of Sitka spruce firewood in shed storage at Toormakeady.

The large net bags filled with conifer firewood on pallets were stored as follows:

1. Outdoors in the forest where they were produced, without a cover (Abbeyfeale);
2. Outdoors in the forest, but covered with a sheet of plastic to protect from rain. The pallets were stacked with two rows of pallets on the ground and one row placed on top. (Ballybofey);
3. The large net bags produced at Bweeng were transported to WIT and stored under a lean-to in a sheltered location;
4. The large net bags produced at Toormakeady were stored in an enclosed shed in the forest.

The broadleaf firewood was stored as follows:

1. The large net bags filled in Stradbally were stored in a well ventilated lean-to, open on three sides on a nearby farm;
2. The ash wood from Greenane estate was stored as two assortments: split and round firewood in separate 1 m^3 net bags. The net bags were placed outside on pallets and covered with plastic.
3. The small net bags of firewood produced at Dovea and Stradbally were stored in an enclosed shed.

Broadleaf firewood was also produced using a variety of firewood processors and stored in small net bags of 30 and 50 l capacity (Figure 35). The purpose of this trial was to determine how long firewood should be stored to get to an acceptable moisture content and what was required to achieve it.

The trials were started in 2007, with the exception of Greenane estate, where work began in February 2008. All storage trials were completed by late 2008. The initial moisture content of the logs was determined during the preparation of the bags. All the bags were sampled at different intervals and when the trials were concluded.

Figure 35: 30 and 50 litre net bags of broadleaf firewood in storage at Stradbally.

1.3.2 BULK DENSITY OF WOODFUELS

Woodfuel is a bulk material comprising wood particles, water and air spaces. Bulk density is the weight of a particular quantity of woodfuel divided by its loose volume, and is expressed in units of kg/m^3. Woodfuel bulk density is very useful for estimating transportation and storage needs, where woodfuel is traded by volume, and in calculating energy density from the calorific value. Bulk density (as received) is the measured bulk density at a particular moisture content, so the weight includes the weight of moisture. Bulk density (dry matter) excludes the weight of moisture. Woodfuel bulk density is determined by the wood density, and by fuel particle size range and shape which influences the amount of free space in a load of pellets, woodchip or firewood. Wood density, the relationship of weight to volume, is determined by the wood basic density and the weight of water present in the wood at the time of measurement. Woodchip ranges in length from less than 1 mm to 200 mm, with most being in the 10-50 mm size range. Chips vary in the proportion of wood and bark they contain, depending on whether it comes from whole trees, roundwood or another assortment. Firewood typically ranges in length from 100-500 mm, and also contains varying proportions of wood and bark. Wood and bark have different basic densities and different moisture contents. Thus, there are many sources of variation in bulk density of woodfuels which need to be considered when sampling.

CEN/TS 14961:2005 *Solid biofuels–fuel specifications and classes* recommends that bulk density (as received) is specified for woodchip traded on a volume basis. In addition, bulk density is required if the energy density of the traded firewood is specified. Energy density is the ratio of net energy content and bulk volume and may be expressed in kilowatt hours per cubic metre (kWh/m^3) or Megajoules per cubic metre (MJ/m^3). The energy density of woodfuel is low compared with fossil fuel, so it is important to have a good understanding of energy density, and bulk density, to ensure fuel requirements are met and maintained.

All woodchip and firewood produced at all of the ForestEnergy trial sites were assessed for bulk density (Figure 36). In total, over 1500 bulk density measurements were taken. These are described by site, species and assortment. Both bulk density (as received) and bulk density (dry matter) are presented in Section 3.2. Sources of variation in woodchip bulk density between species, within species, between harvested assortments and between chippers were examined.

Figure 36: Bulk density sampling in the field; 50 litre stainless steel bulk density pot in left of picture.

1.3.3 BULK/SOLID VOLUME CONVERSION FACTORS

Bulk density can be used to calculate a bulk/solid volume conversion factor for a given woodfuel, once the basic density of the wood is known. The bulk/solid volume conversion factor is a constant that, when multiplied by a given solid volume, will provide an estimate of the bulk volume of woodfuel, whether woodchip or loosely stacked firewood. The factor can vary due to a range of variables: including species, assortment, and type of container, method of filling the container, the particle size distribution and shape, and the method of determining the factor to be applied. Bulk/solid volume conversion factors were determined for woodchip and firewood in both conifers and broadleaves. Separate factors were calculated for woodchip produced from different assortments, which can be used to quantify woodfuel production from solid volume, in order to calculate transportation and storage requirements, to derive the solid volume required to satisfy a stated bulk volume of woodfuel and many other conversions needed to facilitate effective and fair trade of woodfuels.

1.3.3.1 DEFINITIONS

Terms used here are according to CEN TS 14588: *Solid biofuels – Terminology, definitions and descriptions:*

Moisture content is the weight of water contained within the wood expressed as a percentage of the total weight.

Basic density is the ratio of the mass on a dry basis and the solid volume on a green basis.

Bulk density is the mass of a portion of a solid fuel divided by the volume of the container which is filled by that portion under specific conditions.

Bulk density (as received) is the material mass on a green basis divided by the bulk volume.

Bulk density (dry matter) is the material mass on a dry basis divided by the bulk volume.

Bulk volume or loose volume is the volume of a material including space between the particles.

Dry basis is the condition in which the solid biofuel is free from moisture.

Dry matter is material after removal of moisture under specific conditions.

Dry matter content is the portion of dry matter in the total material on a mass basis.

Green basis is the condition based on fresh material at specific total moisture.

Solid volume is the volume of individual particles.


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2. WORKING METHODS

2.1 STAND CHARACTERISTICS AND INVENTORY

Site boundaries as identified on maps were confirmed by walking the sites. Total site area, in each case, was measured by GPS. Sites were sub-divided into production study plots by using visible boundaries, where present, such as ride lines, main drains, ditches or roads. Otherwise, plots boundaries were identified by clearly marking the boundary trees on the edge of the plot. A second survey with the GPS confirmed the individual plot areas. The final treated area per site was the sum of the plot areas.

The five conifer study sites chosen were representative of soil types and infrastructure found on farm forests in Ireland. A further criterion was the geographical spread of the sites: three sites were selected in the West, one in the Midlands and one in the South. Bweeng and Ballybofey were mineral soils; Woodberry and Abbeyfeale were mixed mineral and peat soils while Toormakeady was mainly peat. Sites were between 13 and 20 years old, and were all pure Sitka spruce (*Picea sitchensis*), except Ballybofey which was an intimate mixture of Sitka spruce and Japanese larch (*Larix kaempferi*).

Each conifer site was divided into five working plots, with a thinning method prescribed for each. There was no replication of treatments within sites. Working plot sizes ranged from to 0.2-13.6 ha; the larger plots were assigned to the standard shortwood assortment trials and smaller plots for wholetree-with-winch extraction and firewood trials. Stocking and volume of each working plot were assessed by selecting five sample plots at random with each working plot, each containing a minimum of 50 trees. The plot dimensions and the number of stems were recorded. The dbh of every stem was assessed, from which top height trees were selected and measured by hypsometer. As with normal inventory practice, stems less than 7 cm dbh were excluded.

The four broadleaf trial sites at Stradbally, Dovea, Greenane and Mullinavat had good road access and suitable stacking and storage areas. The stands were mainly clear of woody weeds and bramble, with full stocking. One feature of the broadleaf sites was the high proportion of live trees of less than 7 cm dbh. Typically, trees of this size are not included for stocking or volume estimation purposes but they were counted and their dbh taken for this study, in order to determine the proportion of trees in the category.

Trees were measured in each production study plot at each trial site. Five sample plots were assessed, each containing at least fifty trees. Plot dimensions were measured and recorded. All live trees within the sample plot were counted to estimate stocking. Where plots contained mixtures the proportion of each species was estimated. Diameter at breast height was recorded for all trees, and top height trees were identified and measured.

2.2 STANDING VOLUME ESTIMATION

Different methods of standing volume estimation were used in conifer and broadleaf sites. At conifer sites, the standing volume of each plot was estimated from the inventory data. The quadratic mean dbh was converted to basal area, and then multiplied by the stocking, to estimate basal area/ha. Mean top height was converted to form height using the formula:

Form height = -0.314044+ (0.444794*Top height)
(Forestry Commission 2006)

Standing volume/ha was then calculated by multiplying basal area/ha by form height.

At broadleaf sites, an individual tree basal area/stem volume to 7 cm top diameter relationship was developed for each site by selecting line plots of 30 trees from each production study plot. The trees were felled and total height, height to 7 cm top diameter, dbh and stem diameter at 1 m intervals along the stem were measured and recorded. Stem volume to 7 cm top diameter was regressed on basal area per tree. The standing volume/ha and individual tree volume for each production study plot were calculated from the dbh distribution in the inventory sample plots, using the regressions estimated.

2.3 PRODUCTION STUDY METHODS

2.3.1 TIME STUDIES

Production operations in each working plot were carried out by contractors. Different contractors were used in order to assess specific machines in their ownership. All operations were time-studied, with the productive time for each operation recorded, as well as unproductive time.

The operation of each machine was broken down into components, and the time per cycle of output recorded. A cycle can be defined as a repeating action that produces a unit of output. For example, a forwarder cycle consists of driving empty from the forest road to the extraction rack, loading, driving loaded and unloading at roadside. A cycle for a roadside chipper consists of filling a container-load of chips. Time spent on any other activity was recorded as unproductive time. Unproductive time could be due to machine failure or personnel requirements such as rest or lunch breaks.

Two methods of time recording were used depending on the operation. For operations with many time components per cycle a Husky field computer, running SIWORKS 3 time-study software was used. This allowed very brief actions within a cycle to be timed. For example, the harvester time studies recorded an individual time for selection, felling, taking down, cutting-to-length and stacking, for each tree felled. Recording in this manner meant that an in-depth comparison between thinning methods could be carried out. SIWORKS 3 records time in one-hundredths of a minute, called a centiminute (cmin). Therefore, each centiminute is equal to 0.6 second, and there are 6000 cmin in one hour. The benefit of the centiminute is that it allows for time calculations to be greatly simplified.

For operations with only a few components per cycle, each part was recorded with a stopwatch and field sheet. For example, the roadside chipper operation has only two time components: preparing to chip, and chipping. A further example was the time taken to fill a walking-floor trailer, which was approximately one hour, where a stopwatch was more appropriate.

To determine productivity output variables were recorded as follows:

- chainsaw harvesting/harvester operations: the number of log lengths cut from each tree;
- whole tree harvesting: the number of trees felled;
- extraction operations: the number of logs per extraction cycle;
- chipping operations: the dimensions of the chip container;
- firewood processing: the number of logs processed per cycle.

2.3.2 PRODUCTIVITY ANALYSIS

Time study analysis uses only the productive time recorded in the field, known as productive machine hours (PMH). This is because delays and stoppages such as repairs, rest, maintenance, telephone calls, or coffee breaks are generally infrequent and sometimes unpredictable. For example, machine breakdown is infrequent, and may not be captured even where time studies extend over weeks, or even months. However, when a machine does break down it may be out of action for a number of hours or days. Therefore, when analysing the machine productivity based on relatively short time studies, only the productive time is used.

Unproductive time is accounted for by using standard unproductive time allowance factors. The resulting time is called the scheduled machine hour (SMH). The allowances used are standard figures used in industry, and are based on international historical time study data and experience over many years (Brinker *et al.* 2002). Where there was no prior reference value, allowances were assumed. The allowances are given in Table 1. A benefit of using standard allowances is that is if they are considered as being too low or high they can be adjusted, and the results recalculated. This may be the case if a machine is operating in rough site conditions, operator use is hard on the machine, the operator needs more rest due to environmental conditions, or machine age/condition is causing more delays.

The actual hourly rates that were paid to the contractors were used in the productivity analysis as a cost per scheduled machine hour. These are also presented below.

Table 1: Assumed unproductive allowance and hourly rates.

Operation	Method	Unproductive Time Allowance (% Productive Time)	Hourly Rate (€/SMH)
Harvesting	Chainsaw operator (shortwood/firewood)	50	25
	Chainsaw operator (whole trees)	70	25
	Harvester	30	110
Extraction	Forwarder	30	90
	ATV (with timber arch or trailer)	50	30
	Horse (with timber arch or trailer)	50	30
	Tractor and grapple	30	40
Chipping	Silvatec terrain chipper & chips forwarder	30	300
	MusMax	30	100
	Starchl	30	170
	Jenz 420	30	150
	Jenz 700	30	300
	TP Winch Chipper	50	50
Firewood processing	Chainsaw and log bench	50	25
	Hakke Pilke *Hawk* & 2 operators	50	60
	Posch cross-cutter, tractor & 2 operators	50	75
	Bilke, tractor & 1 operator	50	50

Chainsaw operations were charged at €25 per hour. The unproductive allowance differed between chainsaw operations: at 50% for firewood harvesting, and 70% for wholetree harvesting. This was due to the repetitive nature of wholetree felling, which caused operators to take more breaks. The harvester was charged at €110 per hour, and the forwarder at €90 per hour. Both machines were given a 30% unproductive allowance. All the chippers were allocated an unproductive allowance of 30%, but costs varied from €100 per hour for the *MusMax*, to €300 per hour for the *Jenz* 700 and the *Silvatec* terrain chipper with chip forwarder combination. Operators for the firewood processor were charged at €25 per hour, with an additional €10 per hour cost for the machine. In broadleaves, a tractor and operator was charged at €40 per hour.

The volume processed per hour in each activity was calculated by multiplying the mean volume per cycle by the number of cycles per hour. The cost of the machine per unit volume was estimated from the hourly cost of the machine divided by the volume processed per hour. The method of determining the harvested volume is described below.

2.3.3 TRANSPORTATION STUDIES

Transportation studies were carried out on conifer woodchip container trucks in 2007 and tractors and trailers in 2008. The studies were outside the formal scope of this project, and so were carried out ad hoc and were limited to investigating the type of road on which the vehicle operated and the mean speed achieved by the vehicle on each road type. The roads were classified as:

- Forest road;
- Regional road;
- National secondary road;
- National primary route.

The distance travelled on each road type and the time were recorded.

2.4 HARVESTED VOLUME ASSESSMENT

Standing volume was estimated as stem volume to 7 cm top diameter, and a minimum assortment length of 1.3 m. Standing volume differs from harvested volume in two ways. First, any dead trees or trees less than 7 cm dbh are excluded from standing volume, whereas these may be harvested for energy. Second, shortwood assortments are cut to specific lengths, and volume is lost where there is insufficient stem to produce the required length. An energy wood assortment differs from a shortwood assortment, as the entire stem volume to tip and branch stubs are harvested. The wholetree assortment contains all stem volume to tip and additional volume from the branches. It was therefore necessary to quantify the assortment volume being produced in order to estimate machine productivity.

During harvesting, samples of the shortwood and energy wood assortments were measured before being extracted to the roadside. Measurements were carried out in this manner, as once logs were stacked at the roadside, only those at the top of the stack could be measured. The mean volume per log was estimated using Huber's formula:

$$V = L*(D_{mid})\ 2*\pi/40000$$

Where

V: Log volume (m^3)

L: Log length (m)

D_{mid}: Mid-diameter (cm)

As the volume of the wholetree assortment was comprised of branch wood as well as stem wood, it could not be estimated from stem dimensions alone. Wholetree volume was therefore estimated by determining the volume capacity of the chipper container and converting it to solid volume using a conversion factor. The conversion factors were determined experimentally as described in Section 2.7.

In broadleaves, roundwood was processed to a standard 3 m length. This resulted in substantial harvestable volume being left in the forest from lengths less than 3 m. Conversely, the wholetree assortment contained all stem volume to tip and additional volume from branches. Thus the wholetree assortment contained substantially more volume per tree in comparison with standing volume.

At Greenane and Mullinavat, the total harvested volume was estimated. Roundwood was estimated by counting the total number of logs extracted to roadside and individual log volume to estimate total volume. Wholetree volume was estimated from the total number of woodchip loads extracted to roadside. Harvested volume/ha was then calculated by dividing the total harvested volume by the treated area.

2.5 DETERMINATION OF MOISTURE CONTENT

Moisture content of all woodfuel produced in the field trials was determined at three stages: during the harvesting operations to estimate the moisture content at the time of felling; during the chipping operations in 2007 after the woodfuel had seasoned for one summer period; and again during the 2008 chipping operations, after two summers seasoning. The firewood assortments were similarly sampled for moisture content during harvesting, later in 2007, and again in 2008.

2.5.1 CALCULATION OF MOISTURE CONTENT

Moisture content was determined on a total weight basis. The wet weight of each moisture content sample was measured and recorded in the field on a top pan balance measuring to a precision of 0.1g. All woodchip samples were placed in paper bags and were dried at 105oC for 48 hours in a ventilated oven (Figure 37). Samples were re-weighed to determine sample dry weight. Moisture content was calculated and expressed on a total weight basis using the formula:

$$M\% = [(Ww - Wd)/Ww]*\ 100$$

Where

M%: Moisture content expressed as a percentage of the total weight

Ww: Wet weight

Wd: Dry weight

The objective of the sampling intensity used in assessing the woodfuel for moisture content was to ensure that the sample size is sufficient to determine the mean moisture content at a margin of error of ± 2% at the 95% confidence level.

Figure 37: Drying firewood samples in a convection oven prior to moisture content determination.

2.5.2 MOISTURE CONTENT SAMPLING DURING HARVESTING

Five to 15 sample assortment pieces were taken from each working plot on each site during the harvesting operations. All harvested assortments were individually chipped with a *TP*200 disk chipper (Figure 38). The woodchip was thoroughly mixed and five point samples of chip, amounting to at least 1000g each, were extracted from each pile.

Figure 38: Chipping ash roundwood samples for moisture content determination.

2.5.3 MOISTURE CONTENT SAMPLING DURING CHIPPING

During the chipping operations in 2007 and 2008 moisture content samples were collected as part of the bulk density study and were used to calculate bulk density (dry matter), in addition to determining the effect of seasoning on the change in moisture content since harvesting. Three moisture content sub-samples were taken from each bulk density sample. Each moisture content sample was at least 1000 g. On each site a minimum of 25 moisture content samples was taken for each assortment.

2.5.4 MOISTURE CONTENT SAMPLING OF FIREWOOD

Moisture content samples were also taken from the large and small firewood net bags. Typically, 20 individual pieces were taken from each large net bag and five pieces taken from each small bag. Each piece was split into slivers using a vertical log splitter, so that each sliver was less than 1 cm in cross-section, in order to ensure that the piece would dry completely in the oven over 48 hours.

2.5.6 ASSESSMENT OF SEASONING

The assortments were assessed for in-forest seasoning potential over two summers. The first assessment was during chipping operations in autumn 2007, approximately 21 weeks after harvesting. The second assessment was during chipping operations in autumn 2008, between 63 and 72 weeks after harvesting.

Shortwood and energy wood assortments were left to season in covered and uncovered stacks at the forest roadside. The roadside chippers chipped into either 80 m^3 walking-floor trucks or 30 m^3 trailers, drawn by tractor. Eight point samples were taken from each truck load and four samples from each trailer load. Each point sample consisted of a 60 litre (l) sample taken for bulk density analysis. From each bulk density sample, three moisture content samples of approximately 1000 g in weight were taken.

The firewood assortment was stored in 1 m^3 bags and left in different environments to season: uncovered at the roadside, covered at the roadside, or in sheds. After seasoning, ten sample firewood pieces were taken from each 1 m^3 bag. The firewood was split into 1 cm diameter pieces and analysed for moisture content using the oven-dry method, as per the woodchip samples.

The wholetree assortments were left to season on the forest floor. The *Silvatec* terrain chipper containers were 15 m^3 in 2007 and 17 m^3 in 2008. For each chip forwarder load brought to the roadside, two 60 l bulk density samples were taken. The *TP* winch chipper had a container capacity of 7 m^3. Three 60 l bulk density samples were taken from each load produced. In both cases, three moisture content sub-samples, approximately 1000 g in weight were taken from the bulk density samples; with moisture content determined using the oven-dry method.

Firewood products were processed prior to storage and seasoning. Therefore, the initial product moisture content was the same as that of the shortwood assortment sampled during harvesting. The weight of firewood per bag was recorded at the start of the storage period and the bags were reweighed periodically during the storage period. It was assumed that weight loss corresponded to moisture content loss.

Additionally, at the end of the storage period, firewood log samples were randomly selected from the bags. Logs were prepared for moisture content assessment by splitting each one into slivers of less than 1 cm diameter using a hydraulic vertical log splitter, in accordance with CEN/TS 14780, 2005: *Solid Biofuels - Methods for Sample Preparation*. Moisture content analysis of each sample was carried out as described above.

The wholetree assortments at Mullinavat, Greenane and Dovea were left to season in the stand. The post-storage moisture content was assessed during terrain chipping operations in August-September 2008. Each woodchip load of 17 m^3 extracted by the chip forwarder was sampled twice. Each sample comprised c. 60 l of woodchip. Bulk density was assessed on site and three sub-samples, c. 1000 g each, were taken from each bulk density sample for moisture content analysis.

2.6 DETERMINATION OF BULK DENSITY

Bulk density of woodchip was determined at all trial sites, on all assortments and on all chipper types during chipping operations in 2007 and 2008. A total of 1569 individual woodchip bulk density samples were processed. Due to time and operational constraints, it was not possible to sample each woodchip assortment equally in terms of sample size and sample intensity. Firewood bulk density was determined on-site during harvesting trials, as the firewood was placed into large net bags for storage, and again in 2008 as the field trials were completed.

2.6.1 CALCULATION OF WOODCHIP BULK DENSITY (AS RECEIVED)

The procedure for estimating bulk density of woodchip is described in CEN/TS 15103 - *Methods for the determination of bulk density*. The procedure used a 50 l container for determining the bulk density of individual sub-samples. The container is weighed empty, filled with woodchip and reweighed on an Ohaus bench scale, measuring to a precision of 20 g. The weight of the 50 l woodchip sample is converted to a bulk density (as received), expressed in kilograms per cubic metre loose volume (kg/m^3) as follows:

$$BD_{(ar)} = (W2-W1)*20$$

Where

$BD_{(ar)}$: Bulk density (as received) in kg/m^3

W_1: Container weight empty in kg

W_2: Container weight full in kg

During the chipping operations, a bulk density sample was taken from approximately every 8 m^3 bulk volume of woodchip produced. Eight bulk density samples were taken from each truckload, four from each tractor & trailer load and two from each load brought to roadside by the *Silvatec* chip forwarder.

2.6.2 CALCULATION OF FIREWOOD BULK DENSITY (AS RECEIVED)

Bulk density of firewood was estimated differently. All firewood produced during the harvesting trials was cut to standard lengths and, in most cases, split. Firewood was loosely filled into 1 m^3 volume net bags and placed on pallets. The weight of firewood contained within each net bag was determined using a pallet truck with an integrated load cell, measuring to 0.5 kg precision. The weight of the pallet and net bag was excluded to derive the weight of firewood. As the volume of the net bag was 1 m^3, the bulk density of firewood received could be expressed simply in terms of weight:

$$BD_{(ar)} = (W2-W1)/V$$

Where
$BD_{(ar)}$: Bulk density (as received) in kg/m^3
W_1: Pallet and net bag weight in kg
W_2: Total weight of firewood-filled bag in kg
V: Container volume in m^3

2.6.3 CALCULATION OF BULK DENSITY (DRY MATTER)

The bulk density (as received) of a woodfuel sample is heavily influenced by the weight of water present in the sample at the time of measurement. In order to investigate the other parameters influencing bulk density the effect of moisture content must be removed. This is done by calculating the bulk density (dry matter) as follows:

$$BD_{(dm)} = BD_{(ar)} * [1 - (M\% / 100)]$$

Where
$BD_{(dm)}$: Bulk density (dry matter) in kg/m^3
$BD_{(ar)}$: Bulk density (as received) in kg/m^3
M%: Moisture content, expressed as a percentage of total weight

2.7 ESTIMATION OF BULK/SOLID VOLUME CONVERSION FACTOR

Ratios of solid/bulk volume for woodchip and firewood were developed for conifers and broadleaves using datasets from the trial sites. Ratios were developed using the sampled basic density of roundwood compared with the bulk density of derived woodfuels. The basic density was calculated from the measured green density of sample logs and the moisture content of the same logs.

2.7.1 DETERMINATION OF ROUNDWOOD (SHORTWOOD) GREEN DENSITY

Green density was estimated for each log from the log weight and overbark log volume. The individual log weight was measured on an Ohaus bench scales, precise to 20 g. The volume of each log was determined individually. Roundwood lengths were measured to the nearest centimetre. Mid-diameter was measured to the nearest 0.1 cm. The mean volume per log was estimated using Huber's formula.

Green density was calculated as follows:

$$Dg = Wg/V$$

Where
Dg: Green density (kg/m^3)
Wg: Green weight (kg)
V: Log volume (m^3)

2.7.2 BASIC DENSITY DETERMINATION

Basic density was calculated from green density and moisture content. Moisture content of sample logs was determined in the same manner as described in Section 2.5. The basic density was calculated individually for each conifer log, as both green density and moisture content were measured on an individual log basis. The basic density of ash logs was determined individually also; however, average moisture content was used in the determination. Basic density was calculated as follows:

$$Db = Dg * [1 - (M\% /100)]$$

Where
Db: Basic density (kg/m^3)
Dg: Green density (kg/m^3)
M%: Moisture content expressed as a percentage of total weight

Basic density was determined from roundwood samples from four ForestEnergy study sites. Sitka spruce shortwood from the Toormakeady and Woodberry study sites was sampled. Also, ash roundwood from Greenane and Mullinavat study sites was sampled. At Toormakeady, 20 logs were randomly selected from a stack, while at Woodberry the sample size was increased to 100 logs. Some 128 logs were sampled at Greenane, and 227 at Mullinavat. All logs sampled were cleanly delimbed and had been cut to a nominal 3 m length and 7 cm top diameter.

2.7.3 DETERMINATION OF BULK/SOLID VOLUME CONVERSION FACTOR

The relationship of bulk volume of woodchip to the solid volume of the logs from which it was produced was estimated indirectly by weight. Density describes the relationship of weight to solid volume, and bulk density is the relationship between woodchip weight and bulk volume. Therefore, the bulk density /solid density relationship should equate to the bulk volume /solid volume relationship. Moisture content has a confounding effect, as the total weight may be strongly influenced by the amount of water present in the wood. Because of this, moisture content was excluded by using the basic density of the logs and the bulk density (dry matter) of the woodchip.

The factor was determined as follows:

Where
F: Bulk/solid volume conversion factor
D_b: Basic density (kg/m^3)
$BD_{(dm)}$: Bulk density, dry matter (kg/m^3)

This method assumes that the roundwood density is the same in branches and tree tops from wholetree and energy wood harvested assortments.

Because the estimation of a bulk/solid volume conversion factor is heavily reliant on sample bulk density and basic density estimates, their variation was investigated. Mean, standard deviation and the confidence level of the mean, at the 95% confidence level, was determined for all datasets. The margins of error for the conversion factors were calculated by accumulating constituent variable errors.

2.8 ENERGY CONTENT OF WOODFUEL ASSORTMENTS

The productivity of each woodfuel supply chain was quantified in terms of the solid volume produced per unit time. The production cost/m^3 was calculated from the production time and the hourly rate of each element in the supply chain. The production cost per unit of energy contained within the woodfuel was calculated, as this is useful to compare against the energy price of other fuels. It was expressed in Gigajoules.

In order to calculate the production cost per unit of energy, it was necessary to covert the volume in cubic metres solid volume to the energy unit of Gigajoules. Net calorific value (NCV) is the energy content of the wood per unit of total weight, inclusive of the moisture content of the wood. Thus the net calorific value was calculated, based on the mean woodfuel moisture content after storage. The formulas used differ between woodfuel from conifers and woodfuel from broadleaves, as follows:

Where

NCV: Net calorific value in Gigajoules per tonne (GJ/t)

M%: Moisture content % on a wet weight basis

(Serup, 2005)

The second step was to convert energy content per unit weight to energy per unit volume, using the bulk density measurements taken for each load produced, and the bulk volume to solid volume conversion factor outlined elsewhere in this report.

Where

E: Energy content in Gigajoules per cubic metre solid volume (GJ/m^3)

NCV: Net Calorific Value (GJ/t)

D_{bulk}: Bulk density (kg/m^3) on a wet weight basis

F: Conversion factor of bulk to solid volume

The production cost expressed per unit of solid volume could then be calculated on an energy content basis.

3. RESULTS

3.1 CONIFER WOODFUEL SUPPLY CHAINS

3.1.1 CONIFER STAND DESCRIPTIONS

The five trial sites were even-aged, pure Sitka spruce crops, aged between 13 and 20 years, except for Ballybofey which had an intimate mix of Japanese larch through the Sitka spruce. The Abbeyfeale site had the largest mean dbh at 17 cm, and was also the oldest site. Bweeng and Toormakeady both had the smallest mean dbh at 12 cm. The range in mean dbh between working plots within each site was small; the biggest range was 14-18 cm at Woodberry.

Stocking varied greatly between sites, and within sites. The Toormakeady wholetree terrain chipping plot had the highest stocking at 2915 trees/ha, while the Abbeyfeale wholetree winch extraction plot had the lowest at 1341 tree/ha. At Abbeyfeale stocking varied by 948 trees/ha, the largest range of any site. Stocking does not include stems below 7 cm dbh, which may represent a significant proportion of stems in young stands at first thinning age. This is especially true for wood energy harvesting from forests, as although stems below 7 cm dbh have no standard merchantable volume, they can be used as fuel. Top height ranged from 10-14 m on all sites, except for plots 4 and 5 at Woodberry which had top heights of 17 m.

The size of the working plots for the thinning trials varied depending on the systems being investigated. At each site working plots which were numbered 1, 2 and 3, were allocated to commercial-scale thinning systems, and were larger than plots 4 and 5, where small-scale thinning systems were investigated. This was due to the need to confine the area for manual firewood processing and winch extraction operations. The productivity of these operations was lower than the fully mechanised systems. Stand descriptions and treatment areas for the working plots are outlined in Table 2.

Table 2: Stand composition, growth and productivity at the conifer trial sites.

Site	Working plot*	Species composition	Plot area	Age	Stocking	Mean dbh	Top height	Yield Class
			ha	year	stems/ha	cm	m	m^3/ha/yr
Abbeyfeale	1	Sitka spruce	2.8	20	2134	17	14.0	22
	2	Sitka spruce	2.8	20	2289	17	13.0	22
	3	Sitka spruce	3.2	20	2277	17	13.5	22
	4	Sitka spruce	0.2	20	1341	16	13.5	22
	5	Sitka spruce	0.8	20	1922	16	13.5	22
Ballybofey	1	Sitka spruce/larch	12.4	13	2537	14	11.0	24
	2	Sitka spruce/larch	4.3	13	2356	14	11.9	24
	3	Sitka spruce/larch	3.3	13	2210	14	11.2	24
	4	Sitka spruce/larch	0.2	13	2824	14	11.5	24
	5	Sitka spruce/larch	0.8	13	2625	14	10.9	24
Bweeng	1	Sitka spruce	3.0	17	2157	12	10.4	22
	2	Sitka spruce	3.0	17	2022	14	11.8	24
	3	Sitka spruce	3.0	17	2566	12	10.8	22
	4	Sitka spruce	0.5	17	2296	15	10.8	22
	5	Sitka spruce	0.5	17	2256	15	12.5	24
Toormakeady	1	Sitka spruce	5.0	16	2419	13	11.0	24
	2	Sitka spruce	3.8	16	2534	13	11.0	24
	3	Sitka spruce	3.5	16	2915	12	10.0	22
	5	Sitka spruce	1.7	16	2829	12	12.0	24
Woodberry	1	Sitka spruce	13.6	17	2327	14	11.9	24
	2	Sitka spruce	6.2	17	2086	15	10.7	22
	3	Sitka spruce	4.8	17	1919	18	13.5	24
	4	Sitka spruce	0.5	17	1861	14	17.5	24+
	5	Sitka spruce	1.5	17	2521	15	16.8	24+

Working plot*

1. 3 m shortwood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
2. 3- 4.5 m energy wood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
3. Whole trees harvested by chainsaw, chipped in the stand by a terrain chipper, extracted by chip forwarder.
4. Whole trees harvested by chainsaw, extracted by winch and chipped by a roadside chipper.
5. Variable shortwood lengths, harvested by chainsaw, extracted by ATV and processed into firewood.

3.1.2 STANDING VOLUME ESTIMATION IN CONIFERS

The mean tree volume in each plot was estimated by converting the quadratic mean dbh to basal area, and then multiplying basal area by form height. Volume/ha was estimated by multiplying mean tree volume by stocking. Plot 5 at Woodberry had the highest volume of 319 m^3/ha, while plot 1 at Bweeng had the lowest volume of 105 m^3/ha. Interestingly, at this age mean tree volume had more influence than stocking on the volume/ha. The five plots with the largest mean tree volume had the five highest volumes/ha, whereas, none of the five plots with the highest stocking had. The standing volume estimates for the working plots at each study site are presented in Table 3.

Table 3: Standing volume estimates in working plots at each study site.

Site	Working plot*	Stocking	Mean dbh	Mean basal area/ha	Mean tree volume	Volume/ha
		stems/ha	cm	m^2	m^3	m^3
Abbeyfeale	1	2134	17	48.44	0.134	286
	2	2289	17	51.96	0.124	284
	3	2277	17	51.68	0.129	294
	4	1341	16	26.96	0.114	153
	5	1922	16	38.64	0.114	220
Ballybofey	1	2537	14	39.05	0.070	179
	2	2356	14	36.27	0.077	181
	3	2210	14	34.02	0.072	159
	4	2824	14	43.47	0.074	209
	5	2625	14	40.41	0.070	183
Bweeng	1	2157	12	24.40	0.093	209
	2	2022	14	31.13	0.076	154
	3	2566	12	29.02	0.051	130
	4	2296	15	40.57	0.079	182
	5	2256	15	39.87	0.049	105
Toormakeady	1	2419	13	32.11	0.061	147
	2	2534	13	33.63	0.061	154
	3	2915	12	32.97	0.047	136
	5	2829	12	32.00	0.057	161
Woodberry	1	2327	14	35.82	0.077	178
	2	2086	15	36.86	0.079	164
	3	1919	18	48.83	0.145	278
	4	1861	14	28.65	0.115	214
	5	2521	15	44.55	0.127	319

Working plot*

1. 3 m shortwood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
2. 3- 4.5 m energy wood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
3. Whole trees harvested by chainsaw, chipped in the stand by a terrain chipper, extracted by chip forwarder.
4. Whole trees harvested by chainsaw, extracted by winch and chipped by a roadside chipper.
5. Variable shortwood lengths, harvested by chainsaw, extracted by ATV and processed into firewood.

3.1.3 HARVESTED VOLUME IN CONIFERS

The harvesting systems investigated had different capacities to capture biomass from standing trees. The standing volume estimation assumes a complete stem from base to 7 cm top diameter, whereas the actual method of harvesting may capture less or more than this volume. By their nature, cut-to-length systems incur losses. For example, if a tree has a height of 5 m at 7 cm diameter, the standing volume estimate will include the full 5 m. However standard shortwood assortments are 3 m, and the tree will be cross-cut at 3m, leaving the remaining 2 m in the forest. By reducing or removing the top diameter requirement and having a variable length as with an energy wood assortment, such losses are reduced. Wholetree harvesting goes one step further, capturing the complete stem and also the branches and top of the tree, potentially harvesting more volume than the inventory estimates.

The harvested shortwood volume was calculated from a mean individual log volume and the mean number of logs harvested per tree. As described, wholetree harvested volume was calculated from the bulk volume of woodchip converted to solid volume. The mean harvested volume per tree, in each working plot, for all study sites is presented in Table 4.

Table 4: Impact of harvesting method on the harvested volume per tree at each of the conifer sites.

Site	Working plot*	Standing vol/tree	Piece volume	No. pieces/tree	Vol/tree	Difference between harvested & standing volume	
		m^3	m^3	m^2	m^3	m^3/tree	%
Abbeyfeale	1	0.134	0.038	2.01	0.077	-0.057	-43
	2	0.124	0.045	2.24	0.100	-0.024	-20
	3	0.129	0.189	1.00	0.189	0.060	+46
Ballybofey	1	0.070	0.029	1.82	0.053	-0.018	-25
	2	0.077	0.036	1.83	0.066	-0.010	-13
	3	0.072	0.115	1.00	0.115	0.043	+60
Bweeng	1	0.093	0.038	2.09	0.080	-0.013	-14
	2	0.076	0.042	1.63	0.068	-0.008	-11
	3	0.051	0.136	1.00	0.136	0.085	+167
Toormakeady	1	0.061	0.029	1.18	0.034	-0.026	-43
	2	0.061	0.030	1.55	0.047	-0.014	-22
	3	0.047	0.125	1.00	0.125	0.078	+167
Woodberry	1	0.077	0.032	1.39	0.045	-0.031	-41
	2	0.079	0.035	1.94	0.068	-0.011	-13
	3	0.145	0.202	1.00	0.202	0.057	+39

Working plot*

1. 3 m shortwood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
2. 3-4.5 m energy wood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
3. Whole trees harvested by chainsaw, chipped in the stand by a terrain chipper, extracted by chip forwarder.

The two final columns show the difference between the standing volume per tree and harvested volume. All sites followed the same trend: whereby a lower volume was harvested in the shortwood systems compared with the standing inventory estimate. The energy wood assortment also yielded a lower volume, but the reduction was less substantial than the shortwood system. On the other hand, the wholetree method yielded a much higher volume than the standing estimate. Due to the limited data available it was not possible to assign a relationship between standing volume and harvested volume in the different methods. The ranges given in Tables 4 and 5 are however a useful indicator. Further research is required to establish factors to relate harvested volume to standing volume for wood energy procurement.

The energy wood and wholetree systems recovered more biomass per tree from thinning. The additional biomass recovered, as a proportion of the standard shortwood assortment volume per tree, is presented in Table 5. On average, the energy wood system yielded 26% more biomass per tree compared with the standard shortwood method. The wholetree method, where most of the above-ground biomass was recovered, excluding the needles, yielded 190% more biomass per tree compared with the shortwood method.

Harvestable volume was influenced by mean tree volume; at Woodberry the wholetree method recovered 3.5 times the biomass of the shortwood method, but the mean tree volume in the wholetree plot was twice that of the shortwood plot.

Table 5: Additional conifer biomass recovered from energy wood and wholetree methods.

Site	Working plot*	Harvested vol/tree	Additional biomass compared with shortwood	
		m^3	m^3	%
Abbeyfeale	1	0.077	0.000	-
	2	0.100	0.023	30
	3	0.189	0.112	145
Ballybofey	1	0.053	0.000	-
	2	0.066	0.013	25
	3	0.115	0.062	117
Bweeng	1	0.080	0.000	-
	2	0.068	-0.012	-15
	3	0.136	0.056	70
Toormakeady	1	0.034	0.000	-
	2	0.047	0.013	38
	3	0.125	0.091	268
Woodberry	1	0.045	0.000	0
	2	0.068	0.023	51
	3	0.202	0.157	349

Working plot*

1. 3 m shortwood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
2. 3-4.5 m energy wood lengths harvested by mechanical harvester, extracted by forwarder, chipped by roadside chipper.
3. Whole trees harvested by chainsaw, chipped in the stand by a terrain chipper, extracted by chip forwarder.

3.1.4 CONIFER WOODCHIP PRODUCTION COST FROM STANDARD THINNING

3.1.4.1 HARVESTER PRODUCTIVITY 3 M SHORTWOOD METHOD

Table 6 shows the harvester productivity at each site for the standard shortwood thinning. Between 191 and 1021 cycles were recorded; where one cycle was the felling and processing of a single tree. Each cycle was separated into the time taken to select, fell, pull down, delimb and cross-cut a tree and present lengths for extraction. The total productive time per tree was calculated as the sum of these time elements. An unproductive allowance factor of 30% was added to account for delays and stoppages, and the total time per tree was calculated. To estimate the harvested volume per cycle, the number of logs cut from each tree was recorded, and the volume of sample logs was measured. The mean harvested volume per tree was calculated as the product of the number of logs per tree and mean log volume. The harvested volume per hour was calculated by multiplying the mean harvested volume per tree by the number of trees harvested per hour. The harvester was costed at €110 per hour.

Table 6: Harvester productivity and cost in conifer shortwood assortments at all sites.

Site		Abbeyfeale	Ballybofey	Bweeng	Toormakeady	Woodberry
No. cycles studied		241	379	191	204	1021
Productive Time						
Move	cmin	5	4	0	3	9
Select	cmin	22	28	24	22	19
Fell	cmin	8	8	10	7	6
Pull down	cmin	10	12	10	10	8
Delimb	cmin	18	13	14	11	15
Cross-cut	cmin	11	9	13	8	7
Sundries	cmin	1	0	0	1	0
Sub-total	cmin	75	74	71	62	64
Unproductive allowance	%	30	30	30	30	30
	cmin	22.5	22.2	21.2	18.6	19.2
Total/tree	min	0.98	0.96	0.92	0.81	0.83
Trees/SMH		61.5	62.4	65.3	74.4	72.1
Logs/tree		2.0	1.8	2.1	1.2	1.4
Vol/log	m^3	0.038	0.029	0.038	0.029	0.032
Vol/tree	m^3	0.077	0.053	0.08	0.034	0.045
Vol/hr	m^3	4.7	3.3	5.2	2.6	3.3
Hourly rate	€/hr	110	110	110	110	110
Cost	€/m^3	23.21	33.28	21.06	42.87	33.75

The harvester cost for the shortwood assortment ranged from €21.06/m^3 at Bweeng, to €42.87/ m^3 at Toormakeady. The data show that the volume per tree had the greatest influence on the cost of production. When ranked in descending order of volume per tree, the cost/m^3 rises at lower tree sizes (Table 7).

Table 7: Cost of harvesting 3 m shortwood in relation to conifer mean tree volume.

Site	Vol/tree m^3	€/m^3
Bweeng	0.080	21.06
Abbeyfeale	0.077	23.21
Ballybofey	0.053	33.28
Woodberry	0.045	33.75
Toormakeady	0.034	42.87

3.1.4.2 FORWARDER EXTRACTION OF SHORTWOOD

Forwarder extraction was used at all sites for the standard 3 m shortwood assortment. The duration of time studies varied at each site, ranging between two and 23 cycles. A cycle of forwarder extraction was the time taken to drive empty into the forest, fully load the forwarder bunk, drive back to the roadside and stack the shortwood. The time elements are presented as an average in Table 8. The productive time for a cycle was calculated as the sum of the time elements. An unproductive allowance of 30% was added to account for delays and stoppages, and the total time per forwarder cycle calculated. The volume per load was estimated from a count of the number of logs loaded per cycle, multiplied by the average log volume, obtained from measurement of sample logs after harvesting. The rate for the forwarder was €90 per hour. Extraction distance was also recorded (Table 8); it had a substantial impact on productivity, and differed between loads and sites.

Shortwood extraction cost ranged from €8.78/m^3 at Abbeyfeale, to €26.36/m^3 at Toormakeady. The results show that the typical costs are more inclined to be at the lower end of this range, with Ballybofey and Woodberry having costs/m^3 of €10.76 and €13.52 respectively. The Toormakeady cost of €26.36/m^3 may be considered an outlier, as the total time per load of 69 minutes could not explained by a large extraction distance, nor by difficult terrain as the drive in and out times would reflect these factors. Instead, the long loading time may have been caused by the small mean tree volume, which meant logs were sparsely distributed. Toormakeady had the lowest standing volume of all sites and smallest harvested volume. Thus the forwarder travelled further and spent more time loading, compared with other sites.

Table 8: Forwarder extraction of conifer shortwood assortments.

Site		Abbeyfeale	Ballybofey	Toormakeady	Woodberry
No. cycles studied		8	6	2	23
Mean extraction distance	m	455	425	559	544
Productive Time					
Drive empty	cmin	296	226	717	429
Load	cmin	1269	425	3534	2149
Drive loaded	cmin	92	1474	453	212
Unload	cmin	355	209	650	357
Sub-total	cmin	2012	2334	5354	3147
Unproductive allowance	%	30	30	30	30
	cmin	604	700	1606	944
Total/load	min	26.2	30.3	69.6	40.9
Load/SMH		2.29	1.98	0.86	1.47
Vol/load	m^3	4.47	4.23	3.96	4.54
Vol/hr	m^3	10.25	8.36	3.41	6.66
Hourly rate	€/hr	90	90	90	90
Cost/m^3	€/m^3	8.78	10.76	26.36	13.52

3.1.4.3 SHORTWOOD CHIPPING

Shortwood was chipped in autumn 2007 and 2008. Different machines were used depending on the year and contractor availability. All the chippers were Irish owned and operated machines, apart from the *Silvatec* terrain chipper which was used to chip the stacks at the Abbeyfeale site in 2008, as no local contractor was available. Between one and ten cycles were studied per operation, depending on the amount of shortwood present and the size of the chip container. Container sizes ranged from 80 m^3 walking-floor Bord na Móna trucks, to 17 m^3 tractors and trailers. In most cases the time studies captured the chipping of all the stacked material on each site. A chipping cycle was the filling of the chip container, and comprised two elements: preparing to chip, and chipping. The total productive time was the sum of these two elements. To account for delays and stoppages an allowance factor of 30% was added, and thus the total time per unit bulk volume was estimated. The bulk volume was converted to solid volume using a bulk/solid volume conversion factor. The chippers were costed at different hourly rates depending on the quoted price by the contractor. The rates ranged from €100 per hour for the *MusMax* machine, to €300 per hour for the *Jenz* 700.

The productivity results of chipping the 3 m shortwood assortment are shown in Table 9. The cost ranged from €6.03/m^3 using the *MusMax* on the Abbeyfeale site, to €11.41/m^3 using the *Starchl* chipper at the Ballybofey site. The cost variation may be due to site characteristics and mean log volume, however the data suggest that it may have had more to do with the productivity and hourly rate charged for individual chippers. The productivity of the *MusMax* was 14 m^3 per hour at Woodberry in 2007, whereas at the same site in the following year the *Jenz* 700 productivity was nearly four times greater at 49 m per hour. However, the difference in production cost/m^3 was a lot less, as the hourly cost rate for the *Jenz* 700 was three times that of the *MusMax*. At Ballybofey, the productivity of the *MusMax* was 12 m^3 per hour, while the *Starchl* had a higher productivity of 15 m^3 per hour. However, because of the hourly rates, the actual cost/m^3 was less for the *MusMax*.

Table 9: Variation in chipping productivity of the conifer shortwood assortment.

Site		Abbeyfeale		Ballybofey		Bweeng	Woodberry	
Chipper		MusMax	Silvatec	MusMax	Starchl	MusMax	MusMax	Jenz 700
Year		2007	2008	2007	2008	2007	2007	2008
No. cycles studied		1	2	3	4	1	3	10
Load bulk volume	m^3	80	17	50	51	80	80	32
Productive time								
Prepare to chip	cmin	648	151	211	0	768	288	0
Chip	cmin	7032	1384	6185	5449	10477	8868	1038
Sub-total	cmin	7680	1534	6396	5449	11245	9156	1038
Unproductive allowance	%	30	30	30	30	30	30	30
	cmin	2304	460	1919	1635	3374	2747	311
Total/load	min	100	20	83	71	146	119	13
Load/SMH		0.60	3.01	0.72	0.85	0.41	0.50	4.45
Solid vol/load	m^3	28	6	17	18	28	28	11
Vol/hr	m^3	17	18	12	15	11	14	49
Rate	€/hr	100	200	100	170	100	100	300
Cost	€/m^3	6.03	11.34	8.04	11.41	8.83	7.19	6.12

3.1.4.4 SHORTWOOD CHIP PRODUCTION COST TO ROADSIDE

The production cost for the standard shortwood assortment chipped at roadside from first thinning is shown in Table 10. Costs are separated into felling, extraction and chipping, and the cost/m³ solid volume is presented. The energy content per m³ is estimated using moisture content sample results taken during chipping, and the cost per Gigajoule (GJ) is given.

The cost/m³ solid volume ranged from €38.02 on the Abbeyfeale site using the *MusMax* chipper, to €55.45 on the Ballybofey site using the *Starchl* chipper. The production cost per unit energy was affected by the impact of different drying rates on the woodfuel energy content. The lowest production cost per GJ was on the Bweeng site using the *MusMax* chipper, at €5.65/GJ. The highest cost was on the Ballybofey site also using the *MusMax* chipper, at €8.44/GJ. This illustrates the importance and impact of drying rate and moisture content reduction in the woodfuel supply chain production cost.

Table 10: Standard 3 m conifer shortwood assortment woodchip production cost to roadside.

Site		Abbeyfeale		Ballybofey		Bweeng	Toormakeady	Woodberry	
Fell method						Harvester			
Vol/tree	m³	0.077		0.053		0.08	0.034	0.045	
Vol/hr	m³	4.74		3.31		5.22	2.57	3.26	
Hourly rate	€/hr	110		110		110	110	110	
Cost/m³	€/m³	23.21		33.28		21.06	42.87	33.75	
Extraction method						Forwarder			
Vol/load	m³	4.47		4.23			3.96	4.54	
Vol/hr	m³	10.25		8.36		7.17	3.41	6.66	
Rate	€/hr	90		90		90	90	90	
Cost/m³	€/m³	8.78		10.76		12.55	26.36	13.52	
Year		2007	2008	2007	2008	2007		2007	2008
Chipper		MusMax	Silvatec	MusMax	Starchl	MusMax		MusMax	Jenz 700
Vol/load	m³	28	6	17	18	28		28	11
Vol/hr	m³	17	18	12	15	11		14	48
Rate	€/hr	100	200	100	170	100		100	300
Cost	€/m³	6.03	11.34	8.04	11.41	8.83		7.19	6.21
Total cost	€/m³	38.02	43.33	52.07	55.45	42.44		54.46	53.48
Bulk/solid volume factor		2.9	2.9	2.9	2.9	2.9		2.9	2.9
Total cost (bulk volume)	€/m³	13.11	14.94	17.96	19.12	14.64		18.78	18.44
MC post seasoning	%	47.7	44.1	57.1	46.3	46.7		49.9	38.6
Bulk density	kg/m³	248	258	311	265	285		300	264
Net calorific value	GJ/tonne	8.88	9.66	6.84	9.18	9.09		8.40	10.85
Energy content (bulk volume)	GJ/m³	2.2	2.5	2.1	2.4	2.6		2.5	2.9
Production cost	€/GJ	5.95	5.99	8.44	7.86	5.65		7.45	6.44

3.1.5.1 HARVESTER PRODUCTIVITY OF ENERGY WOOD ASSORTMENT

Table 11 details the harvester productivity at each site for the energy wood thinning plots. Between 29 and 382 cycles were captured by time studies per site. A cycle was the felling and processing of a single tree. Each cycle was separated into the time taken to select, fell, pull down, delimb and cross-cut a tree and present lengths for extraction, and are presented as an average time per tree. The total productive time per tree was calculated as the sum of these time elements. An unproductive allowance factor of 30% was added to account for delays and stoppages, and the total time per tree estimated. To estimate the harvested volume per cycle, the number of logs cut from each tree was counted, and sample logs were measured for volume. The mean harvested volume per tree was calculated as the product of the number of logs per tree and mean log volume. The harvested volume per hour was calculated by multiplying the mean harvested volume per tree by the number of trees harvested per hour. The harvester was costed at €110 per hour.

The harvester cost of the energy wood assortment ranged from €15.02/m^3 at Abbeyfeale, to €30.34/m^3 at Toormakeady. The data suggest that tree volume had a large influence on the cost/m^3. On the Toormakeady site, the harvester processed the most trees per hour: 77 per scheduled machine hour. However, as Toormakeady had the smallest tree volume, the cost of harvesting was actually the highest.

Table 11: Harvester productivity in conifer energy wood assortment.

Site		Abbeyfeale	Ballybofey	Bweeng	Toormakeady	Woodberry
No. cycles studied		282	382	29	251	135
Productive time						
Move	cmin				2	na
Select	cmin	15	18	27	20	na
Fell	cmin	6	7	8	7	na
Pull down	cmin	8	8	10	11	na
Delimb	cmin	27	19	23	11	na
Cross-cut	cmin	7	8	9	9	na
Sundries	cmin		1			na
Sub-total	cmin	63	61	77	60	74
Unproductive allowance	%	30	30	30	30	30
	cmin	18.9	18.3	23.1	18	22.2
Total/tree	min	0.82	0.79	1.00	0.78	0.96
Trees/SMH		73.26	75.66	59.94	76.92	62.37
Logs/tree		2.24	1.83	1.63	1.55	1.94
Vol/log	m^3	0.045	0.036	0.042	0.03	0.035
Vol/tree	m^3	0.1	0.066	0.068	0.047	0.068
Vol/hr	m^3	7.33	4.99	4.08	3.63	4.24
Rate	€/hr	110	110	110	110	110
Cost	€/m^3	15.02	22.03	26.99	30.34	25.94

na: not available

3.1.5.2 FORWARDER PRODUCTIVITY OF ENERGY WOOD ASSORTMENT

Forwarder extraction was used at all sites for the extraction of the energy wood assortment. The time study data are shown in Table 12. Between two and 17 cycles were studied per site. A cycle of forwarder extraction represented the time taken to drive empty into the forest, fully load the forwarder bunk with energy wood, drive back to the roadside and unload at the stack. These time elements are presented (Table 12) as an average. The productive time for a cycle was calculated as the sum of the time elements. An unproductive allowance of 30% was added to account for delays and stoppages, and the total time per forwarder cycle calculated. The volume per load was estimated from the number of logs loaded per cycle, multiplied by the average log volume as estimated by measurement of sample logs after harvesting. The forwarder was costed was €90 per hour. The extraction distance was also recorded.

The energy wood extraction cost ranged from €6.96/m^3 at Bweeng, to €14.85/m^3 at Woodberry. The productivity of the forwarder was influenced by extraction distance, mean log volume and terrain conditions. It is also possible that the long assortment lengths may have affected load time, as they were more cumbersome than shortwood to load into the forwarder bunk, especially when handling multiple logs per grab.

Table 12: Forwarder productivity in energy wood assortment.

Site		Abbeyfeale	Ballybofey	Bweeng	Toormakeady	Woodberry
Mean extraction distance	m	933	1008	591	358	807
Productive time						
Drive empty	cmin	569	715	393	518	493
Load	cmin	1563	1424	1133	1948	1675
Drive loaded	cmin	385	649	172	305	507
Unload	cmin	523	397	323	598	409
Sub-total	cmin	3040	3185	2021	3369	3084
Unproductive allowance	%	30	30	30	30	30
	cmin	912	955.5	606.3	1010.7	925.2
Total/load	min	39.52	41.41	26.27	43.80	40.09
Load/SMH		1.52	1.45	2.28	1.37	1.50
Vol/load	m^3	7.13	5.36	5.66	4.65	4.05
Vol/hr	m^3	10.82	7.8	12.93	6.37	6.06
Rate	€/hr	90	90	90	90	90
Cost	€/m^3	8.31	11.59	6.96	14.13	14.85

3.1.5.3 ENERGY WOOD CHIPPING

As with shortwood harvesting, the chipping of the energy wood assortment occurred in the autumn of 2007, and 2008. All the chippers were Irish owned and operated apart from the *Silvatec*, which was used to chip the energy wood at the Abbeyfeale site in 2008. Between one and 16 cycles were studied depending on the amount of energy wood available. The time studies captured the chipping of all the material at each site. Container sizes ranged from 80 m^3 walking-floor Bord na Móna trucks, to 17 m^3 tractors and trailers. A chipping cycle was the filling of the chip container, and comprised two elements: preparing to chip, and chipping. The total productive time was the sum of the two. To account for delays and stoppages an allowance factor of 30% was added, and thus the total time per unit bulk volume was estimated. The chippers were costed at different hourly rates depending on the quoted price by the contractor. The rates ranged from €100 per hour for the *MusMax*, to €300 per hour for the *Jenz* 700.

Table 13 shows the time study and productivity analysis of the energy wood chipping from both years. The cost/m^3 ranged from €4.97 using the *Jenz* 700 on the Woodberry site, to €14.25 using the *MusMax* on the Bweeng site. The low cost of the chipping at Woodberry in 2008 was a result of the high productivity of the *Jenz* 700; at three times the cost per hour of the *MusMax*, the *Jenz* 700 was still cheaper per unit volume.

Table 13: Productivity and costs of chipping the conifer energy wood assortment.

Site		Abbeyfeale		Ballybofey		Bweeng	Toormakeady	Woodberry	
Chipper		MusMax	Silvatec	MusMax	Starchl	MusMax	Jenz 420	MusMax	Jenz 700
Year		2007	2008	2007	2008	2007	2008	2007	2008
No. cycles studied		1	7	1	4	1	16	2	5
Load bulk volume	m^3	80	17	50	54.5	80	25	80	31.2
Productive time									
Prepare to chip	cmin	1240	184	0	0	0	445	473	0
Chip	cmin	11615	1493	8020	6759	18147	1732	10708	823
Sub-total	cmin	12855	1677	8020	6759	18147	2177	11180	823
Unproductive allowance	%	30	30	30	30	30	30	30	30
	cmin	3857	503	2406	2028	5444	653	3354	247
Total/load	min	167	22	104	88	236	28	145	11
Load/SMH		0.36	2.75	0.58	0.68	0.25	2.12	0.41	5.61
Solid vol/load	m^3	28	6	17	19	28	9	28	11
Vol/hr	m^3	10	16	10	13	7	18	11	60
Rate	€/hr	100	200	100	170	100	150	100	300
Cost	€/m^3	10.10	12.40	10.08	13.25	14.25	8.21	8.78	4.97

3.1.5.4 ENERGY WOOD WOODCHIP PRODUCTION COST TO ROADSIDE

Table 14 shows the energy wood woodchip production cost to roadside from the first thinning trials. As with the shortwood results, the system costs are separated into felling, extraction and chipping, and the production cost/m^3 solid volume and production cost per GJ are presented.

The cost/m^3 ranged from €33.43 at Abbeyfeale using the *MusMax* chipper, to €52.68 at Toormakeady using the *Jenz* 420 chipper. Taking into account the moisture content at harvesting and estimating the cost per unit energy, the lowest cost of €5.05/GJ was at the Abbeyfeale site using the *Silvatec* chipper. The highest cost was at Toormakeady, using the *Jenz* 420 chipper, at €7.52/GJ.

Table 14: Energy wood chip production cost to roadside, using harvester felling and forwarding to roadside.

Site		Abbeyfeale		Ballybofey		Bweeng	Toormakeady	Woodberry	
Vol/tree	m^3	0.100		0.066		0.068	0.047	0.068	
Vol/hr	m^3	7.3		4.9		4.08	3.63	4.24	
Rate	€/hr	110		110		110	110	110	
Cost	€/m^3	15.02		22.03		26.99	30.34	25.94	
Vol/load	m^3	7.13		5.36		5.66	4.65	4.050	
Vol/hr	m^3	10.82		7.8		12.93	6.37	6.06	
Hourly rate	€/hr	90.00		90.00		90.00	90.00	90.00	
Cost/m^3	€/m^3	8.31		11.59		6.96	14.13	14.85	
Year		2007	2008	2007	2008	2007	2008	2007	2008
Chipping method		MusMax	Silvatec	MusMax	Starchl	MusMax	Jenz 420	MusMax	Jenz 700
Vol/load	m^3	28	6	17	19	28	9	28	11
Vol/hr	m^3	10	16	10	13	7	18	11	60
Rate	€/hr	100	200	100	170	100	150	100	300
Cost	€/m^3	10.10	12.40	10.08	13.25	14.25	8.21	8.78	4.97
Total cost	€/m^3	33.43	35.73	43.69	46.86	48.20	52.68	49.57	45.76
Bulk/solid volume factor		2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Total cost (bulk volume)	€/m^3	11.53	12.32	15.07	16.16	16.62	18.17	17.09	15.78
MC post seasoning	%	53.6	50.9	58.6	57	54.7	56.2	49.5	40.8
Bulk density	kg/m^3	289.5	298	336	347	326	343	325	300
Net calorific value	GJ/tonne	7.60	8.19	6.52	6.87	7.36	7.04	8.49	10.37
Energy content (bulk volume)	GJ/m^3	2.2	2.4	2.2	2.4	2.4	2.4	2.8	3.1
Production cost	€/GJ	5.24	5.05	6.88	6.78	6.92	7.52	6.20	5.07

3.1.6 WOODCHIP PRODUCTION COST FROM CONIFER WHOLETREE THINNING

3.1.6.1 CHAINSAW HARVESTING OF CONIFER WHOLE TREES

The harvesting of whole trees was performed by chainsaw operators at all of the trial sites. Between 102 and 289 cycles per site were captured in the time studies. A cycle was the time spent felling, pulling down, and stump spraying an individual tree. No cross-cutting or delimbing took place. No time was spent on presentation as the trees were left in the line for terrain chipping and winch extraction. An unproductive allowance of 70% was used to account for delays and stoppages. This allowance is quite high, but was deemed appropriate as the operation is highly repetitious, requiring more breaks for the operators. The number of trees per hour, harvested volume per tree and volume harvested per hour were calculated. An hourly rate of €25 was used for a chainsaw operator. The time study results and productivity analysis are shown in Table 15.

The cost/m^3 ranged from €3.17/m^3 at Abbeyfeale to €8.01/m^3 at Bweeng. The highest rate of tree felling was at the Toormakeady site, where 45 trees were felled per scheduled hour, but mean tree volume was less than the Abbeyfeale site. It is probable that the time taken to harvest a larger tree using this method is only marginally greater relative to the volume produced, as the trees are easily felled and no additional cutting is required. The other main factor affecting productivity was the operator's experience. Chainsaw work is manually demanding, and as such, physical health and working experience of the operator can affect output.

Table 15: Chainsaw harvesting of conifer whole trees.

Site		Abbeyfeale	Ballybofey	Bweeng	Toormakeady	Woodberry
Extraction method		Terrain chipping				
No. cycles studied		179	289	102	204	222
Productive time						
Select	cmin	32	25	64	32	58
Fell	cmin	28	29	32	19	73
Down	cmin	18	16	36	16	78
Spray	cmin	11	11	20	9	12
Sub-total	cmin	89	82	153	77	221
Unproductive	%	70	70	70	70	70
allowance	time	62	57	107	54	154
Total/tree	min	1.51	1.39	2.60	1.31	3.75
Trees/SMH		39.8	43.3	23.1	45.7	16.0
Vol/tree	m^3	0.198	0.114	0.135	0.144	0.219
Vol/hr	m^3	7.9	4.9	3.1	6.6	3.5
Rate	€/hr	25	25	25	25	25
Cost	€/m^3	3.17	5.07	8.01	3.79	7.13

3.1.6.2 TERRAIN CHIPPING OF CONIFER WHOLE TREES

The time study results and productivity analysis of the terrain chipping system are shown in Table 16. The *Silvatec* terrain chipper and chip forwarder worked in tandem, chipping and forwarding the chips to the roadside. The time study captured between six and 12 cycles per site during the study. A cycle was the time taken to fill the terrain chipper silo and unload it to the chip forwarder. While the chip forwarder was extracting to the roadside, the terrain chipper could continue chipping, and therefore the productivity of the system is analysed from the terrain chipper activities only. The cost/m^3 was estimated from the solid volume produced per hour and an hourly rate of €300 for the *Silvatec* terrain chipper and chips forwarder system.

In all cases a higher productivity was achieved in the second year on the same sites using the same machine models. The increased productivity was due to the use of band tracks on the machines which increased their mobility. Without band tracks in the first year, the machines had a tendency to get bogged down and were slower to move, often needing to fell trees and use them as a brash mat. The cost/m^3 in the first year without band tracks ranged from €18.55-24.57/m^3. In the second year when using band tracks, the cost ranged from €13.27-17.42/m^3. In addition, the *Silvatec* silo carrying capacity was increased from 15 m^3 in 2007 to 17 m^3 in 2008.

At Bweeng and Ballybofey in 2007, a time element was recorded as 'waiting'. This is the impact of the chip forwarder on the productivity of the system. On these occasions, the chip forwarder did not return to the terrain chipper before it was ready to unload. When this occurred, the terrain chipper had to stop chipping as its silo was full and it could not start again until it had unloaded. During this waiting time, the productivity of the *Silvatec* system was zero. To prevent this from happening too often, the operators of the machines were in constant communication with each other using radio transmissions.

Table 16: Terrain chipping of conifer whole trees, following harvester felling and forwarder extraction.

Site		Abbeyfeale		Ballybofey		Bweeng	Toormakeady	Woodberry	
Year		2007	2008	2007	2008	2007	2008	2007	2008
Load bulk volume	m^3	15	17	15	17	15	17	15	17
No. cycles studied		6	11	8	12	7	11	8	8
Productive time									
Drive empty	cmin	92	193	104	106	115	98	249	164
Chipping	cmin	1483	811	623	841	677	1290	871	794
Drive Full	cmin	242	95	298	96	254	29	269	112
Unload	cmin	138	135	142	192	180	154	148	127
Brashing	cmin			36		121			
Waiting	cmin			273		385			
Total time	cmin	1955	1234	1476	1235	1732	1571	1537	1197
Unproductive allowance	%	30	30	30	30	30	30	30	30
	time	587	370	443	371	520	471	461	360
Total time/load	min	25	16	19	16	23	20	20	16
Loads/hr		2.36	3.74	3.13	3.74	2.66	2.94	3.00	3.86
Vol/load	m^3 solid	5	6	5	6	5	6	5	6
Vol/hr	m^3 solid	12	22	16	22	14	17	16	23
Rate	€/hr	300	300	300	300	300	300	300	300
Cost	€/m^3 solid	24.57	13.68	18.55	13.69	21.77	17.42	19.31	13.27

3.1.6.3 WHOLE TREE TERRAIN CHIPPING SUPPLY CHAIN COST TO FOREST ROADSIDE

Table 17 shows the cost of wholetree terrain chipping production to forest roadside in first thinnings from the five trial sites. Costs are displayed as the individual system components of felling and chipping. The extraction of material using this system is an integral part of the chipping operation. The cost/m^3 solid volume is presented as the sum of the felling and chipping costs. Using moisture content samples taken during chipping the energy content/m^3 is estimated, and the cost per GJ given. The cost of production to forest roadside ranged from €2.22-4.36/GJ.

Table 17: Cost to forest roadside of wholetree terrain chipping by *Silvatec* following chainsaw felling.

Site		Abbeyfeale		Ballybofey		Bweeng	Toormakeady	Woodberry	
Vol/tree	m^3	0.198		0.114		0.135	0.144	0.219	
Vol/hr	m^3	8		5		3	7	4	
Rate	€/hr	25		25		25	25	25	
Cost/m^3	€/m^3	3.17		5.07		8.01	3.70	7.13	
Year		2007	2008	2007	2008	2007	2008	2007	2008
Vol/load (solid)	m^3	5	6	5	6	5	6	5	6
Vol/hr (solid)	m^3	12	22	16	22	14	17	16	23
Rate	€/hr	300	300	300	300	300	300	300	300
Cost (solid)	€/m^3	24.57	13.68	18.55	13.69	21.77	17.42	19.31	13.27
Total cost(solid)	€/m^3	27.74	16.85	23.62	18.77	29.77	21.12	26.44	20.40
Bulk/solid volume factor		2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Total cost/m^3 (bulk volume)	€/m^3	9.56	5.81	8.15	6.47	10.27	7.28	9.12	7.04
MC post seasoning	%	52.4	43.1	53.9	49.8	45.2	48.5	50.1	47.1
Bulk density	kg/m^3	299	265	286	282	250	311	284	322.00
Net calorific value	GJ/tonne	7.86	9.87	7.54	8.42	9.42	8.70	8.36	9.01
Energy content (bulk volume)	GJ/m^3	2.4	2.6	2.2	2.4	2.4	2.7	2.4	2.9
Production cost	€/GJ	4.07	2.22	3.78	2.72	4.36	2.69	3.84	2.43

3.1.7 WOODCHIP PRODUCTION COST FROM CHEMICAL THINNING IN CONIFERS

3.1.7.1 COST OF CHEMICAL TREATMENT

Chemical treatment productivity results are presented in Table 18. The first treatment was carried out in 2006, but was not completely effective. Therefore a second treatment was applied in early 2007. The results presented are those studied in 2006 and adjusted to account for the second treatment. The use of a knapsack sprayer for applying herbicide was found to be more productive and easier than using a brush. The total treatment cost was €8.73/m^3 in Kilbrin and €10.48/m^3 in Swan.

Table 18: Chemical thinning treatment costs.

Site		Kilbrin	Swan
Treatment method		Chainsaw & knapsack sprayer	Chainsaw & brush
Productive time	cmin	61	81
No. treatments		2	2
Sub-total	cmin	122	162
Unproductive allowance	%	70	70
	cmin	85	113
Total/tree	min	2.07	2.75
Trees/SMH		28.9	21.8
Vol/tree	m^3	0.10	0.11
Vol/hr	m^3	2.9	2.4
Rate	€/hr	25	25
Cost	€/m^3	8.73	10.48

3.1.7.2 FELLING, CHIPPING AND EXTRACTION COST

The time study results and calculated production cost of felling, chipping and extraction by the *Silvatec* terrain chipping system in chemically treated Sitka spruce are presented in Table 19. Production was slower in Kilbrin, compared with Swan, largely due to ground conditions, as the *Silvatec* placed brash under the wheels in order to traverse the site. The production was 9.1m^3 per hour in Kilbrin and 14.1m^3 per hour in Swan. The felling, chipping and extraction cost was €33.00/m^3 at Kilbrin and €21.28/m^3 at Swan.

Table 19: Chemical thinning felling, chipping & extraction cost using the *Silvatec* terrain chipping system.

Site		Kilbrin	Swan
Drive empty	cmin	28	209
Chipping	cmin	1391	1266
Drive full	cmin	381	12
Unload	cmin	193	153
Brash under wheels	cmin	633	53
Sub-total	cmin	2626	1693
Unproductive allowance	%	30	30
	cmin	788	508
Total time/load	min	34.1	22.0
Loads/hr		1.76	2.73
Vol/load (bulk volume)	m^3	15	15
Vol/hr (bulk volume/SMH)	m^3	26.4	40.9
Solid /bulk volume factor		2.9	2.9
Vol/ hr	m^3	9.1	14.1
Rate	€/hr	300	300
Cost	€/m^3	33.00	21.28

3.1.7.3 WHOLE TREE WOODCHIP PRODUCTION COST FROM CHEMICAL THINNING TO ROADSIDE

The supply chain cost of wholetree woodchip from chemical thinning is shown in Table 20. Chemical treatment and felling, chipping and extraction costs were €41.73/m^3 and €21.28/m^3 at Kilbrin and Swan respectively. The cost per GJ was calculated from the measured moisture content after seasoning. The woodfuel produced at Kilbrin was particularly dry, at 32.3% moisture content, resulting in a net calorific value of 12.2 GJ/tonne. Despite this, the woodchip produced at Swan was cheaper, costing €4.36/GJ, whereas the woodchip at Kilbrin cost €5.86/GJ.

Table 20: Chemical thinning supply chain cost to forest roadside.

Site		Kilbrin	Swan
Treatment method		Chainsaw & knapsack sprayer	Chainsaw & brush
Vol/hr	m^3	2.9	2.4
Rate	€/hr	25	25
Cost/m^3	€/m^3	8.73	10.48
Chipping vol/hr	m^3	9.1	14.1
Rate	€/hr	300	300
Cost/m^3	€/m^3	33.00	21.28
Total cost (solid volume)	€/m^3	41.73	31.76
Solid/bulk volume factor		2.9	2.9
Total cost (bulk volume)	m^3	14.39	10.95
Moisture content after seasoning	%	32.3	45.6
Bulk density	kg/m^3	201	269
Net calorific value	GJ/tonne	12.2	9.3
Energy content (bulk volume)	GJ/m^3	2.45	2.51
Production cost	€/GJ	5.86	4.36

3.1.8 WOODCHIP PRODUCTION COST FROM SMALL-SCALE METHOD IN CONIFERS

3.1.8.1 CHAINSAW FELLING OF SELECTED WHOLE TREES

Results from time studies taken during selective harvesting of whole trees by chainsaw are shown in Table 21. The time studies were carried out at Abbeyfeale, Bweeng and Woodberry. Between 25 and 408 cycles were captured during the time studies at each site. A cycle represented the time taken to select and fell the tree, and apply urea to the stump. The total productive time was calculated as the sum of these elements. An unproductive allowance of 70% was used to account for rest stops and delays. The harvested volume was calculated using the methodology described in the next section (3.1.8.2). The cost/m^3 was estimated from the volume produced per hour and an hourly rate of €25 for a chainsaw operator.

The cost/m^3 ranged from €2.67-5.18/m^3. Tree volume and operator experience contributed to cost variation. The largest time element on each site was the selection of the trees to be cut. Twice as much time was spent doing this by the operator in Bweeng, compared to the operator in Woodberry. Woodberry also had the trees of greatest volume.

Table 21: Selectively cutting whole trees by chainsaw for winch extraction and chipping.

Site		Abbeyfeale	Bweeng	Woodberry
Harvest method			Chainsaw	
No. cycles studied		25	72	408
Productive time				
Select	cmin	20	28	14
Fell	cmin	10	12	7
Urea application	cmin	12	9	8
Sub-total	cmin	42	49	29
Unproductive	%	70	70	70
allowance	time	29	34	20
Total/tree	cmin	71	83	49
Trees/SMH		84	72	122
Vol/tree	m^3	0.060	0.067	0.077
Vol/hr	m^3	5.0	4.8	9.4
Rate	€/hr	25	25	25
Cost	€/m^3	4.96	5.18	2.67

3.1.8.2 WINCH EXTRACTION AND CHIPPING OF WHOLE TREES FOLLOWING CHAINSAW FELLING

A PTO-driven *TP* chipper with attached winch, towed by tractor, was tested at Abbeyfeale, Bweeng and Woodberry. The operation of the chipper was manually intensive as it was fed by hand, and the operator had to pull the cable into the stand to choke the trees for extraction. The time studies captured between 1 and 5 cycles per site. A cycle represented the time taken to fill the chipper silo, including winch extraction of whole trees to the chipper. The solid volume per load of 2.41m^3 was estimated using the chipper's silo volume of 7m^3 and a bulk/solid volume conversion factor of 2.9. The cost/m^3 was estimated using an hourly rate of €50. An unproductive allowance of 50% was used as the winch extraction and chipping required a large manual effort from the operator.

The chipping cost/m^3 ranged from €41.73 at Bweeng, to €64.56 at Abbeyfeale, as shown in Table 22. A large proportion of the cycle time was spent extracting. Operator inexperience was possibly responsible for the low productivity. For instance, at Abbeyfeale, nearly 2 hours were spent extracting the trees, while chipping only took about 11 minutes.

Table 22: Winch extraction and chipping of whole trees.

Site		Abbeyfeale	Bweeng	Woodberry
No. cycles studied		1	2	5
Load bulk volume	m^3	7	7	7
Productive time				
Winch extraction	cmin	11315	7448	5904
Chip	cmin	1080	565	3751
Sub-total	cmin	12395	8013	9655
Unproductive	%	50	50	50
allowance	cmin	6198	4006	4828
Total/load	min	186	120	145
Load/SMH		0.32	0.50	0.41
Solid vol/load	m^3	2.4	2.4	2.4
Vol/hr	m^3	0.77	1.20	0.99
Rate	€/hr	50	50	50
Cost	€/m^3	64.56	41.73	50.29

3.1.8.3 WHOLETREE WINCH EXTRACTION AND ROADSIDE CHIPPING COST TO FOREST ROADSIDE

Table 23 shows the cost of woodchip production from whole trees felled, winch extracted and chipped at the forest roadside. Costs are for individual system components of felling and chipping. Using moisture content samples taken during chipping, the energy content per cubic metre was estimated, as well as the cost per GJ. The cost of production to roadside ranged from €6.47-10.20/GJ.

Table 23: Wholetree winch extraction and chipping cost to forest roadside.

Site		Abbeyfeale	Bweeng	Woodberry
Vol/tree	m^3	0.06	0.067	0.077
Vol/hr	m^3	5.0	4.8	9.4
Rate	€/hr	25	25	25
Harvest Cost	€/m^3	4.96	5.18	2.67
Vol/load (solid)	m^3	2.41	2.41	2.41
Vol/hr (solid)	m^3	0.77	1.20	0.99
Rate	€/hr	50	50	50
Chipping Cost (solid volume)	€/m^3	64.56	41.73	50.29
Total cost (solid volume)	€/m^3	69.52	46.91	52.96
Bulk/solid volume factor		2.9	2.9	2.9
Total cost (bulk volume)	€/m^3	23.97	16.18	18.26
MC post seasoning	%	52.4	42.3	45.1
Bulk density	kg/m^3	299	249	273
Net calorific value	GJ/tonne	7.86	10.05	9.44
Energy content (bulk volume)	GJ/m^3	2.4	2.5	2.6
Production cost	€/GJ	10.20	6.47	7.09

3.1.9 PRODUCTION COST OF FIREWOOD FROM CONIFER FIRST THINNING

3.1.9.1 CHAINSAW HARVESTING OF FIREWOOD ASSORTMENT

Results from time studies taken during chainsaw harvesting of variable length shortwood for firewood are shown in Table 24. The time studies were carried out at Bweeng, Toormakeady and Woodberry. Between 19 and 48 cycles were captured during the time studies at each site. A cycle represented the time taken to select, fell, pull down, delimb and cross-cut the tree and present shortwood lengths for extraction. The total productive time was calculated as the sum of these elements. An unproductive allowance of 50% was used to account for rest stops and delays. The harvested volume is the standing volume estimate, as shortwood was cut into variable lengths to utilise most of the stem, leaving only the bushy top in the forest. The cost/m^3 was estimated from the volume produced per hour and an hourly rate of €25 for a chainsaw operator.

The cost/m^3 ranged from €17.86-84.65/m^3. Tree volume and operator experience contributed to cost variation. Felling, delimbing and cross-cutting of spruce in first thinning can be a physically demanding job and operator experience strongly influences productivity. In operations such as this an incorrectly felled or hung-up tree can take a long time to get down, tiring the operator. A skilled operator can fell trees in a manner that eases delimbing, cross-cutting, and presentation.

Table 24: Chainsaw harvesting of firewood assortment and extraction by ATV.

Site		Bweeng	Toormakeady	Woodberry
No. cycles studied		29	19	48
Productive time				
Select	cmin	28	207	34
Fell	cmin	37	43	29
Down	cmin	39	219	21
Delimb	cmin	275	203	206
Cross-cut	cmin	26	52	32
Present	cmin	69	48	41
Sub-total	cmin	474	772	363
Unproductive allowance	%	50	50	50
	cmin	237	386	181.5
Total/tree	min	7.11	11.58	5.45
Trees/SMH		8.44	5.18	11.02
Vol/tree	m^3	0.093	0.057	0.127
Vol/hr	m^3	0.785	0.295	1.399
Rate	€/hr	25	25	25
Cost	€/m^3	31.86	84.65	1786

3.1.9.2 FIREWOOD ASSORTMENT EXTRACTION BY ATV

Variable firewood lengths were extracted to the roadside by ATV and timber arch trailer. Time studies were conducted at Ballybofey, Bweeng and Woodberry. The time studies captured between 21 and 26 cycles per site. A cycle was the time taken to extract one load of shortwood to the roadside, and consisted of the time elements of driving empty, loading, driving loaded, and unloading. The total productive time was calculated as the sum of these elements. An unproductive allowance of 50% was used to account for stoppages and delays. The mean log volume was assumed from production studies of the firewood processor and bulk density measurements, as outlined in the next section of this report. The cost/m^3 was estimated using an hourly rate of €30 for the ATV and operator.

The cost/m^3 varied widely, from €37.93 at Woodberry, to €112.59 at Bweeng. Operator experience, log volume and extraction distance all have an impact on the productivity of ATV extraction. The productivity of ATV extraction is shown in Table 25.

Table 25: Cost of firewood extraction by ATV.

Site		Ballybofey	Bweeng	Woodberry
No. cycles studied		21	21	26
Extraction distance	m	318	72	86
Productive time				
Drive empty	cmin	568	167	88
Loading	cmin	295	184	165
Drive loaded	cmin	429	177	101
Unload	cmin	138	136	77
Sub-total	cmin	1430	664	431
Unproductive allowance	%	50	50	50
	cmin	715	332	215.5
Total/load	min	21.45	9.96	6.47
Loads/hr		2.8	6.0	9.3
Logs/load		5.9	2.3	3
Vol/log	m^3	0.025	0.019	0.028
Vol/load	m^3	0.148	0.044	0.085
Vol/hr	m^3	0.41	0.27	0.79
Rate	€/hr	30.00	30.00	30.00
Cost	€/m^3	72.71	112.59	37.93

3.1.9.3 FIREWOOD PRODUCTION USING FIREWOOD PROCESSOR

Firewood was processed from the variable shortwood lengths brought to the roadside by the ATV. The firewood was processed with a *Hakke Pilke Hawk* firewood processor into large 1 m^3 bags. Two operators were used in the processing: one loaded the logs onto the in-feed, while the other cross-cut and split the logs using the machine. The split pieces were conveyed automatically into the bags. The time studies captured between 6 and 9 cycles per site. A cycle represented the filling of one large 1 m^3 bag with firewood pieces. An unproductive allowance of 50% was added to account for stoppages and delays. The cost/m^3 was estimated using an hourly rate of €60 per hour, which includes the machine cost at €10 per hour and two operators at €25 per hour.

Table 26 shows the cost/m^3 solid volume of firewood processing productivity, which ranged from €69.93/m^3 at Abbeyfeale, to €105.66/m^3 at the Ballybofey site. The productivity of this processor is low as a chainsaw is used to cross-cut the logs and the splitting is a separate operation. Other processors can have a much higher productivity however this machine was selected an entry level machine that required no level of expertise to run, and was mobile and so could be set-up in the forest.

Table 26: Firewood processor productivity and costs.

Site		Abbeyfeale	Ballybofey	Bweeng	Toormakeady	Woodberry
No. cycles studied		9	6	6	8	9
Productive time/log	cmin	137	176	120	166	141
Unproductive allowance	%	50	50	50	50	50
	cmin	68.6	88.1	60.2	83.2	70.4
Solid vol/cycle	m^3	0.5	0.5	0.5	0.5	0.5
Total time/log	min	2.06	2.64	1.81	2.50	2.11
Logs/hr		29.17	22.71	33.24	24.04	28.42
Vol/log	m^3	0.029	0.025	0.019	0.026	0.028
Vol/hr	m^3/hr	0.86	0.57	0.64	0.63	0.81
Rate	€/hr	60.00	60.00	60.00	60.00	60.00
Cost	€/m^3	69.93	105.66	93.87	95.34	74.31

3.1.9.4 CONIFER FIREWOOD SUPPLY CHAIN PRODUCTION COST TO FOREST ROADSIDE

Table 27 shows the production cost of conifer firewood using the *Hawk* processor as estimated in the study. At Bweeng and Woodberry, the supply chains consisted of chainsaw harvesting and ATV extraction. As chainsaw harvesting was not tested at Abbeyfeale or Ballybofey, the shortwood harvester cost was used. The ATV was did not operate at Abbeyfeale or Toormakeady, and therefore the shortwood forwarder cost was used. The cost of each phase of production is provided, and the total cost/m^3 solid volume is presented. The solid volume is also converted to bulk volume, representing the cost of production of a 1 m^3 bag filled with firewood pieces. Using moisture content results from samples taken from the firewood bags after seasoning, the calorific value and energy content was estimated, and the cost per GJ calculated.

The cost/m^3 solid volume at Bweeng was €242.56 and €132.48 at Woodberry. The most manually-intensive chainsaw harvesting and ATV extraction systems were used at these sites. The more mechanised approach at Abbeyfeale, using harvester and forwarder resulted in the lowest production cost of €101.92/m^3 solid volume.

Table 27: Conifer firewood supply chain production cost to forest roadside.

Site		Abbeyfeale	Ballybofey	Bweeng	Toormakeady	Woodberry
Fell method		Harvester	Harvester	Chainsaw	Chainsaw	Chainsaw
Vol/tree	m^3	0.077	0.053	0.093	0.057	0.127
Vol/hr	m^3	4.74	3.31	0.69	0.26	1.23
Rate	€/hr	110	110	25	25	25
Fell cost (solid volume)	€/m^3	23.21	33.28	36.10	95.94	20.25
Extraction method		Forwarder	ATV	ATV	Forwarder	ATV
Vol/load	m^3	4.47	0.15	0.04	3.96	0.09
Vol/hr	m^3	10.25	0.41	0.27	3.41	0.79
Rate	€/hr	90	30	30	90	30
Extract cost (solid volume)	€/m^3	8.78	72.71	112.59	26.36	37.93
Vol/hr	m^3/hr	0.86	0.57	0.64	0.63	0.81
Rate	€/hr	60	60	60	60	60
Processing cost (solid volume)	€/m^3	69.93	105.66	93.87	95.34	74.31
Total cost (solid volume)	€/m^3	101.92	211.65	242.56	217.64	132.48
Solid /bulk volume factor		2	2	2	2	2
Total cost (bulk volume)	€/m^3	50.96	105.82	121.28	108.82	66.24
MC post seasoning	%	22	30	18	20	32
Bulk density	kg/m^3	257	237	235	259	311
Net calorific value	GJ/t	14.44	12.71	15.30	14.87	12.28
Energy content (bulk volume)	GJ/m^3	3.7	3.0	3.6	3.9	3.8
Production cost	€/GJ	13.73	35.14	33.72	28.25	17.35

3.1.10 COMPARISON OF WOODFUEL SUPPLY CHAIN COSTS IN CONIFER THINNINGS

The average woodfuel production costs of the three main supply chains tested in conifer thinning are presented in Table 28. Production cost results for 2007 and 2008 are compared with results of trials carried out in 2006. Differences in costs between 2007 and 2008 were solely due to different chipping productivity and different energy content due to moisture content reduction over time. Differences in production costs between 2006 and 2007/8 were also due to trials being carried out on different site types: the 2006 sites were selected as being productive sites with good ground bearing capacity, in order to demonstrate machines and methods, whereas the sites used in 2007/8 were selected to represent the range of typical conifer thinning sites.

The shortwood method production costs were very similar between years, based on averaged results from three sites in 2006 and five sites in 2007 and 2008. In fact, the slight increase in costs between 2006 and 2007/8 may be explained by the difference in ground conditions between sites. Production cost results for the energy wood assortment method showed continuous reduction over the three years. The big difference between 2006 and 2007 may be explained by the substantial reduction in harvesting cost, from on average €34.70/m^3 in 2006 to €22.50/m^3 in 2007. In 2006, the harvester operator needed to learn a new harvesting system/assortment production process, whereas the operator was already skilled at energy wood production in 2007. The energy wood production cost was slightly lower than the shortwood production cost, which could be largely explained by the greater biomass recovery in harvested material from the energy wood thinning.

Woodchip production costs from wholetree terrain chipping were substantially lower than the other two methods. Harvesting cost was much lower, as there was no time spent delimbing, cross-cutting or presenting assortments. Also, the extraction cost was part of the *Silvatec* system and was a sub-set of the terrain chipper operating cost. While the terrain chipping cost/m^3 was higher than the roadside chipping operation, this was more than offset by savings in extraction and also the substantial additional biomass harvested in comparison with the shortwood and energy wood methods. Wholetree woodchip production costs nearly doubled from €14.31/m^3 in 2006 to €26.90/m^3 in 2007. The main reason was that the ground conditions were poorer on the 2007 sites, causing more delays and production losses. The *Silvatec* chipper was fitted with band tracks to aid traction in 2008 and this resulted in a notable improvement in productivity on the same sites that caused delays in the previous year.

Table 28: Comparison of conifer woodfuel production costs.

Assortment/harvesting method		Shortwood			Energy wood			Wholetree		
Trial year		2006	2007	2008	2006	2007	2008	2006	2007	2008
Felling method		Harvester			Harvester			Chainsaw		
Harvesting cost	€/m^3	29.40	27.83	33.28	34.70	22.50	23.33	3.42	5.85	4.77
Extraction method		Forwarder			Forwarder			Silvatec chip forwarder		
Extraction cost	€/m^3	8.79	11.40	14.86	9.87	10.43	12.22	(Cost included with chipper)		
Chipping method		Jenz	MusMax	Various	Jenz	MusMax	Various	Silvatec terrain chipper		
Chipping cost	€/m^3	7.87	7.52	9.65	7.87	10.80	9.71	10.89	21.05	14.52
Production cost	€/m^3	46.05	46.75	57.79	52.43	43.73	45.26	14.31	26.90	19.28
Cost of energy	€/GJ	6.53	6.87	6.76	6.78	6.31	6.11	2.03	4.01	2.52

3.1.11 TRANSPORTATION STUDY RESULTS

3.1.11.1 WOODCHIP TRANSPORT BY CONTAINER TRUCKS

Table 29 below describes the mean speeds on different road categories achieved by the container trucks carrying full loads of woodchip. As expected, there was a good correlation between road type and speed achieved. These studies did not account for the time required to load containers in the forest or empty at the end-user.

In Denmark the total gross permissible vehicle weight is 48 t. The gross empty weight of the Danish trucks was 26 t, allowing 22 t of woodchip to be carried. The bulk volume capacity of the container trucks was 80 m^3. In Ireland the maximum gross vehicle weight is 44 t so with a gross empty weight of 26 t, only 18 t of payload could be carried. The average wholetree woodchip bulk density from the 2007 trials was 280 kg/m^3. Therefore, a container truck with 18 t carrying capacity could only carry 64 m^3 on Irish roads. In order for container trucks to operate most productively on Irish roads, significant reductions would need to be made to the weight of the base vehicle and empty containers. Otherwise, the mean moisture content of woodchip would have to be substantially lower than that achieved in the trials reported here.

Table 29: Mean speed of woodchip container trucks on Irish roads.

Road classification	Average speed	Minimum speed	Maximum speed
		km/hr	
Forest road	22	10	30
Regional road	38	12	90
National secondary road	46	15	93
National primary route	58	27	86

3.1.11.2 WOODCHIP TRANSPORT BY TRACTOR AND TRAILER

This study was carried out at Woodberry only in 2008, where the *Jenz* 700 chipped into tractors and trailers. The tractors then transported chip to a small sawmill c. 11 km from the forest site, where the chip was unloaded for reloading onto walking-floor trucks. The *Jenz* 700 took just 13 minutes to fill the 32 m^3 capacity trailer. Unloading and turnaround at the sawmill was also very fast: two minutes on average. The mean speeds achieved by the tractors and trailers empty and full on the different road types is shown in Table 30.

Interestingly, the tractor and trailer speed was similar to the truck speed on smaller roads. On one hand the container trucks had double the capacity of the tractors and trailers. On the other hand, the time spent handling containers in the forest and unloading at the end-user would probably be greater than the much faster turnaround of tractor and trailer combinations. Most trips between a forest and local end-user in Ireland are likely to take place on minor roads. Therefore, there may be circumstances where tractors are the most cost-effective means of transport. The parameters affecting road transportation productivity would require a comprehensive study of the different transportation options available.

Table 30: Mean speed of woodchip tractors & trailers on Irish roads.

Road classification	Average speed empty	Average speed loaded
	km/hr	
Forest road	22.9	17.7
Regional road	38.4	36.0
National secondary road	43.3	46.0

3.2 BROADLEAF WOODFUEL SUPPLY CHAINS

3.2.1 BROADLEAF STAND DESCRIPTIONS

The four broadleaf trial sites ranged in area between 1.9 ha and 7.7 ha, with an age range of 12-14 years. Three of the four sites were 100% ash, while Greenane was a non-intimate mixture of ash and sycamore. Stocking varied considerably between sites, though the stocking density does not tell the entire story as this refers to live trees greater than 7 cm dbh. The proportion of trees less than 7 cm dbh at the four sites was as follows:

- Greenane, 32%,
- Dovea, 15%,
- Mullinavat, 18% and
- Stradbally, 10%.

Mean dbh was similar at all sites, ranging from 9-11 cm. Top height was lowest at Mullinavat, and highest at Stradbally. Working plot 2 at Stradbally had already received a selective tending. Little or no ash canker was visible on trees at three of the sites, the exception being Mullinavat, where sections were heavily infected. The initial inventory and treatment area for each working plot is shown in Table 31.

Table 31: Stand composition, growth and productivity at the broadleaf trial sites.

Site	Working plot*	Species composition	Plot area ha	Age year	Stocking stems/ha	Mean dbh cm	Top height m	Yield Class m^3/ha/yr
Dovea	1	Ash	1.20	13	2765	10	10	12
	2	Ash	0.45	13	3143	9	11	12
	4	Ash	1.10	13	3143	9	11	12
	9	Ash	1.30	13	3570	9	10	12
Greenane	1	Ash/sycamore	2.25	12	2074	10	10	12
	2	Ash/sycamore	0.50	12	1881	9	9	10
	3	Ash/sycamore	0.50	12	1881	9	9	10
	5	Ash/sycamore	0.65	12	2440	10	11	12
	6	Ash/sycamore	1.50	12	1833	10	10	12
Mullinavat	1	Ash	1.80	14	2752	10	9	8
	7	Ash	0.70	14	2681	10	10	10
	8	Ash	3.10	14	2523	9	8	8
	9	Ash	2.10	14	2397	9	8	8
Stradbally	1	Ash	1.40	14	2312	10	10	12
	2	Ash	0.50	14	1817	11	15	12+

* Working plots:

1. 3 m lengths harvested by chainsaw, extracted by forwarder, processed into firewood.
2. 3 m lengths harvested by chainsaw, skidded by quad and timber arch, processed into firewood.
3. 3 m lengths harvested by chainsaw, extracted by quad and trailer, processed into firewood.
4. 3 & 6 m lengths harvested by chainsaw, extracted by skidded by horse and timber arch, processed into firewood.
5. 3 m lengths harvested by chainsaw, extracted by horse and trailer, processed into firewood.
6. 3m lengths harvested by chainsaw, bunched by horse and extracted by forwarder, processed into firewood.
7. 3 m lengths harvested by chainsaw, extracted by tractor and grapple, processed into firewood.
8. 3 m lengths harvested by mechanical harvester, extracted by forwarder, processed into firewood.
9. Whole trees harvested by chainsaw, chipped in the stand with terrain chipper and extracted by chip forwarder.

3.2.2 STANDING VOLUME ESTIMATION

Estimation of standing volume for each study site was carried out by felling sample trees. The stem volume to 7 cm top diameter, for each felled sample tree, was calculated and plotted against the tree's basal area in MS Excel. The trend line yielded a regression equation for tree volume based on basal area. An example of the regression of volume on basal area is provided in Figure 39. Graphs and regression equations for standing tree volume were estimated and produced for each study site.

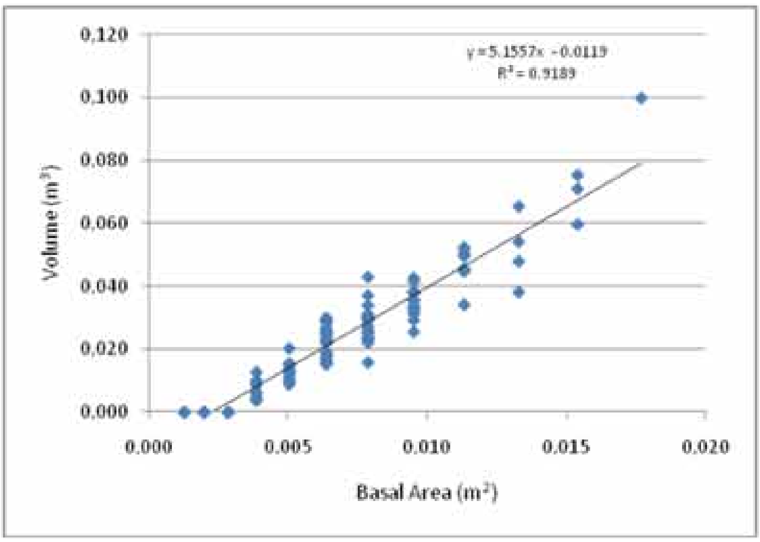

Figure 39: Regression of stem volume (to 7 cm top diameter) on basal area at Greenane.

Table 32 summarises the regression of basal area on volume for each study site. The number of felled sample trees per site ranged from 30 trees at Stradbally to 114 trees at Greenane. The co-efficient of determination, which shows what proportion of the variation in stem volume is accounted for by basal area, is provided.

Table 32: Regression of stem volume (to 7 cm top diameter) on basal area for each study site.

Site	Treated area	Sample size	Regression*	Co-efficient of determination
	ha			R^2
Dovea	4.05	84	y = 5.4029x - 0.0126	0.91
Greenane	5.40	114	y = 5.1557x - 0.0119	0.92
Mullinavat	7.70	60	y = 4.6791x - 0.0096	0.87
Stradbally	1.90	30	y = 5.9139x - 0.0143	0.92

* x is basal area per tree (m^2), y is stem volume to 7 cm top diameter (m^3)

Sample dbhs, from around 250 trees per working plot, were converted to basal area and a sample volume was estimated using the site-specific regressions. This was expanded to a plot level volume estimate by incorporating the stocking density of live trees greater than 7 cm dbh. The standing volume estimate results for working plots at each study site are presented in Table 33.

Table 33: Estimated standing volume per working plot at each study site.

Site	Working	Stocking	Mean dbh	Mean basal area/tree	Mean vol/tree	Vol/ha
	plot	stems/ha	cm	m^2	m^3	m^3
Dovea	1	2765	10	0.0079	0.029	79
	2	3143	9	0.0067	0.024	74
	4	3143	9	0.0067	0.024	74
	9	3570	9	0.0066	0.024	85
Greenane	1	2074	10	0.0079	0.026	54
	2	1881	9	0.0064	0.022	41
	3	1881	9	0.0064	0.022	41
	5	2440	10	0.0079	0.030	74
	6	1833	10	0.0079	0.026	47
Mullinavat	1	2752	10	0.0079	0.025	69
	7	2681	10	0.0079	0.029	79
	8	2523	9	0.0064	0.022	56
	9	2397	9	0.0064	0.021	50
Stradbally	1	2312	10	0.0079	0.034	79
	2	1817	11	0.0095	0.041	74

3.2.3 HARVESTED VOLUME IN BROADLEAF SITES

The harvested volume of roundwood was calculated from individual log volume and the mean number of logs harvested per tree. The wholetree harvested volume was calculated from the bulk volume of woodchip converted to solid volume using a conversion factor. The mean harvested volume per tree, for each working plot, for all study sites is presented in Table 34.

The final two columns of the table present the difference between the standing volume per tree and harvested volume. In principle, it would be expected that the roundwood harvested volume per tree would be lower than the standing volume due to harvesting losses. Instead in some plots on some sites the harvested volume was higher. Partially, this result may be because smaller trees may not have yielded any roundwood so the harvested volume is skewed towards the larger trees. This seems to be confirmed in the three shortwood treatment plots at Mullinavat, where the harvested volume was about one third less than the standing volume, and where the mean tree volume was generally very small.

Conversely, it could be expected that the wholetree harvested volume would be greater than the standing volume per tree, due to the additional branch and top material. This was confirmed at Dovea and Mullinavat, with volume increases of 11% and 44%, respectively.

It could be possible to extract more roundwood volume from each tree if the top diameter limit was reduced, or if variable pole lengths were cut, rather than a standard 3 m length – though variable lengths can create handling, extraction, stacking and transport problems.

The main conclusion to be drawn from these results is that standing and harvested volume are not equivalent. More research is needed to provide an allowance or factor for determining harvested volume from standing volume, which would be very useful for harvest planning and resource quantification.

Table 34: Harvested volume per tree at broadleaf study site working plots.

Site	Working plot	Piece volume	Pieces/tree	Vol/tree	Harvested-standing volume	
		m^3		m^3	m^3/tree	%
Dovea	1	0.0131	2.55	0.034	0.005	17
	2	0.0127	1.94	0.025	0.001	4
	4	0.0126	1.48	0.019	-0.005	-21
	9	0.0267	1.00	0.027	0.003	11
Greenane	1	0.0165	1.41	0.023	-0.003	-10
	2	0.0178	1.46	0.026	0.004	19
	3	0.0178	1.46	0.026	0.004	19
	5	0.0154	1.60	0.025	-0.006	-18
	6	0.0176	1.37	0.024	-0.002	-6
Mullinavat	1	0.0174	1.03	0.018	-0.007	-29
	7	0.0175	1.04	0.018	-0.011	-38
	8	0.0163	0.94	0.015	-0.007	-31
	9	0.0329	1.00	0.033	0.009	44
Stradbally	1	0.0120	2.79	0.033	-0.001	-2
	2	0.0157	3.16	0.049	0.009	21

The total thinning volume harvested and extracted to roadside was estimated at Mullinavat and Greenane. At Mullinavat, both shortwood harvested volume and wholetree harvested volume were estimated (Table 35).

The shortwood harvested volume ranged from 16.3-20.6m^3/ha at Mullinavat, and from 10.6-18.1m^3/ha at Greenane. The wholetree harvested volume in Mullinavat was higher, at 27.1m^3/ha. Differences in harvested volume between shortwood treatment plots are most likely caused by a mix of factors related to mean tree volume, and the intensity of marking. The difference between shortwood and wholetree harvested volume can be explained by the substantial additional biomass found in the stem top and branches.

Table 35: Total thinning volume in broadleaves at Greenane and Mullinavat.

Site	Working plot	Treated area ha	No. logs	Log volume m^3	Total volume m^3	Volume per ha m^3/ha
Mullinavat	1	1.70	2010	0.0174	34.9	20.6
	7	0.70	654	0.0175	11.4	16.3
	8	3.10	3229	0.0163	52.6	17.0
	9	2.10	1728*	0.0329*	56.8	27.1
Greenane	1	2.25	2471	0.0165	40.7	18.1
	2	0.50	362	0.0178	6.4	12.9
	3	0.50	297	0.0178	5.2	10.6
	5	0.65	717	0.0154	11.0	17.0
	6	1.50	1291	0.0176	22.7	15.2

*Whole trees

3.2.4 PRODUCTIVITY OF HARVESTING BROADLEAF ROUNDWOOD FOR FIREWOOD

Work carried out in 2006 showed that mechanised harvesting was expensive. Broadleaf trees, at first thinning stage, were too diverse in size with too many bends and forks to allow a rational use of the harvester. Therefore all the broadleaf thinning trials in the work reported here focused on chainsaw harvesting. However one trial of shortwood harvesting with the mechanical harvester was carried out for comparison. All broadleaf thinning sites were marked prior to thinning. A combined line-and-selection thinning was carried out in all working plots, with the exception of the ATV and timber arch plot at Stradbally, where some prior thinning had been carried out and the ATV could travel between tree rows.

A forwarder was used to extract roundwood on all sites. Small-scale extraction methods were trialled for comparison. Many broadleaf plantations are small in area and may not have good access. In addition, the harvestable volume/ha is low compared with conifer plantations. There is an opinion that small-scale equipment is cheaper and more suitable for harvesting young broadleaf plantations. This work allowed such small-scale/DIY extraction methods to be demonstrated and their relative productivity to be studied objectively.

The small size and lack of stem straightness render broadleaf thinnings unsuitable, and certainly uneconomic, to be used for the same conventional conifer shortwood assortment and products. Therefore, the target product of these trials was firewood. Several methods were used to produce both split and round firewood. Much of the firewood produced was used in the storage trials referred to previously to examine rate of moisture content loss. The productivity trial results are presented separately for each element of the thinning operation. The full supply chain production costs were calculated for each harvesting, extraction and firewood processing method.

3.2.4.1 CHAINSAW HARVESTING OF ROUNDWOOD

The results of the time studies on thinning using a chainsaw to produce 3 m length roundwood are presented in Table 36 for each trial site and each working plot within the sites. The number of cycles refers to the number of individual trees that were time studied. The time study elements were separated into the time taken to select, fell, pull down, delimb and cross-cut the tree and present the roundwood lengths for extraction. The thinning plan for the Dovea and Mullinavat sites specified that the stumps be sprayed with *Glyphosate* to prevent coppicing. The total productive cycle time was calculated from the sum of the time elements for each cycle. The unproductive time allowance (50% of the productive time) was added to give the total time per tree. The number of trees harvested per hour was calculated from the total time per tree. The number of logs produced from each tree was recorded. The harvested volume per tree was calculated as the product of the number of logs per tree and mean log volume. Thus, the harvested volume per hour was calculated. Chainsaw harvesting costs/m^3 were derived from harvested volume per hour and an hourly rate of €25. One plot at Dovea was sub-divided after the harvesting operations to trial ATV and timber arch and horse and timber arch extraction methods. Similarly, a plot at Greenane was sub-divided after harvesting into ATV and timber arch and ATV and trailer extraction plots.

In overview, there were nine separate time studies of roundwood harvesting by chainsaw carried out on four trial sites. Productivity ranged from 11 trees per hour at Stradbally to 34 trees per hour at Mullinavat. The volume harvested was lowest at Mullinavat at 0.4 m^3 per hour and highest in Dovea at 1.01 m^3 per hour. As a result, the cost of harvesting was lowest at Dovea (€24.70 per hour) and highest at Mullinavat at (€62.56 per hour). On three of the four sites, felling for the forwarder was most productive, while felling for the tractor and grapple was least productive.

The two main variables affecting productivity were the harvestable volume per tree, which was site dependent, and the time taken to harvest a tree, which was dependent on several factors. Several operators were time-studied in different plots. It is clear from the time study results that operator ability had a substantial impact on productivity. At Mullinavat, on the same site and with the same harvested volume per tree, one operator cut 34 trees per hour, whereas another only managed to cut 22 trees per hour. Similarly, at Greenane, a chainsaw operator working in the forwarder extraction plot cut 31 trees per hour, whereas another cut just 21 trees per hour in the horse and trailer extraction plot.

These differences may be partially explained by the different amount of time spent handling logs for correct presentation, which depended on the extraction method. At Greenane, an operator presenting logs for the forwarder spent, on average, 38 cmin less per tree, compared with another presenting for the horse and trailer. This accounted for the majority of the 46 cmin per tree difference between the two operators. On the other hand, at Mullinavat, the slower operator overall, was also slower on each element in the harvesting operation, indicating that the method of log presentation was not responsible for the time difference.

Table 36: Productivity and cost of harvesting broadleaf roundwood by chainsaw.

Site		Dovea		Greenane				Mullinavat		Stradbally	
Extraction method		Forwarder	ATV & arch / Horse & arch	Forwarder	ATV & arch / ATV & trailer	Horse & Trailer	Horse bunching & forwarder	Forwarder	Tractor & grapple	Forwarder	ATV & arch
No. cycles studied		116	29	580	346	181	289	245	24	58	51
Productive time											
Select	cmin	28	21	19	26	16	25	23	35	53	68
Fell	cmin	11	11	16	17	15	22	35	53	25	29
Down	cmin	13	27	11	12	19	15			42	51
Delimb	cmin	44	13	40	33	44	42			74	77
Cross-cut	cmin	10	13	6	8	12	13	37	58	27	40
Present	cmin	25	39	35	43	81	50	16	36	90	106
Spray	cmin	1	18					6			
Sub-total	cmin	132	142	128	139	187	167	117	182	310	370
Unproductive	%	50	50	50	50	50	50	50	50	50	50
allowance	cmin	66	71	64	70	93	83	59	91	155	185
Total/tree	min	1.99	2.13	1.92	2.09	2.80	2.50	1.76	2.73	4.65	5.54
Trees/PMH		30	28	31	29	21	24	34	22	13	11
Logs/tree		2.55	1.94	1.41	1.46	1.60	1.37	1.03	1.04	2.79	3.16
Vol/log	m^3	0.013	0.013	0.016	0.018	0.015	0.018	0.017	0.017	0.012	0.016
Vol/tree	m^3	0.034	0.025	0.023	0.026	0.025	0.024	0.018	0.018	0.033	0.049
Vol/hr	m^3	1.012	0.692	0.727	0.746	0.529	0.579	0.612	0.400	0.431	0.536
Rate	€/hr	25	25	25	25	25	25	25	25	25	25
Cost	€/m^3	24.70	36.12	34.39	33.49	47.23	43.18	40.82	62.56	57.94	46.68

3.2.4.2 HARVESTING BROADLEAF ROUNDWOOD BY MECHANISED HARVESTER

At Mullinavat, a harvester was trialled over several days harvesting roundwood. Processing of 1990 trees was time-studied, with each harvesting element recorded separately. The number of logs cut from each tree was also recorded. An unproductive allowance of 30% was added to the productive time to give the total time per tree and the number of trees harvested per hour. A harvester cost rate of €110 per hour was used to calculate the harvesting cost.

Table 37 shows productivity results for the harvester; chainsaw harvesting at the same site is presented for comparison. As expected, the mechanical harvester was much more productive than a single chainsaw operator, harvesting 102 trees per hour, compared with 34 trees per hour for chainsaw felling. The harvester produced on average 1.57 m^3 of roundwood product per hour, compared with 0.61 m^3 per hour for the chainsaw operator. The harvester was faster at carrying out each element of the harvesting process, with the exception of presenting the logs.

However, the harvester was slightly less efficient at converting felled trees to roundwood, as each tree yielded only 0.94 logs. The chainsaw operator managed to do better on average, converting 1.03 logs per tree. Crucially, the cost of using the harvester was higher, €70.07/m^3 compared with chainsaw harvesting at €40.82/m^3. The trees on the Mullinavat site were the smallest of all trial sites, and it is clear that the small average tree size had the biggest impact on the productivity of the harvester. The harvester head, capable of processing trees of up to 47 cm diameter, struggled with the small size, irregular stem shape, and relatively large branch size of the trees. An additional problem with using the harvesting head was identified when processing bent or crooked stems: trees were fed through the head horizontally to shear the branches off, where the tree was crooked the stem would often hit and damage a standing tree, even though the operator intended to direct delimbed stems between two trees to the side of the rack.

Table 37: Productivity and cost comparison between harvester and chainsaw production of broadleaf roundwood at Mullinavat.

Fell method		Chainsaw	Harvester
Extraction method		Forwarder	
No. cycles studied		245	1990
Productive time			
Select	cmin	23	3
Fell	cmin	35	13
Cross-cut	cmin	37	5
Present	cmin	16	16
Spray	cmin	6	8
Sub-total	cmin	117	45
Unproductive allowance	%	50	30
	cmin	59	14
Total/tree	mins	1.76	0.59
Trees/PMH		34	102
Logs/tree		1.03	0.94
Vol/log	m^3	0.017	0.016
Vol/tree	m^3	0.018	0.015
Vol/hr	m^3	0.612	1.570
Rate	€/hr	25	110
Cost	€/m^3	40.82	70.07

3.2.4.3 EXTRACTION OF ROUNDWOOD BY FORWARDER

Forwarder extraction of roundwood was time-studied at four sites, with two separate time studies carried out at Mullinavat on the plots harvested by chainsaw and by harvester. At Greenane, an additional trial was carried out where logs were bunched into very large stacks on the main extraction rack using the horse and arch and subsequently extracted to roadside by forwarder. Between three and nine cycles were followed in each time study, with a cycle comprising of the time taken to accomplish the following: drive empty from the forest road to the first loading point on the extraction rack, loading, drive with the load to roadside and unloading. An unproductive allowance of 30% of productive time was added in order to calculate the average time per load and number of loads per hour. The average one-way distance from forest road to loading point was also recorded. The number of logs carried on each load was counted, so the volume per load and volume extracted each hour could be estimated. Finally, the operation cost/m^3 was calculated using a forwarder rate of €90 per hour.

The extraction cost of forwarding ranged from €12.91/m^3 with 6.97 m^3 per hour extracted in Dovea, to €29.47/m^3 with 3.05 m^3 per hour extracted in Stradbally (Table 38). Extraction distance contributed to the difference in productivity but does not entirely explain it. One contractor was used at Dovea and Greenane, while a different contractor was used at Mullinavat and Stradbally. Loading times differed greatly between the two contractors, with the slower operator taking over twice the time to load. Loading at Mullinavat on the harvester-felled plot was particularly slow, as there was a gap of two months between harvesting and extraction and vegetation had grown over the stacks making them difficult to see.

Interestingly, the mean number of logs per load between sites was very similar, ranging from 210 to 238 logs. There was a large difference in the volume per load however, ranging from 2.83 m^3 at Stradbally, to 4.09 m^3 at Greenane. This may be due to differences in the straightness of logs between sites. Straight logs could be stacked more compactly, thus allowing a greater volume to be carried. Bent logs were awkward to handle, and wet logs often slid from the forwarder bunk as the bark became greasy when wet.

The effect of bunching using the horse and arch, prior to extraction by forwarder was compared with standard forwarding in Greenane. Bunching resulted in a lower forwarder extraction cost, higher number of loads per hour, less time loading and a shorter extraction distance. However the forwarding cost differential, of €12.74/m^3 with bunching versus €18.87/m^3, would hardly be sufficient in this case to offset the additional cost of bunching by horse.

Table 38: Productivity and cost of forwarder extraction of broadleaf roundwood.

Site		Dovea	Greenane		Mullinavat		Stradbally
Fell method		Chainsaw	Chainsaw	Chainsaw	Chainsaw	Harvester	Chainsaw
Extraction method		Forwarder	Forwarder	Horse bunch & forwarder	Forwarder	Forwarder	Forwarder
No. cycles studied		6	9	3	4	7	8
Extraction distance	m	262	406	320	374	403	469
Productive time							
Drive empty	cmin	188	636	476	414	267	590
Loading	cmin	1203	1431	908	3095	3277	2630
Drive loaded	cmin	289	719	594	356	374	485
Unload	cmin	391	675	440	457	549	574
Sub-total	cmin	2071	3461	2418	4322	4467	4279
Unproductive	%	30	30	30	30	30	30
allowance	cmin	621	1038	725	1297	1340	1284
Total time/Load	min	26.92	44.99	31.43	56.19	58.07	55.63
Loads/hr		2.23	1.33	1.91	1.07	1.03	1.08
No. logs		238	217	210	235	216	236
Vol/log	m^3	0.013	0.016	0.018	0.017	0.016	0.012
Vol/load	m^3	3.129	3.576	3.700	4.090	3.520	2.831
Vol/hr	m^3	6.973	4.769	7.063	4.368	3.637	3.054
Rate	€/hr	90	90	90	90	90	90
Cost	€/m^3	12.91	18.87	12.74	20.61	24.75	29.47

3.2.4.4 EXTRACTION OF BROADLEAF ROUNDWOOD BY ATV

Extraction using an ATV and timber arch was trialled at three sites. The ATV was coupled with a trailer, in addition to the timber arch, at the Greenane site. Between 16 and 36 cycles were time-studied, with each cycle consisting of the time taken to drive empty from the forest road to loading point, the loading of logs, extraction to roadside and unloading. An unproductive allowance of 50% of the productive time was added to give the total time per load. The one-way extraction distance and number of logs per load was recorded for each cycle. The number of loads per hour and the volume per load were calculated and the extraction cost per cubic metre was calculated using an ATV rate of €30 per hour.

The productivity of all ATV and arch trials was broadly similar with between 0.61 and 0.76 m^3 of roundwood extracted per hour (Table 39). Highest productivity was achieved at Dovea with the timber arch, even though the extraction distance was longer than the other two sites. The number of logs carried per load, and volume per load, was higher at Dovea.

The trailer had a higher loading capacity than the arch, carrying on average three times the volume. However, productivity with the trailer was lower than with the arch. The drive time when loaded was substantially slower than with the arch and the unloading time was also slower. It should be noted that both the arch and the trailer were loaded and unloaded by hand.

However, loading and unloading the trailer required that the full weight of each log be carried by the operator. The operator was not required to lift the logs when filling the arch, and lifting logs was only required when stacking at roadside. However, skidding logs with the arch resulted, on many occasions, in logs being shed along the extraction route. Wet logs were slippery and separated from the bunch easily at times.

Table 39: Productivity and cost of broadleaf roundwood extraction by ATV following chainsaw felling.

Site		Dovea	Greenane		Stradbally
Extraction method		ATV & arch	ATV & arch	ATV & trailer	ATV & arch
No. cycles studied		20	36	16	20
Extraction distance	m	217	133	225	154
Productive Time					
Drive empty	cmin	185	116	225	120
Loading	cmin	211	183	490	254
Drive loaded	cmin	162	190	562	121
Unload	cmin	64	249	886	132
Sub-total	cmin	622	739	2163	627
Unproductive allowance	%	50	50	50	50
	cmin	311	369	1082	314
Total/load	min	9.33	11.08	32.45	9.41
Loads/hr		6.43	5.42	1.85	6.38
Logs/load		9	6	18	6
Vol/log	m^3	0.013	0.018	0.018	0.016
Vol/load	m^3	0.119	0.114	0.328	0.099
Vol/hr	m^3	0.765	0.616	0.606	0.629
Rate	€/hr	30	30	30	30
Cost	€/m^3	39.22	48.70	49.47	47.67

3.2.4.5 HORSE EXTRACTION OF BROADLEAF ROUNDWOOD

Extraction by horse was trialled at two sites: with three different methods examined. At Dovea, the horse was worked with a timber arch to extract mixed 3 and 6 m lengths to roadside. At Greenane, the horse was again used with a timber arch, though this time the objective was to bunch the logs onto the main extraction rack in very large stacks to facilitate forwarder extraction to roadside. The horse was attached to a trailer in a separate plot, to extract roundwood to roadside. Each timed cycle was divided into the following elements: drive from forest road to loading point, loading, drive to roadside and unloading. The total time per load was estimated by adding an unproductive allowance of 50%. The one-way extraction distance and number of logs per load was recorded. The number of loads per hour, and extraction cost was calculated using a rate of €30 per hour.

The productivity and cost of roundwood extraction by horse is detailed below in Table 40. The most productive method was using the horse with the trailer at Greenane, extracting 0.64 m^3 per hour. The horse and timber arch achieved a similar productivity 0.62 m^3 per hour at the same site, though the extraction distance was less in this plot, as the purpose was to bunch the logs only. At Dovea, the horse and timber arch managed just 0.46 m^3 per hour, as the extraction distance was longer.

The timber arch was underutilised on both sites. At Dovea, the mean log volume was low, even though logs were cut to 6 m lengths where possible. At Greenane, fewer logs were skidded on each load because the logs were widely dispersed. Also all logs were cut to a standard 3 m length at Greenane, so more logs of larger volume could be skidded by the horse and arch. The horse and trailer took longer to load and unload in comparison to the arch, as each log was lifted by hand.

It should be noted that the cost of bunching logs by horse to facilitate the forwarder was €48.26/m^3, whereas the margin between forwarding without bunching and forwarding with bunching was €6.13/m^3. Thus, on this trial, horse bunching did not improve productivity sufficiently to be cost effective.

Table 40: Productivity and cost of horse extraction of broadleaf roundwood following chainsaw felling.

Site		Dovea	Greenane	
Extraction method		Horse & arch	Horse & trailer	Horse & arch bunching
No. cycles studied		39	34	75
Extraction distance	m	275	226	103
Productive time				
Drive empty	cmin	592	486	222
Loading	cmin	269	687	395
Drive loaded	cmin	515	229	94
Unload	cmin	278	452	233
Sub-total	cmin	1654	1855	943
Unproductive allowance	%	50	50	50
	cmin	827	927	472
Total/load	min	24.81	27.82	14.15
Loads/hr		2.42	2.16	4.24
No. logs		15	19	8
Vol/log	m^3	0.013	0.015	0.018
Vol/load	m^3	0.191	0.296	0.147
Vol/hr	m^3	0.462	0.639	0.622
Rate	€/hr	30	30	30
Cost	€/m^3	64.98	46.93	48.26

3.2.4.6 TRACTOR AND GRAPPLE EXTRACTION OF BROADLEAF ROUNDWOOD

A 60 kW tractor was fitted with a grapple on the three-point linkage and used at Mullinavat to extract roundwood. The tractor was fitted with a steel skid plate underneath and bars around the cab to protect the tractor from damage. A total of 36 extraction cycles were time-studied, with each cycle sub-divided into time taken for driving empty, loading, driving full and unloading at roadside. An unproductive allowance of 30% was added to the productive time per cycle. The one-way extraction distance was measured for each cycle and the number of logs per load was counted. The number of loads and volume extracted per hour were calculated. The cost of extraction was calculated using an hourly rate of €40 for the tractor. The productivity study results are presented in Table 41, with the forwarder extraction results from the same site presented for comparison.

The tractor and grapple averaged 8.79 loads per hour, compared with 1.07 loads per hour for the forwarder. However, the load carrying capacity of the grapple was just 0.21 m^3 per load, whereas the forwarder carried 4.09 m^3 per load. Surprisingly, the cost of extraction was similar for the two extraction methods, with the tractor and grapple costing €21.70/m^3, while the forwarder cost €20.61/m^3. However, the extraction distance for the tractor was much shorter than that of the forwarder.

Closer examination of the time study results reveals that the tractor and grapple was slower per unit volume than the for warder for driving empty, driving full and unloading. On the other hand, the grapple was much faster than the forwarder in loading. Overall, the tractor and grapple was less productive, though it had a lower hourly rate than the forwarder. The slower speed of the tractor and grapple indicates that this extraction method would become less productive in comparison to forwarding as extraction distance increased. It would be most productive on a small site, where the extraction distance is short.

The number of logs in each stack presented for the grapple was crucial to working it efficiently. Too many logs and the grapple could not grip them all in one load, and so had to return for the remainder. Too few logs and the tractor would have to move to a second stack, release the logs from the grapple and then try to grip all the logs.

Table 41: Productivity and cost of tractor and grapple and forwarder broadleaf roundwood extraction following chainsaw felling at Mullinavat.

Extraction method		Tractor & grapple	Forwarder
No. cycles studied		36	4
Extraction distance	m	80	374
Productive time			
Drive empty	cmin	211	414
Loading	cmin	63	3095
Drive loaded	cmin	194	356
Unload	cmin	57	457
Sub-total	cmin	525	4322
Unproductive allowance	%	30	30
	cmin	158	1297
Total/load	min	6.83	56.19
Loads/hr		8.79	1.07
No. logs		12	235
Vol/log	m^3	0.017	0.017
Vol/load	m^3	0.210	4.090
Vol/hr	m^3	1.843	4.368
Rate	€/hr	40	90
Cost	€/m^3	21.70	20.61

3.2.4.7 PROCESSING FIREWOOD FROM BROADLEAF ROUNDWOOD

The main objective of harvesting small-sized roundwood from early thinning of broadleaves was the production of firewood. Four different methods of producing firewood were trialled as follows:

- Posch cross-cutter   Greenane
- *Bilke*   Mullinavat
- *Hakke Pilke Hawk*   Greenane, Stradbally
- Sawhorse   Dovea, Greenane

Firewood processing in the forest has a number of advantages. Seasoning is promoted by cutting and splitting logs quickly after harvesting. The harvested material is kept secure as there are workers on site continuously until the firewood is removed for storage or sale. The processing can be integrated with harvesting and extraction, so that the working space is optimised and need for stacking is minimised. On the other hand, this approach requires more complicated logistics and more resources than may be available. Access and the quality of roading on-site may dictate that roundwood is transported to a yard for processing. The firewood may need to be removed immediately after processing to a secure storage area.
Also, roundwood may be sold on to a third party firewood producer.

The simple saw bench and the *Hawk* firewood processor were timed at two sites, the Posch cross-cutter and the *Bilke* processor at one site each. The *Bilke* was timed producing two different standard lengths. The *Hawk* time study at Stradbally and the Posch time study included packing firewood in large 1 m^3 net bags. The *Hawk* time study at Greenane and the *Bilke* time study were taken with the firewood being fed loose by a conveyor into a trailer. The saw bench time at Greenane included hand filling a trailer, while the saw bench time at Dovea included the time needed to fill small 30 l net bags. Firewood production was linked to a particular harvesting and extraction process at each site. The four systems trialled were time-studied with each cycle being the time required to process one log. An unproductive allowance of 50% was added to determine the processing time per log. The number of logs per hour and volume processed per hour were estimated. The processing cost/m^3 was calculated from the hourly rate for each processor.

It is clear from the results presented in Table 42 that the *Bilke* was extremely productive in comparison with the other methods trialled. The processing time per log was less than half that of the next fastest processor. The volume produced was 1.91 m^3 per hour compared with 0.74, 0.57 and 0.53 m^3 per hour for the Posch, *Hawk* and saw bench, respectively.

Consequently, the *Bilke* produced firewood at a cost of €26.14/m^3, or half the cost of the saw bench method and 25% of the other processors' cost. Equally, the *Hawk* was a very slow method of processing firewood, particularly at Stradbally.

There are a number of factors to consider regarding productivity. The first is the resources needed to operate the method. The saw bench relied solely on one chainsaw operator. The *Bilke* required one operator with a tractor to power the processor and a trailer to collect the firewood. The *Hawk* was self-powered with a petrol engine but required two operators to load process and stack the firewood in net bags. Finally, the Posch also required two operators and a tractor to power the processor.

The second factor to consider is the quality of firewood produced. The firewood from the saw bench was cross-cut only and was cut to a variable length by the chainsaw operator. The Posch also cross-cut only, but did cut to a standard length. The *Bilke* and *Hawk* both produced cut and split firewood to a standard length, but the *Bilke* produced a less even cut surface, which would affect subsequent packaging.

The third factor having an impact on productivity was the operation method of the processor. It was necessary to manually feed the log to the cutting head as each firewood piece was cut, on both the Posch and *Hawk*, whereas the *Bilke* used a conveyor to move the log on as it was cut. The *Hawk* cross-cut and split the log in two separate operations; the hydraulic splitting ram had a fixed time that could not be changed. The *Bilke* cut and split in one continuous operation.

Log size and straightness had a substantial impact on processor productivity. The broadleaf roundwood produced was ideal in size for the *Bilke*, but small for the other processors. They were capable of handling much larger log diameters, and would be more productive when processing such sizes. On the other hand, the *Bilke* in-feed conveyor was limited to a maximum diameter of 20 cm, and even though almost all logs were less than this, blockages did occur if the log was misshapen, reducing productivity.

Table 42: Broadleaf firewood processing methods and associated productivity and costs following chainsaw felling.

Firewood method		Hakke Pilke Hawk		Posch Cross-cutter	Bilke (20 cm length)	Bilke (50 cm length)	Saw bench	
Site		Greenane	Stradbally	Greenane	Mullinavat	Mullinavat	Greenane	Dovea
Extraction method		Forwarder	ATV & arch	Forwarder	Tractor & grapple	Tractor & grapple	ATV & trailer	Horse & arch
No. cycles studied		230	143	76	107	115	166	123
Productive time/log	cmin	116.0	206.6	89.2	36.5	24.4	133.0	115.8
Unproductive allowance	%	50	50	50	50	50	50	50
	cmin	58.0	103.3	44.6	18.3	12.2	66.5	57.9
Total time/log	min	1.74	3.10	1.34	0.55	0.37	2.00	1.74
Logs/hr		34	19	45	109	164	30	35
Vol/log	m^3	0.016	0.016	0.016	0.017	0.017	0.018	0.013
Vol/hr	m^3/hr	0.57	0.30	0.74	1.91	2.87	0.53	0.44
Rate	€/hr	60	60	75	50	50	25	25
Cost	€/m^3	105.56	197.96	101.49	26.14	17.44	46.77	57.44

3.2.4.8 COMPARISON OF BROADLEAF ROUNDWOOD PRODUCTION COST TO FOREST ROAD

Table 43 summarises the production cost of broadleaf roundwood to the forest road for all methods at each study site. The total cost in each case is the sum of the harvesting cost and the extraction cost for that working plot. The lowest overall cost was achieved by the forwarder extraction method at Dovea at €37.61/m^3, while the highest cost was horse bunching and forwarding at Greenane at €104.18/m^3. In fact, chainsaw harvesting and forwarder extraction was the lowest cost method on all study sites. The small-scale methods were much more expensive, ranging from €75.33-101.10/m^3. There was greater variation in harvesting costs in comparison with extraction costs, indicating the importance of skilled chainsaw operators. The tractor and grapple method would be comparable to the forwarder method, except the harvesting costs on this trial were so high.

Table 43: Cost comparison of broadleaf roundwood production methods to roadside.

Site		Dovea			Greenane						Mullinavat			Stradbally	
Fell method		Chainsaw	Chainsaw		Chainsaw	Chainsaw		Chainsaw	Chainsaw		Chainsaw	Chainsaw	Harvester	Chainsaw	Chainsaw
Vol/tree	m^3	0.034	0.025		0.023	0.026		0.025	0.024		0.018	0.018	0.015	0.033	0.049
Vol/hr	m^3	1.012	0.692		0.727	0.746		0.529	0.579		0.612	0.400	1.570	0.431	0.536
Rate	€/hr	25	25		25	25		25	25		25	25	110	25	25
Cost/m^3	€/m^3	24.70	36.12		34.39	33.49		47.23	43.18		40.82	62.56	70.07	57.94	46.68
Extraction method		Forwarder	ATV & arch	Horse & arch	Forwarder	ATV & arch	ATV & trailer	Horse & trailer	Horse bunching	Forwarder	Forwarder	Tractor & grapple	Forwarder	Forwarder	ATV & arch
Vol/load	m^3	3.129	0.119	0.191	3.576	0.114	0.328	0.296	0.147	3.700	4.090	0.210	3.520	2.831	0.099
Vol/hr	m^3	6.973	0.765	0.462	4.769	0.616	0.606	0.639	0.622	7.063	4.368	1.843	3.637	3.054	0.629
Rate	€/hr	90	30	30	90	30	30	30	30	90	90	40	90	90	30
Cost	€/m^3	12.91	39.22	64.98	18.87	48.70	49.47	46.93	48.26	12.74	20.61	21.70	24.75	29.47	47.67
Total cost	€/m^3	37.61	75.33	101.10	53.26	82.19	82.96	94.16	104.18		61.42	84.26	94.82	87.41	94.35

3.2.4.9 COMPARISON OF BROADLEAF FIREWOOD PRODUCTION COST AT FOREST ROAD

In seven working plots at the four study sites, different firewood production methods were trialled in conjunction with roundwood harvesting and extraction. The overall costs/m^3 of firewood production at the forest road are presented in Table 44. Costs ranged from €101.71/m^3 for the *Bilke* in Mullinavat to €292.31/m^3 for the *Hawk* in Stradbally.

Production costs were also calculated on an energy content basis. Cost on a solid volume basis was converted to a bulk volume basis, using a bulk/solid volume conversion factor of 2. Net calorific value was calculated from sample post-seasoning moisture contents. The measured bulk density of firewood was used to derive the energy content on a bulk volume basis and the production costs were then expressed on an energy basis. Firewood production costs, expressed on a net energy content basis, ranged from €8.67-26.05/GJ, with the *Bilke* method in Mullinavat again the cheapest.

Obviously, overall production cost was dependent on the cost of the individual elements of the supply chain for that method. By selecting the most productive harvesting, extraction and firewood processing method, it would be possible to substantially improve on the production cost results found in these trials. Clearly, for this type of assortment, extraction by forwarder and firewood production with the *Bilke* processor will enhance productivity. Chainsaw harvesting is the element that is least predictable or controllable, as it will largely depend on the skills of the individual operator. One way of reducing uncertainty in production cost would be to agree a piece rate payment system with the contractor. The volume production datasets presented here provide some guidance for such arrangements.

Table 44: Comparison of costs of firewood supply chains following chainsaw felling.

Site		Dovea	Greenane			Mullinavat		Stradbally
Vol/tree	m^3	0.019	0.023	0.023	0.026	0.018	0.018	0.049
Vol/hr	m^3	0.526	0.727	0.727	0.746	0.400	0.400	0.536
Rate	€/hr	25	25	25	25	25	25	25
Cost (solid volume)	€/m^3	47.55	34.39	34.39	33.49	62.56	62.56	46.68
Extraction method		Horse & arch	Forwarder	Forwarder	ATV & trailer	Tractor & grapple	Tractor & grapple	ATV & arch
Vol/load	m^3	0.191	3.576	3.576	0.328	0.210	0.210	0.099
Vol/hr	m^3	0.462	4.769	4.769	0.606	1.843	1.843	0.629
Rate	€/hr	30	90	90	30	40	40	30
Cost (solid volume)	€/m^3	64.98	18.87	18.87	49.47	21.70	21.70	47.67
Firewood method		Saw bench	*Hawk*	Posch	Saw bench	Bilke (20 cm)	Bilke (50 cm)	*Hawk*
Vol/hr	m^3/hr	0.44	0.57	0.74	0.53	1.91	2.87	0.30
Rate	€/hr	25	60	75	25	50	50	60
Cost (solid volume)	€/m^3	57.44	105.56	101.49	46.77	26.14	17.44	197.96
Total cost (solid volume)	€/m^3	169.96	158.82	154.76	129.73	110.41	101.71	292.31
Solid/bulk volume		2	2	2	2	2	2	2
Total cost (bulk volume)	€/m^3	84.98	79.41	77.38	64.86	55.20	50.85	146.15
MC post seasoning	%	19.9	23.5	24.9	27.8	19.5	19.5	21
Bulk density	kg/m^3	289	359	411	444	396	396	387
Net calorific value	GJ/t	14.7	14.0	13.7	13.0	14.8	14.8	14.5
Energy content (bulk volume)	GJ/m^3	4.3	5.0	5.6	5.8	5.9	5.9	5.6
Production cost	€/GJ	19.96	15.84	13.78	11.20	9.41	8.67	26.05

3.2.5 PRODUCTIVITY OF WOODCHIP PRODUCTION FROM BROADLEAF WHOLE TREES

3.2.5.1 CHAINSAW HARVESTING OF WHOLE TREES IN BROADLEAVES

At Dovea and Mullinavat, working plots were defined to trial line-and-selection thinning using chainsaws to fell whole trees and the *Silvatec* terrain chipper to process the seasoned whole trees into woodchip. The chainsaw harvesting operation on both sites was time-studied. Each time study cycle consisted of the elements involved in selecting, felling, dragging down and presenting one tree. An unproductive allowance of 70% of the productive cycle time was added to give the total time per tree. The number of trees per hour, harvested volume per tree and volume harvested per hour were calculated. The cost/m^3 was derived from a chainsaw operator rate of €25/m^3 per hour.

The results are shown in Table 45. The chainsaw operation at Mullinavat was more productive, as a higher number of trees per hour were felled, 59 trees per hour compared with 52 trees per hour at Dovea. This could be mainly attributed to the additional time the operator spent spraying stumps in Dovea, at the request of the owner. In addition, the harvested volume per tree was greater at Mullinavat. Harvesting whole trees by chainsaw had much higher productivity compared with harvesting roundwood. The most productive roundwood harvesting operation was 1.01 m^3 per hour, while the average for the roundwood trials was 0.6 m^3 per hour. Wholetree harvesting productivity was 1.24 m^3 per hour and 1.77m^3 per hour at Dovea and Mullinavat, respectively. Each tree was felled faster, as there was no delimbing or cross-cutting and the harvested volume was higher as there was no volume loss due to delimbing and cutting to a fixed length.

Felling extraction-line trees using this system is fast and quite easy for the operator. The main requirement is that the felled trees are all in a line with the butt end facing out towards the forest road or headland. Felling the trees selected for thinning between the extraction racks can be more problematic, as the operator must ensure that tree does not get hung up on neighbouring trees. Also, it may be necessary to pull the tree at an acute angle through several tree rows to get the butt end onto the extraction rack, and presented correctly for the terrain chipper.

Table 45: Productivity and cost of harvesting broadleaf whole trees by chainsaw.

Site		Dovea	Mullinavat
No. cycles studied		157	804
Productive time			
Select	cmin	20	21
Fell	cmin	11	21
Down	cmin	19	15
Present	cmin	2	2
Spray	cmin	16	0
Sub-total	cmin	68	60
Unproductive allowance	%	70	70
	time	47	42
Total/tree	mins	1.15	1.01
Trees/SMH		52	59
Vol/tree	m^3	0.024	0.030
Vol/hr	m^3	1.241	1.775
Rate	€/hr	25	25
Cost	€/m^3	20.14	14.09

3.2.5.2 TERRAIN CHIPPING OF WHOLE TREE BROADLEAVES

The *Silvatec* terrain chipper and chip forwarder were employed at Dovea and Mullinavat in processing the whole trees and extracting the woodchip to roadside, after one summer's seasoning. At Dovea the available plot size was small and each extraction rack linked directly to the forest road. Therefore it was decided that the terrain chipper would deposit woodchip directly on the forest road, rather than transfer it to the chip forwarder, whereas at Mullinavat the chipper worked in conjunction with the chip forwarder.

The volume per load for both sites was similar, which could be expected as the *Silvatec* had a fixed volume container of 17 m^3. The productivity at Mullinavat was the higher, at 1.58 loads per hour compared with 1.15 loads per hour at Dovea (Table 46). The main reason was the use of the chip forwarder at Mullinavat, so the chipper could be productive for more time. Also, the trees were bigger in Mullinavat, so fewer trees were required to fill a load. Thus, the mean loading time was five minutes per load less in Mullinavat than in Dovea.

Table 46: Productivity and cost of broadleaf wholetree *Silvatec* terrain chipping following chainsaw felling and woodchip extraction by chip forwarder.

Site		Dovea	Mullinavat
No. cycles studied		3	7
Productive time			
Drive empty	cmin	747	129
Loading	cmin	2594	2036
Drive loaded	cmin	582	598
Unload	cmin	81	156
Sub-total	cmin	4004	2919
Unproductive allowance	%	30	30
	cmin	1201	876
Total/load	min	52.05	37.95
Loads/hr		1.15	1.58
No. trees		212	173
Vol/tree	m^3	0.024	0.030
Vol/load	m^3	5.046	5.175
Vol/hr	m^3	5.816	8.182
Rate	€/hr	300	300
Cost	€/m^3	51.58	36.66

3.2.5.3 BROADLEAF WHOLETREE WOODCHIP SUPPLY CHAIN PRODUCTION COST TO FOREST ROAD

The production cost of whole tree harvesting and terrain chipping in broadleaf first thinning is presented in Table 47. The cost of felling by chainsaw and chipping with the *Silvatec* is presented on a cubic metre solid volume basis. The cumulative cost of €50.75/m^3 for Mullinavat and €71.72/m^3 for Dovea were converted to cost/m^3 bulk volume, using the bulk/solid volume conversion factor of 3.28. The energy content of woodchip from both sites was calculated from the mean post-seasoning moisture content and bulk density data. The production cost to roadside was €4.52/GJ at Mullinavat and €6.49/GJ at Dovea. The woodchip production cost on both sites was substantially lower than even the best firewood production costs on a solid volume or energy content basis. However, given the moisture content achieved after seasoning in the forest and the particle size distribution of whole tree woodchip produced by the *Silvatec*, it is unlikely that this chip would be suitable in small to medium commercial boilers. The likely market for this would be large industrial boilers, CHP or even electricity generation. Therefore, the price-paying potential for this woodfuel may be more limited than consumers of firewood. The market value of woodfuels was not studied in this work programme.

Table 47: Production cost of wholetree broadleaf woodchip using *Silvatec* terrain chipping following chainsaw felling.

Site		Dovea	Mullinavat
Solid vol/tree	m^3	0.024	0.030
Vol/hr	m^3	1.241	1.775
Rate	€/hr	25.00	25.00
Cost (solid volume)	€/m^3	20.14	14.09
Vol/hr	m^3	5.816	8.182
Rate	€/hr	300	300
Cost (solid volume)	€/m^3	51.58	36.66
Total cost (solid volume)	€/m^3	71.72	50.75
Bulk/solid volume factor		3.28	3.28
Total cost (bulk volume)	€/m^3	21.87	15.47
MC post seasoning	%	38.45	36.47
Bulk density	kg/m^3	313	306
Net calorific value	GJ/t	10.8	11.2
Energy content (bulk volume)	GJ/m^3	3.4	3.4
Production cost	€/GJ	6.49	4.52

3.2.6 COMPARISON OF WOODFUEL SUPPLY CHAIN COSTS FROM BROADLEAF THINNINGS

The average woodfuel supply chain production costs of the main supply chains trialled in broadleaf thinning are presented in Table 48. Production costs for 2007 and 2008 trials are compared with results from previous trials carried out in 2006. One site was thinned in 2006, and several woodchip production systems were trialled. In 2007 and 2008 four broadleaf sites were thinned with both woodchip and firewood production systems trialled.

Wholetree woodchip production was carried out in 2006 and 2008. Harvesting of whole trees with feller-buncher and by chainsaw operator was trialled in 2006. In 2008, harvesting was done by chainsaw only. The feller buncher cost €10.95/m^3 in the terrain chipping system, and €15.88/m^3 in the forwarder and roadside chipping system. This difference was possibly due to site and tree size differences, but also because of the different way in which trees awere left on the ground after harvesting. For terrain chipping the tree butts were simply pulled into the line for the chipper to grab, while for extraction with forwarder, the trees had to be stacked along the line. There is a large difference in the cost of chainsaw harvesting between 2006 and 2008, this too would be heavily influenced by tree size and site conditions. Also, operator experience and fitness have a major impact on the productivity of chainsaw operations, due to the physically demanding nature of the work. Chainsaw felling is a manual operation, and therefore relies more on the operator's condition, experience and skill than mechanical harvesting. The *Silvatec* terrain chipper also showed a large increase in cost in 2008, again suggesting that site conditions and tree size were more optimal in 2006. Also, in 2008 the chip forwarder could not operate at the Dovea site, and was severely restricted at the Mullinavat site where it had a long extraction distance to a farmer's yard.

Firewood production costs varied with method, as both chainsaw operators and a harvester were used for tree felling and crosscutting in the different trials. Chainsaw harvesting costs were very similar in 2007 and 2008, and were much lower than the mechanical harvester cost. Various small-scale methods were used for extraction, such as ATV and trailer, ATV and timber arch, horse and timber arch, horse and trailer, tractor and grapple, all of which had a higher cost than forwarder extraction. A huge difference in the firewood processing cost can be seen in the results. The most expensive processing method was the use of the *Hakke Pilke Hawk* processor, which had a cost of €113/m^3. It must be noted that this processor required two persons to operate it effectively. Various other processing methods such as a saw bench and chainsaw were trialled, and gave a mean cost of €65.54/m^3. The lowest cost processor trialled was the *Bilke* processor, which was driven off a tractor PTO and could be operated by a single person. The results suggest that although not directly trialled in the study, the most cost effective system for producing firewood could be chainsaw harvesting, forwarder extraction and processing with the *Bilke* processor.

All small-scale methods trialled were costed on a professional contractor pay rate basis. These methods are technically sound and could be carried out by the forest owner, at little expense other than the individual's time, training and equipment cost.

Table 48: Broadleaf woodfuel supply chain cost comparisons.

Assortment		Wholetree woodchip				Firewood		
Trial year		2006	2006	2008	2006	2007	2008	2008
Felling method		Feller buncher	Chainsaw	Chainsaw	Feller buncher	Chainsaw	Chainsaw	Harvester
Harvesting cost	€/m^3	10.95	5.88	17.12	15.88	41.36	43.61	70.07
Extraction method		Silvatec chip forwarder			Forwarder	Various	Various	Forwarder
Extraction cost	€/m^3	(Cost included with Silvatec)			16.57	38.85	33.41	24.75
Chipping / processing method		Silvatec terrain chipper			Jenz	Hakke Pilke *Hawk*	Various	Bilke
Chipping/processing cost	€/m^3	19.99	21.96	44.12	11.91	112.78	65.54	26.14
Production cost	€/m^3	30.94	27.84	61.24	44.36	192.99	142.56	120.96
Cost of energy	€/GJ	3.37	2.85	5.51	4.07	20.95	11.78	10.25

3. 3 MOISTURE CONTENT & BULK DENSITY OF WOODFUELS

3.3.1 WOODFUEL MOISTURE CONTENT

Summary results of moisture content samples measured during the harvesting, chipping and firewood processing operations are shown in Table 49. The mean moisture content for each assortment at each trial site is presented, as this was used to determine its rate of seasoning. Also, the mean moisture content per assortment after one and two summers' seasoning was used to determine the energy content of the assortment. The energy content was then used to estimate the production cost per GJ for each assortment at each site.

The mean moisture content in each case was derived from sampling, carried out at an intensity to ensure that the estimated mean moisture content would be within ±2% of the true mean moisture content at the 95% confidence level. The margin of error is a function of the variation between individual sample moisture contents, the number of samples taken and the confidence level chosen. In some cases the margin of error exceeded 2%, meaning that the level of variation within the assortment was higher than assumed when deciding on the number of samples, and that a greater sampling intensity was required. As such, the margin of error can be used as an indication of the uniformity of drying during storage of the assortment.

3.3.1.1 CONIFER SHORTWOOD AND ENERGY WOOD MOISTURE CONTENT

The change in moisture content was assessed for the following assortments:

- Conifer 3 m shortwood stacked at roadside uncovered or with a top cover for one or two summers;
- Conifer 3-4.5 m energy wood stacked at roadside uncovered or with a top cover for one or two summers.

Shortwood assortments were harvested at five sites in 2007. The mean moisture content at the time of harvesting was compared with autumn 2007 and in 2008 during chipping. Moisture content in Sitka spruce at harvest ranged from 59% at Bweeng to 63% at Ballybofey, with an average of 61% across the five sites. Moisture had reduced to 50% on average after c. 5 months. Moisture content reduced to 46% on average 12 months later. All shortwood stacks were covered with special-purpose paper, apart from one stack at Woodberry. The paper cover was in effect a barrier to rewetting in the first summer, but had largely disintegrated over the winter of 2007. This, at least partly, explains the poor drying throughout 2008.

Table 49: Moisture content change in conifer shortwood stacks.

Site	Spring 2007		Autumn 2007		Autumn 2008	
	Mean	Margin of error	Mean	Margin of error	Mean	Margin of error
	%					
Abbeyfeale	61.3	1.3	46.6	1.5	44.3	2.4
Ballybofey	62.6	1.2	56.6	0.8	46.2	2.1
Bweeng	59.0	1.1	47.3	1.9		
Toormakeady	61.2	1.0			54.5	2.6
Woodberry	60.0	0.7	50.2	3.1	38.7	2.9
Mean	60.8		50.2		45.9	

Figure 40 presents the mean moisture content of shortwood stacks at Woodberry with and without a top cover. The vertical bars are the margins of error associated with the mean moisture content. The change in moisture content over time was significant for both uncovered and covered stacks. However, the covered stack dried to a significantly greater extent, compared with the uncovered stack. It is worth noting that the paper cover on the shortwood stack at Woodberry had least deteriorated. This may have had the effect of ensuring that the logs dried and water did not on lodge on the stack. It is also worth noting that the moisture content achieved in the covered stack after two summers was less than 35%, meaning woodchip from this assortment was suitable for smaller commercial boilers.

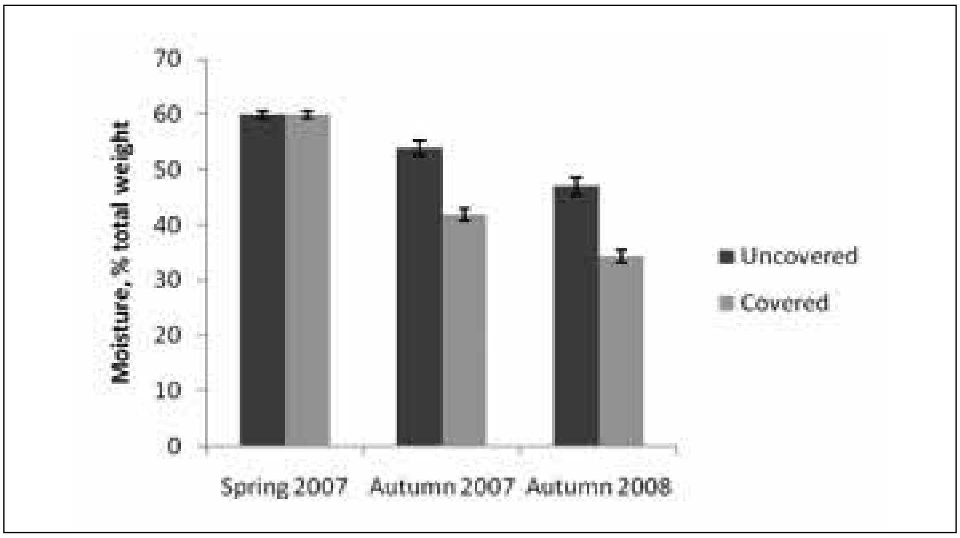

Figure 40: Moisture content change in covered and uncovered Sitka spruce shortwood stacks at Woodberry.

Most of the energy wood assortments had a paper top cover, apart from a single stack at Woodberry. The energy wood assortment initial moisture content was slightly, but not significantly, lower than the shortwood assortment. However the energy wood was more variable, due to its longer length, smaller top diameter, and the presence of branchwood and some leaf material. The energy wood assortment did not dry as consistently as shortwood, and, at some sites, it was not possible to definitively conclude if any drying had taken place, such was the level of variation in sample moisture contents, and the consequent overlap in margins of error. At Woodberry, the only site where significant drying took place after two summers, the energy wood mean moisture content decreased from 58.5% to 41.3%. This was broadly similar to shortwood at the same site.

Certainly, the deterioration of the top cover over the winter in 2007 meant rainfall penetrated the stacks (Figure 41). It is likely that the branches and leaf material present trapped at least some of this water causing it to lodge in the stacks.

Figure 41: Typical deterioration of shortwood stack paper covers by the second year.

Figure 42 shows the effect of the deterioration of the top cover, as dry logs are sandwiched between wet material at the top and bottom of the stack.

Figure 42: Exposed energy wood stack, showing variable drying with wet (darker coloured) layers at top (from rain), and at bottom (from ground contact).

Table 50 presents the initial mean moisture content of energy wood on each site and the moisture content after one and two summers.

Table 50: Moisture content change in conifer energy wood stacks.

Site	Spring 2007		Autumn 2007		Autumn 2008	
	Mean	Margin of error	Mean	Margin of error	Mean	Margin of error
	%					
Abbeyfeale	60.4	5.1	53.5	2.5	50.9	6.0
Ballybofey	60.6	3.0	58.4	4.9	57.4	5.0
Bweeng	55.4	3.1	52.8	3.5		
Toormakeady	63.9	5.5			56.5	3.8
Woodberry	58.5	2.5	50.0	11.1	41.3	4.5
Mean	59.8		53.7		51.5	

3.3.1.2 WHOLE TREE CONIFER AND BROADLEAF WOODCHIP MOISTURE CONTENT

Moisture contents for wholetree assortments are shown in Table 51. Results are presented separately for the following:

- conifer whole trees seasoned in the extraction rack and chipped with the *Silvatec* terrain chipper after one and two summers' seasoning,
- conifer whole trees selectively felled and seasoned at the stump over one summer and winched to roadside for chipping;
- conifer whole trees chemically thinned, seasoned standing and felled and chipped with the *Silvatec* terrain chipper;
- broadleaf whole trees seasoned in the extraction rack and chipped with the *Silvatec* terrain chipper.

The mean moisture content at the time of felling was 56.5%; it reduced to 49.3% after one summer's seasoning and to 47.2% after a second summer. There was no significant difference in moisture content between one and two summers' seasoning, with the exception of the Abbeyfeale site. Even so, the variability of moisture content in the wholetree assortment was high as indicated by the margin of error associated with each mean.

Table 51: Moisture content change in conifer wholetree assortment stored on extraction racks.

Site	Spring 2007		Autumn 2007		Autumn 2008	
	Mean	Margin of error	Mean	Margin of error	Mean	Margin of error
	%					
Abbeyfeale	56.3	2.3	52.7	3.3	43.1	4.8
Ballybofey	59.8	3.5	50.9	4.6	49.8	2.8
Bweeng	52.3	2.8	44.6	2.7		
Toormakeady	59.4	2.7			48.9	2.5
Woodberry	54.6	1.3	48.9	3.9	46.9	3.2
Mean	56.5		49.3		47.2	

The small working plots, where trees were selectively felled and left standing to dry over summer 2007, were subsequently winched to roadside and chipped. Trees were sampled for initial moisture content during the felling and sampled again during the chipping operation to assess drying. The initial mean moisture content of the trees was 55.6%, which had reduced to 45% after one summer's seasoning in the stand (Table 52).

Table 52: Moisture content change in conifer wholetree assortment felled selectively.

Site	Spring 2007		Autumn 2007	
	Mean	Margin of error	Mean	Margin of error
	%			
Ballybofey	59.8	3.5	47.8	1.5
Bweeng	52.3	2.8	42.3	1.1
Woodberry	54.6	1.3	44.9	0.9
Mean	55.6		45.0	

Sitka spruce at Kilbrin and Swan was chemically thinned in 2006, but many of the larger trees survived the first treatment. Trees received a second treatment in spring 2007, and were felled and chipped by the *Silvatec* terrain chipper in autumn 2007. The initial moisture content of the trees in 2006 prior to treatment was 58.7% (Table 53). After two chemical treatments and two summers the moisture content had reduced to 39% on average. The first treatment at Kilbrin resulted in a better response and as a consequence trees had dried more than at Swan.

Table 53: Moisture content change in chemically-thinned Sitka spruce.

Site	Spring 2006		Autumn 2007	
	Mean	Margin of error	Mean	Margin of error
	%			
Kilbrin	56.8	1.3	32.3	1.0
Swan	60.5	1.1	45.6	0.9
Mean	58.7		39.0	

The moisture content of whole ash trees felled in summer 2007 compared with their moisture content when chipped in autumn 2008 is shown in Table 54. The average moisture content of freshly felled ash trees was 43.1%, which had reduced to 37.5% after seasoning, a small but statistically significant reduction. One disadvantage in using the wholetree terrain chipping method in ash plantations is the development of undergrowth in the extraction racks during the seasoning period. This reduces air flow, and creates a humid microclimate around the felled trees which probably reduced drying potential.

Table 54: Moisture content change in ash whole trees stored on extraction racks.

Site	Summer 2007		Autumn 2008	
	Mean	Margin of error	Mean	Margin of error
	%			
Dovea	45.2	0.63	38.5	1.23
Mullinavat	41.0	0.58	36.5	0.43
Mean	43.1		37.5	

3.3.1.3 CONIFER AND BROADLEAF FIREWOOD MOISTURE CONTENT

The impact of the following firewood storage methods on reducing firewood moisture content is shown in Table 55:

- conifer split firewood stored in large net bags inside under cover, outside under cover and outside uncovered,
- broadleaf split and round firewood stored in large and small net bags, indoors under cover and outside under cover.

On average, initial moisture content of freshly harvested conifer shortwood used for firewood processing was 61%. Over the 18-month storage period the average moisture content reduced to 24.5%. Firewood stored indoors at Bweeng and Toormakeady dried better than when stored outside. Drying was also more uniform in firewood stored indoors, as indicated by the lower margin of error. There was little difference storing firewood outside with a cover (Ballybofey) or without a cover (Abbeyfeale). In both cases the moisture content achieved after storage was similar, and the variability of moisture content between individual pieces was high.

Table 55: Moisture content change in conifer firewood.

Site	Storage method	Spring 2007		Autumn 2008	
		Mean	Margin of error	Mean	Margin of error
		%			
Abbeyfeale	Outside	61.3	1.3	29.8	3.1
Ballybofey	Outside	62.6	1.2	30.5	2.3
Bweeng	In shed	59.0	1.1	18.0	0.5
Toormakeady	In shed	61.2	1.0	19.6	0.9
Mean		61.0		24.5	

Figure 43 shows the change in moisture content of conifer firewood over the storage period. All firewood had achieved a mean moisture content of 30% by autumn 2008. Firewood stored indoors dried to less than 20% moisture content. Firewood stored outside at Abbeyfeale in a very exposed location also dried close to 20% moisture content but subsequently gained in moisture later in 2008 as the net bags were not covered.

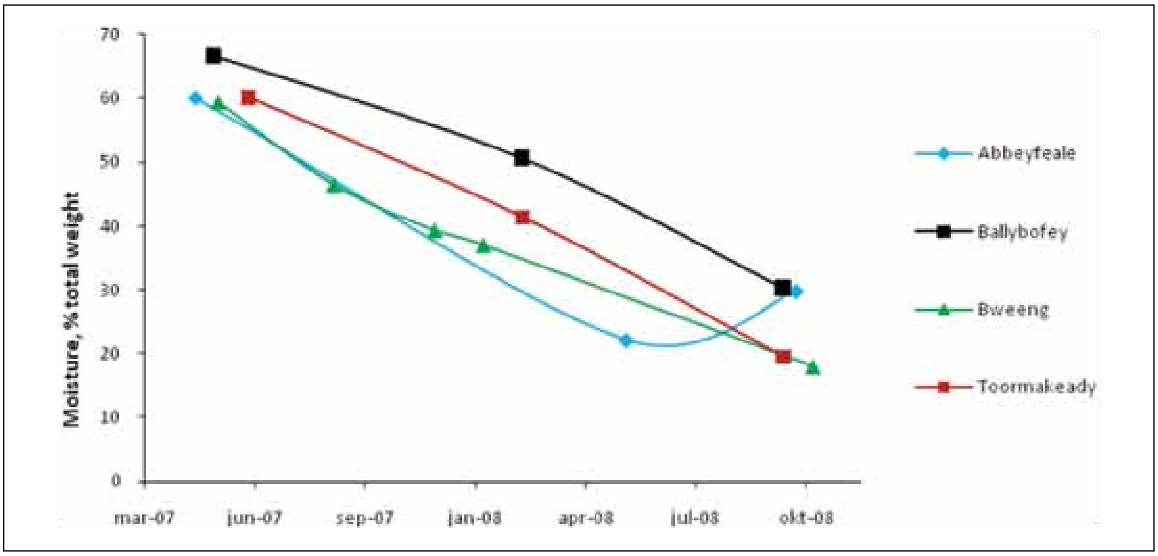

Figure 43: Pattern of moisture content reduction during storage of conifer firewood at four trial sites.

Firewood was produced from thinned ash roundwood at Dovea and Stradbally in the summer 2007 and stored in lean-to sheds until autumn 2008. Further firewood was produced from ash thinned from Greenane and Mullinavat in spring 2008 and stored outdoors under cover over the summer of 2008. All firewood was assessed for moisture content in autumn 2008. The natural moisture content of freshly felled ash is much lower than that of Sitka spruce. In addition, there was a significant difference between the moisture content of ash roundwood harvested during the summer (42.6%) and harvested during the dormant season (36.1%). In all cases, the ash firewood had dried to close to 20% moisture content by autumn 2008. A summary of mean moisture contents for each sample period are presented below in Table 56.

Table 56: Moisture content change in ash firewood over two summers.

Site	Storage method	Summer 2007		Spring 2008		Autumn 2008	
		Mean	Margin of error	Mean	Margin of error	Mean	Margin of error
		%					
Dovea	In shed	44.8	1.00			19.9	0.6
Stradbally	In shed	40.4	0.84			21.0	0.4
Greenane	Outside with top cover			34.3	0.38	24.3	0.8
Mullinavat	In shed			37.8	0.12	19.5	1.2
Mean		42.6		36.1		21.2	

Figure 44 shows the change in moisture content of ash firewood during storage. All firewood behaved similarly, with a decrease in moisture content to c. 20% by June 2008. Ash firewood from Greenane stored either split or in the round outside under a top cover showed little difference in drying rate, though the moisture content of this firewood increased over late summer in 2008 during high rainfall. This was not found in firewood stored indoors.

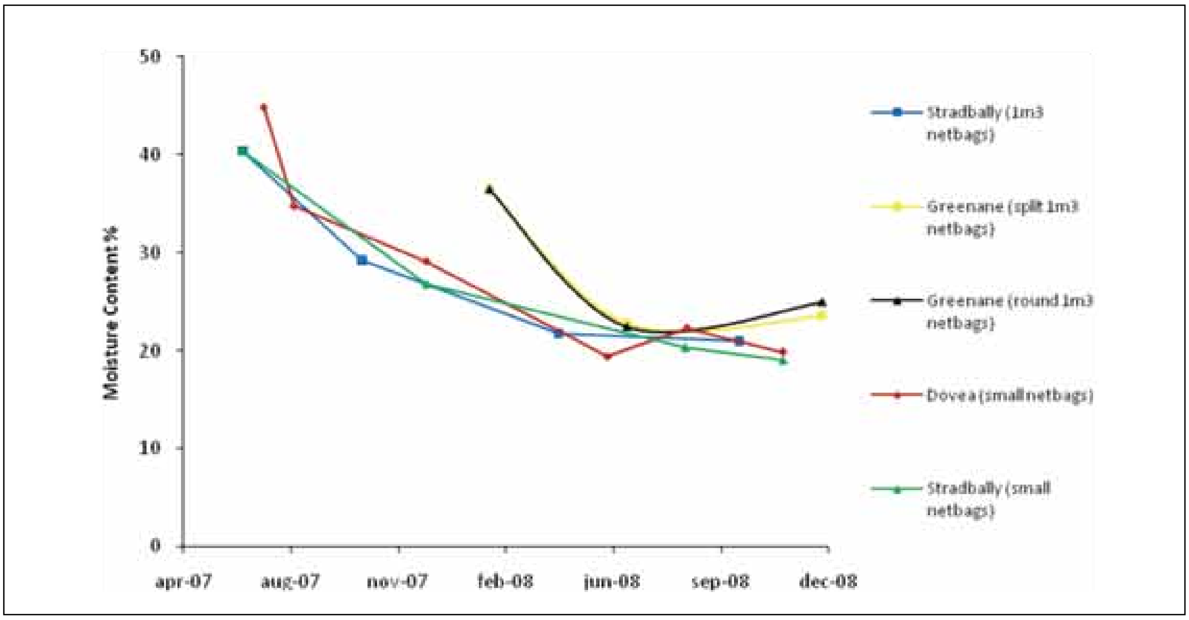

Figure 44: Pattern of moisture content reduction during storage of ash firewood at three trial sites.

3.3.2 WOODFUEL BULK DENSITY

The mean bulk density (as received), mean moisture content and mean bulk density (dry matter) of all woodfuel assortments from all trial sites are shown in Tables 57, 58, 59, 60, 61, and 62. Results are presented separately for conifers and broadleaves and for woodchip and firewood. Figure 45 shows bulk density (as received) and bulk density (dry matter) from 241 samples of Sitka spruce wholetree woodchip and illustrates the impact of increasing moisture content on bulk density (as received) and indicates the similarity of bulk density (dry matter) between samples.

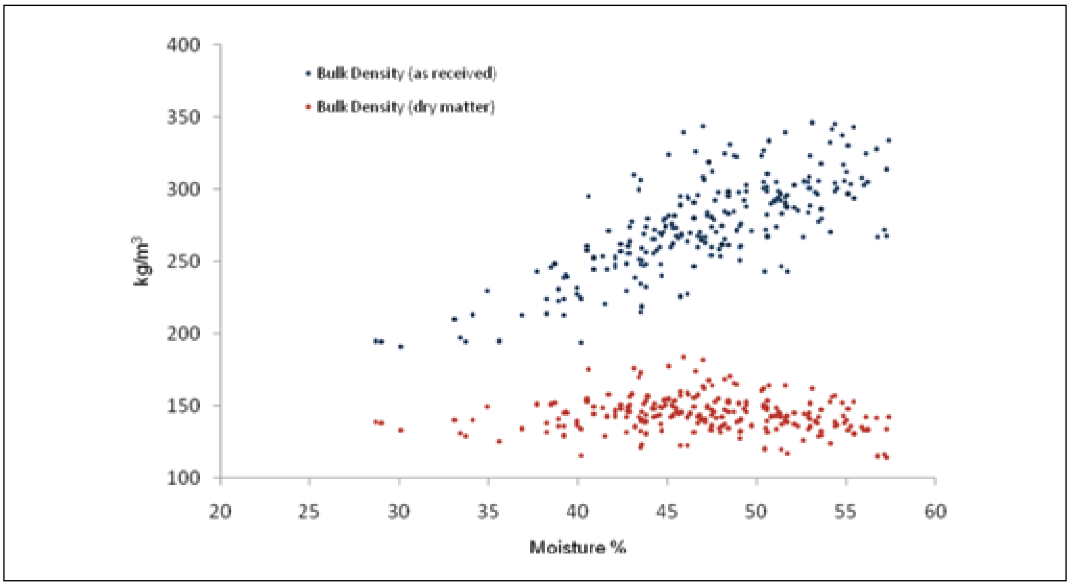

Figure 45: Impact of moisture content on bulk density (as received) and bulk density (dry matter) for Sitka spruce wholetree woodchip.

3.3.2.1 CONIFER WOODCHIP BULK DENSITY

Tables 57-59 present bulk density values for woodchip for the three conifer assortments: shortwood, energy wood and wholetree, respectively. Table 57 shows bulk density values for the shortwood assortment. Bulk density (dry matter) of conifer shortwood varied between 132 and 160 kg/m^3 at six trial sites. Table 58 presents energy wood woodchip bulk density values: it ranged from 134-175 kg/m^3. Whole tree woodchip bulk density, presented in Table 59, ranged from 124-169 kg/m^3. A range of chippers was used in each assortment. Moisture content varied between sites and between assortments due to different rates of drying and different lengths of seasoning.

Table 57: Bulk density variation in Sitka spruce shortwood woodchip from trial sites.

Site	Condition	Chipper	Bulk density (as received)	MC	Bulk density (dry matter)
			kg/m^3	%	kg/m^3
Abbeyfeale	Brown	MusMax	248	47	132
Abbeyfeale	Brown (2 summers)	Silvatec	258	44	144
Ballybofey*	Brown	MusMax	312	57	135
Ballybofey*	Brown	Silvatec	312	57	134
Ballybofey*	Brown	TP Winch	264	46	139
Bweeng	Brown	MusMax	285	47	152
Toormakeady	Brown (2 summers)	Jenz 420	342	55	155
Woodberry	Brown (2 summers)	Jenz 700	264	39	160
Woodberry	Brown	MusMax	300	50	147

* Sitka spruce/Japanese larch mix

Table 58: Bulk density variation in Sitka spruce energy wood woodchip from trial sites.

Site	Condition	Chipper	Bulk density (as received)	MC	Bulk density (dry matter)
			kg/m^3	%	kg/m^3
Abbeyfeale	Brown	MusMax	289	53	134
Abbeyfeale	Brown (2 summers)	Silvatec	298	51	144
Ballybofey*	Brown	MusMax	336	59	137
Ballybofey*	Brown (2 summers)	Starchl	347	57	146
Bweeng	Brown	MusMax	313	53	147
Toormakeady	Brown (2 summers)	Jenz 420	349	57	151
Woodberry	Brown (2 summers)	Jenz 700	299	41	175
Woodberry	Brown	MusMax	321	50	154

* Sitka spruce/Japanese larch mix

Table 59: Bulk density variation in Sitka spruce wholetree woodchip from trial sites.

Site	Condition	Chipper	Bulk density (as received)	MC	Bulk density (dry matter)
			kg/m³	%	kg/m³
Abbeyfeale	Brown	Silvatec	299	53	140
Abbeyfeale	Brown (2 summers)	Silvatec	264	43	149
Ballybofey*	Brown	Silvatec	286	54	132
Ballybofey*	Brown (2 summers)	Silvatec	282	50	141
Ballybofey*	Brown	TP Winch	240	46	130
Bweeng	Brown	Silvatec	249	45	137
Bweeng	Brown	TP Winch	249	42	144
Kilbrin	Brown	Silvatec	222	38	137
Swan	Brown	Silvatec	276	47	146
Toormakeady	Brown (2 summers)	Silvatec	302	49	154
Woodberry	Brown	Silvatec	284	50	141
Woodberry	Brown (2 summers)	Silvatec	319	47	169
Woodberry	Brown	TP Winch	273	46	149

* Sitka spruce/Japanese larch mix

3.3.2.2 BROADLEAF WOODCHIP BULK DENSITY

Mean bulk densities of ash wholetree woodchip, sampled at Dovea and Mullinavat, are presented in Table 60. The mean bulk density (as received), mean moisture content and mean bulk density (dry matter) were similar on both sites.

Table 60: Bulk density variation in broadleaf wholetree woodchip from trial sites.

Site	Species	Condition	Chipper	Bulk density (as received)	MC	Bulk density (dry matter)
				kg/m³	%	kg/m³
Dovea	Ash	Brown	Silvatec	313	38	193
Mullinavat	Ash	Brown	Silvatec	306	36	194

3.3.2.3 BULK DENSITY OF CONIFER FIREWOOD

The bulk density of Sitka spruce firewood stacked loosely in 1 m^3 net bags at five trial sites is shown in Table 61. Bulk density as received varied with moisture content and ranged from 356-522 kg/m^3. Excluding the effect of moisture content, the bulk density (dry matter) ranged from 165-212 kg/m^3.

Table 61: Bulk density of Sitka spruce firewood loosely packed in bulk bags.

Site	Bulk density (as received)	MC	Bulk density (dry matter)
	kg/m³	%	kg/m³
Abbeyfeale	502	60	201
Ballybofey	496	67	165
Bweeng	449	57	193
Toormakeady	522	60	208
Woodberry	356	40	212

3.3.2.4 BULK DENSITY OF BROADLEAF FIREWOOD

The bulk density of ash firewood stacked loosely in 1 m^3 net bags on three trial sites is presented below in Table 62. The bulk density as received varied with moisture content and ranged from 483-531kg/m^3. Excluding the effect of moisture content, the bulk density (dry matter) ranged from 311-352kg/m^3.

Table 62: Bulk density of ash firewood loosely packed in bulk bags.

Site	Bulk density (as received)	MC	Bulk density (dry matter)
	kg/m^3	%	kg/m^3
Stradbally	531	40	317
Greenane	490	37	311
Mullinavat	483	27	352

3.3.3 BULK/SOLID VOLUME CONVERSION FACTORS

3.3.3.1 ROUNDWOOD (SHORTWOOD) DENSITY

Green density, moisture content and basic density of roundwood sampled from two Sitka spruce and two ash trial sites are presented in Table 63. The green density of Sitka spruce and ash was similar, whereas the basic density of the two species was significantly different, as is made clear once the effect of the weight of moisture in the log is removed. There was no significant difference in the basic density of Sitka spruce or ash at the two study sites. The mean basic density of Sitka spruce was approximately 447 kg/m^3 and that of ash was 633 kg/m^3.

Table 63: Basic density of Sitka spruce and ash roundwood.

Site	Species	Green density	MC	Basic density	
		kg/m^3	%	kg/m^3	Margin of error %
Toormakeady	Sitka spruce	1169	61.2	453	5.2
Woodberry	Sitka spruce	1043	57.6	442	3.8
Greenane	Ash	1046	40.2	626	4.1
Mullinavat	Ash	1027	37.8	639	3.1

3.3.3.2 WOODCHIP BULK DENSITY

Similarly, the woodchip bulk density as received was heavily influenced by the moisture content at the time of measurement. Removing the effect of moisture content on bulk density allowed the bulk density (dry matter) to be calculated. The woodchip bulk density (dry matter) of all the Sitka spruce assortments differed significantly from the dry matter bulk density of ash (Table 64). There was no significant difference between the bulk density of individual assortments of Sitka spruce, ranging from 150-164 kg/m^3. Ash wholetree bulk density (dry matter) was 197 kg/m^3.

Table 64: Woodchip bulk density of Sitka spruce and ash assortments.

Site	Species	Assortment	Bulk density (as received)	MC	Bulk density (dry matter)	
			kg/m^3	%	kg/m^3	Margin of error %
Toormakeady	Sitka spruce	Shortwood	342	55	155	5.9
Toormakeady	Sitka spruce	Energy wood	349	57	151	2.9
Toormakeady	Sitka spruce	Wholetree	302	49	154	4.2
Woodberry	Sitka spruce	Shortwood	281	44	154	7.5
Woodberry	Sitka spruce	Energy wood	311	46	164	6.4
Woodberry	Sitka spruce	Shortwood	291	48	150	2.8
Greenane	Ash	Shortwood	300	34	197	1.4
Mullinavat	Ash	Shortwood	319	38	198	3.4

3.3.3.3 FIREWOOD BULK DENSITY

Firewood bulk density was also heavily influenced by moisture content. The bulk density (dry matter) again differed significantly between Sitka spruce and ash, but did not differ significantly within species between the trial sites (Table 65). The mean firewood bulk density (dry matter) for Sitka spruce at Toormakeady and Woodberry was 203 kg/m^3 and 212 kg/m^3, respectively. The ash firewood bulk density at Greenane and Mullinavat was 321 kg/m^3 and 352 kg/m^3, respectively.

Table 65: Bulk density of Sitka spruce and ash firewood.

Site	Species	Bulk density (as received)	MC	Bulk density (dry matter)	
		kg/m^3	%	kg/m^3	Margin of error %
Toormakeady	Sitka spruce	522	61.2	203	3.5
Woodberry	Sitka spruce	356	40.0	212	7.2
Greenane	Ash	490	34.5	321	4.8
Mullinavat	Ash	483	27.2	352	4.8

3.3.3.4 WOODCHIP BULK/SOLID VOLUME CONVERSION FACTOR

The bulk/solid volume conversion factor was determined by dividing the mean basic density by the mean bulk density (dry matter). The Sitka spruce woodchip factor range between 2.7 and 3.0 for different assortments, with an overall average of 2.9 (Table 66). The cumulative margin of error associated with the overall factor was 17%, meaning the bulk/solid volume conversion factor could vary between 2.4 and 3.4.

Table 66: Sitka spruce woodchip bulk/solid volume conversion factors.

Site	Assortment	Bulk/solid volume	Margin of error %
Toormakeady	Shortwood	2.9	7.9
Toormakeady	Energy wood	3.0	6.0
Toormakeady	Wholetree	3.0	6.7
Woodberry	Shortwood	2.9	8.4
Woodberry	Energy wood	2.7	7.4
Woodberry	Wholetree	3.0	4.7
Overall		2.9	17.0

Two bulk/solid volume conversion factors for ash wholetree woodchip are presented in Table 67. The cumulative margin of error associated with the overall factor was 6%, meaning the bulk/solid volume conversion factor could vary between 3.0 and 3.4.

Table 67: Ash woodchip bulk/solid volume conversion factors.

Site	Assortment	Bulk/solid volume	Margin of error %
Greenane	Wholetree	3.2	4.3
Mullinavat	Wholetree	3.2	4.6
Overall		3.2	6.0

3.3.3.5 FIREWOOD BULK/SOLID VOLUME CONVERSION FACTOR

Firewood bulk/solid volume conversion factors are presented in Table 68. The factors for Sitka spruce firewood was higher than those for ash firewood, but again the differences were not wholly significant. Overall, the mean bulk/solid volume conversion factor was 2.0. The cumulative margin of error associated with the overall factor was 10%, meaning the bulk/solid volume conversion factor could range from 1.8 to 2.2.

Table 68: Sitka spruce and ash firewood bulk/solid volume conversion factors.

Site	Species	Assortment	Bulk/solid volume	Margin of error %
Toormakeady	Sitka spruce	Split firewood	2.2	6.3
Woodberry	Sitka spruce	Split firewood	2.1	8.1
Greenane	Ash	Split firewood	2.0	6.3
Mullinavat	Ash	Split firewood	1.8	5.7
Overall			2.0	10

4. CONCLUSIONS

4.1 CONIFER WOODFUEL SUPPLY CHAIN PRODUCTIVITY

4.1.1 CONIFER WOODFUEL PRODUCTION COSTS

- The production costs for shortwood harvesting, forwarder extraction and roadside chipping ranged from €5.65-8.64/GJ
- The production cost for energy wood harvesting, forwarder extraction and roadside chipping ranged from €5.05-7.52/GJ
- The production costs for wholetree harvesting and terrain chipping ranged from €2.22-4.36/GJ.
- On sites that were chemically treated and the *Silvatec* chipper was also used to fell the trees, the production costs ranged from €4.36-5.86/GJ.
- The cost for wholetree harvesting, winch extraction and roadside chipping ranged from €6.47-10.20/GJ.
- The cost of firewood production using chainsaw harvesting, ATV extraction, and a firewood processor ranged from €17.35-33.72/GJ. Using a harvester, forwarder and the same firewood processor the production cost was €13.73/GJ.

In all cases, the *Silvatec* terrain chipping system was much more cost effective for the production of woodchip from conifer first thinnings. In 2008, the *Silvatec* system experienced a substantial improvement in productivity due to the use of band tracks which increased mobility for the chipper. Opinions regarding the unsuitability of this system in Irish conditions, for example on wet sites with low ground bearing capacity, are not supported by the results presented here. Certainly, on some sites, in particular at Toormakeady, steep terrain, soft ground and very poor weather conditions presented a very challenging work environment for any machine operation. However, the *Silvatec* terrain chipper and chip forwarder remained productive throughout.

Currently, the standard shortwood system is used for woodchip production for energy. The trials convincingly demonstrate that production costs may be significantly lowered and the quantity of woodfuel recovered for energy from harvesting increased by modifying first thinning harvesting methods. An advantage of the shortwood system is that it provides flexibility in assortment harvesting if a market of higher value, such as stake wood, is available for a portion of thinnings. Also, stands with a large mean tree volume, where a large proportion of harvested logs are of a larger assortment size, should be harvested using the shortwood system for sawlog. However if the sole production objective of thinning is to supply woodchip (as may be the case in younger crops with smaller tree sizes) then both the energy wood and wholetree systems will provide considerably more biomass from the same number of harvested trees.

Also, producing woodchip from the shortwood assortment was shown to be expensive. Tops and branches are left in the forest as a brash mat, leaving behind material which could be utilised for energy. Therefore the cost of harvesting is carried by a smaller volume of wood than the energy wood or wholetree methods. On the other hand, the quality of woodchip obtained from shortwood is generally higher, and suitable for smaller woodchip boilers. Therefore, the price paying potential for this woodfuel may be higher than wholetree woodchip. It must be noted that the *Silvatec* wholetree chip has a large particle size distribution, which may exclude its use in smaller commercial boilers. Therefore, the marketable value of this fuel may be less than the shortwood or energy woodchip. This work programme only studied production costs, the market price and value margin were outside its scope.

The energy wood method is also a relatively expensive way of producing woodchip, but substantially cheaper than the standard 3 m shortwood system. Branches are not utilised, and are left on the forest floor as a brash mat, but a greater proportion of the stem is captured. At all sites, except for Bweeng, the cost of production for the energy wood assortment chip was lower than shortwood chip. Even taking the Bweeng site into account, the average cost/m^3 for the energy wood assortment across all sites was 11% lower than the shortwood assortment.

Woodfuel production costs for small-scale systems were higher than the larger-scale methods. Wholetree harvesting and winch extraction with roadside chipping had a relatively low productivity due to the physically demanding nature of the work. The same could be said for the firewood supply chain, which was the most expensive system studied. However, the production costs generated for these methods assumed that all work was carried out at professional contractor payment rates. These small-scale operations could be carried out by the forest owner at low capital investment and a small investment in training, particularly from an operation safety point of view. Production costs would then reflect the rate of return expected by the forest owner for their own time investment. Also, firewood could be produced at much lower costs by mechanical harvesting and forwarding. Similarly, alternative firewood processors would have much higher productivity than the processor trialled.

4.1.2 QUANTITY OF WOODFUEL PRODUCED IN CONIFERS

The production cost of woodfuel from thinnings is largely determined by the quantity of biomass harvested, as many of the operation costs are fixed. Harvesting more biomass from the same number of trees allows fixed costs to be spread over a greater quantity of woodfuel. The standard shortwood, fixed length assortment yielded the lowest amount of biomass from thinning. The energy wood assortment yielded, on average, 26% more biomass in comparison with the shortwood method. The additional biomass came from recovering more stem wood by taking a variable length log and by recovering some branch wood by loosening the position of the knives on the harvesting head. On average over the five trial sites, the wholetree method yielded 190% more biomass per tree compared with the shortwood method. Recovering this additional biomass from thinning may improve the financial viability of first thinning on sites otherwise considered uneconomic to thin using standard methods. In addition, as competition for wood biomass increases between established panel board markets and new energy markets, it may be essential to extract this additional wood resource to support the demand level in both sectors.

4.1.3 HARVESTER PRODUCTIVITY IN CONIFERS

At each of the sites, except for Bweeng, the integrated energy wood assortment was more cost effective during the harvesting operation than the 3 m shortwood system. The mean volume harvested per tree was greater than in the shortwood system. At the Bweeng site, the shortwood assortment had a larger mean harvested tree volume. These results reflected variation in mean tree size between plots in Bweeng. While every effort was made at the initial stages to ensure that treatment plots had similar tree sizes, during operations it became apparent that the shortwood plot had an initially larger tree size.

The largest single time element in a harvester cycle is the select element; about 30% of the total productive time is spent in manoeuvring the harvester into position to fell the next tree. This may partially explain the lower cost of the energy wood assortment, as the harvester is not affected in any way by the assortment type during this time element, but is however gaining substantially more volume when producing energy wood. The other time elements are possibly affected by the assortment type, such as the delimbing component which was larger for the energy wood harvesting at the Abbeyfeale, Ballybofey and Bweeng sites. Any comparison between these other time elements would require further research.

4.1.4 FORWARDER PRODUCTIVITY IN CONIFERS

At all sites, apart from Woodberry, the energy wood forwarder load volume was substantially larger than the shortwood loads. In particular, at Abbeyfeale the energy wood load volume was 60% greater than in the shortwood system. This additional volume resulted in energy wood extraction being cheaper than shortwood extraction, even though the mean extraction distance was 478 m longer, and the total time per load was 13 minutes longer for energy wood compared with the shortwood system.

4.1.5 ROADSIDE CHIPPER PRODUCTIVITY IN CONIFERS

The *MusMax* and *Starchl* chippers had similar productivity, between 11-17 m^3 per hour, for shortwood chipping at roadside. The *Jenz* 700 operated at a completely different level of productivity, at 49 m^3 per hour. The higher operating cost of the *Jenz* was compensated for by its productivity, so that it had the lowest chipping cost/m^3. It is important to note that the main factor that affects chipper productivity is the availability of transport vehicles to receive the woodchip. The *Starchl* and *MusMax* would require at least a tractor and trailer per hour or a walking-floor articulated truck every two hours in order to stay productive. On the other hand, the *Jenz* 700 would demand nearly two walking-floor trucks per hour in order to maintain output. The alternative in all cases would be to chip on the ground, but this would only lead to additional reloading costs. Interestingly, with the exception of the *Jenz* 700 at the Woodberry site, the productivity of all chippers was lower chipping energy wood compared with chipping shortwood, and as a result the chipping cost/m^3 tended to be greater. This was possibly due to a greater difficulty in handling longer energy wood lengths. The energy wood lengths were longer, more cumbersome, and more likely to snag because of branch stubs, compared with the standard 3 m lengths which operators were used to handling.

4.1.6 WHOLETREE TERRAIN CHIPPING PRODUCTIVITY IN CONIFERS

The wholetree woodchip production cost was consistently and substantially lower than the other methods examined on all trial sites. Operation costs were lower compared with the other methods and costs were spread over a greater quantity of harvested biomass. Production costs also differed substantially between the two trial years. The trial sites had variable ground bearing capacity from poor to good and this was reflected in the fall in productivity where conditions were poor. The addition of band tracks to aid traction, the increase in the chipper bin capacity from 15 to 17 m^3 and the additional woodfuel drying in the second summer season all contributed to much lower production costs in 2008.

In 2007, where trees were chemically thinned, the *Silvatec* chipper was used to cut the tree, as well as chip it. This had the effect of increasing the chipper production cost from €21.05/m^3 on average to €27.14/m^3. This resulted in increased woodchip supply chain costs of €5.11/GJ compared with €4.01/GJ for chainsaw felling prior to chipping. Some of the additional cost was offset by the lower moisture content achieved by the chemical thinning method.

4.1.7 ROAD TRANSPORTATION OF WOODCHIP

A comprehensive study of woodfuel road transportation was outside the scope of this project. However, small studies were carried out in 2007 on woodchip container trucks and in 2008 on tractors and trailers. The container trucks, which are an integral part of the woodchip supply chain in Denmark, were trialled in conjunction with the *Silvatec* terrain chipper and chip forwarder. The system is highly integrated and allows for very efficient woodchip supply, but demands well planned logistics and a comprehensive infrastructure for the system. This does not currently exist in Ireland. One particular issue with the container trucks was the lower maximum carrying capacity of 44 tonnes on six axles in Ireland, compared with 48 tonnes in Denmark.

Surprisingly, tractors and trailers travelled at similar average speeds to the trucks, particularly on minor roads. While the carrying capacity was lower compared with the trucks, the fast loading and unloading speeds of the tractor and trailer resulted in high productivity. The wide availability and low operating costs of tractors and trailers mean that this method of woodchip road transport could be cost effective in many cases in Ireland, particularly on shorter journeys to smaller end-users. A comprehensive study of road transportation options would identify the optimum circumstances for each road transport method.

4.2 BROADLEAF WOODFUEL SUPPLY CHAIN PRODUCTIVITY

4.2.1 BROADLEAF WOODFUEL PRODUCTION COSTS

Firewood production costs (cubic metres solid):

- Chainsaw harvesting into 3 m shortwood lengths ranged from €24.70-62.56/m^3.
- The cheapest extraction cost was €12.91/m^3 using a forwarder. The most expensive was €64.98/m^3 using horse and arch. The tractor and grapple was comparable with the forwarder at €21.70/m^3 at the Mullinavat site, where the average forwarder cost was €22.68/m^3. The ATV was expensive for extraction at an average cost of €45.20/m^3 using a timber arch, and €49.47/m^3 using a trailer.
- Firewood processing costs differed considerably, depending on the machine used. The most cost effective method was the *Bilke* machine, which cost €17.44/m^3 when cutting to a 50 cm length, or €26.14/m^3 when cutting to a 20 cm length. The most expensive method was the *Hakke Pilke Hawk* processor, which cost €197.96/m^3 at the Stradbally site, and €105.56/m^3 at the Greenane site. The Posch firewood processor had a comparable cost of €101.49/m^3. Using a saw bench and chainsaw was more cost effective, with a range of €46.77-57.44/m^3 across sites.
- From the systems trialled, the lowest total cost was €101.71/m^3 using chainsaw harvesting, tractor and grapple extraction, and processing with the *Bilke*. This equates to €8.67/GJ, which was estimated using moisture content samples taken from the firewood.
- The system with the highest cost was chainsaw harvesting, ATV with timber arch extraction, and processing with the *Hawk* firewood processor, at €292.31/m^3, which equates to €26.05/GJ, estimated using moisture content samples taken from the firewood.

Woodchip production costs (cubic metres solid):

- Chainsaw harvesting of whole trees ranged from €14.09-20.14/m^3 at the two sites where it was carried out.
- The cost of *Silvatec* terrain chipping and extraction with chip forwarder ranged from €36.66- 51.58/m^3.
- The total cost for woodchip production using chainsaw felling, *Silvatec* terrain chipping and chip forwarder extraction ranged from €50.75-71.72/m^3, which equates to €4.52-6.49/GJ, estimated using moisture content samples taken from the woodchip.

The terrain chipping system proved to be a lower cost method to produce woodfuel from broadleaf first thinnings than firewood production. Even the upper range of cost of the terrain chipping method is substantially less than the cheapest firewood production system. Some concern is often expressed about the ability of these heavy machines to operate in Irish forest conditions. Broadleaf plantations are usually located on better ground with better load bearing capacity than conifer plantations. The *Silvatec* machine system is capable of working in softer conifer plantations, as has been shown elsewhere, and therefore should have little problem operating in broadleaf plantations even without a brash mat.

Firewood production was shown to be expensive. Mechanical harvesting did not compare favourably with motor manual (chainsaw) harvesting in first thinning due to the small tree size. The manual nature of the work involved in crosscutting the stems into 3 m lengths and stacking along the lines is slow and labour intensive. So too are small-scale methods for extraction, such as horse and ATV extraction. These physically demanding activities require highly skilled and conditioned personnel to be able to operate over long periods of time. Some cost reduction may be attainable from automating where possible along the supply chain. For instance, it may not be feasible for a forwarder to work in a small plantation of 1 or 2 ha due to transport and other fixed costs. However, on larger sites the cost benefit is apparent from the results presented here.

Although it was found that firewood production costs can be expensive, it must be noted that the value of firewood brought to market may be higher than that of woodchip. Currently, the woodchip market in Ireland primarily consists of large commercial and industrial boilers. Contracts to supply these boilers are drawn up between supplier and customer, and are based on the economies of scale of having a large fuel requirement. A small number of commercial boilers or even one large industrial boiler may be sufficient to keep a woodfuel producer in business. Firewood on the other hand is primarily a domestic product with a large number of customers. Marketing firewood to consumers in bulk bags for delivery, or in small hand carrier bags for purchase at local convenience stores, has the potential for a high market price.

It must be noted that the production costs in this report assume that all work is carried out at professional contractor payment rates. Particularly on smaller sites, this work could be carried out by the forest owner using small-scale machinery which would require minimum capital investment. In this case, the main cost would be the investment of time by the forest owner. The forest owner could produce firewood to provide their own personal fuel requirements, and sell the surplus locally.

4.2.2 QUANTITY OF WOODFUEL PRODUCED AT BROADLEAF SITES

The volume of material attainable during harvesting largely affects the production cost of woodfuel from thinnings. Many of the costs associated with the production are fixed, and productivity dramatically increases with a larger tree volume, as the extra time taken to handle a larger tree is only marginal compared with the additional woodfuel produced. In principle, it would be expected that harvested shortwood would be lower than the standing volume due to losses arising from cutting to length. This however was not the case in the broadleaf plantations, where instead increases of up to 21% were recorded. The small tree size meant that a large proportion of the trees were below the 7 cm dbh threshold, normally used in estimating standing volume. As such, many of the trees that were harvested as shortwood were not included in the standing volume estimate. Both terrain chipping trials showed an increase in volume recovery over the standing volume estimate; at the Dovea site the increase was 11%, and at Mullinavat a larger increase of 44% was found.

4.2.3 HARVESTING PRODUCTIVITY IN BROADLEAVES

Two parameters affect the productivity of harvesting in broadleaf thinning: tree volume, and time taken to harvest a tree. Tree volume is site specific, and will affect the productivity of any method used to harvest as the extra time required to harvest a larger tree is marginal compared with the additional volume attained. The time taken to harvest is mainly dependant on the method/machine used and operator experience. The mechanised harvester did not perform well in broadleaf thinnings, as the small dbh and crooked stem form were difficult for the harvester head to handle. The harvester head was capable of handling stem diameters up to 47 cm, and was not designed for such small diameter trees. It was also found that the harvester was less efficient at converting felled trees to roundwood than chainsaw operators. At the Mullinavat site, the harvester managed to convert each tree into an average of 0.94 logs (3 m length), while the chainsaw operators managed an average of 1.03

logs (3 m length). Operator experience also affected productivity, especially in chainsaw harvesting of roundwood. At the Mullinavat site, with the same harvested volume per tree, one operator cut 34 trees per hour, whereas another only managed 22 trees per hour. Chainsaw harvesting of whole trees is much more productive and easier for the operator than cutting logs to length, as the operator simply fells the trees in the same direction without any cross-cutting or delimbing. Felling of the trees is much faster, and the harvested volume much higher as there is no volume loss from cutting to length or delimbing.

4.2.4 EXTRACTION PRODUCTIVITY IN BROADLEAVES

Extraction productivity is highly dependent on extraction distance, but this does not entirely explain the level of variation likely to be found. Two different contractors were used for forwarder extraction of shortwood at Mullinavat and Stradbally. The loading times were different between the two contractors, with the slower operator taking over twice the time to load compared with the faster operator. Also, although the number of logs per load was very similar on all sites, ranging from 210 to 238 logs per load, the volume per load was quite different, ranging from 2.83 to 4.09 m^3. This was possibly due to the straightness of the logs on the site, small diameter trees are usually more crooked, and therefore cannot be stacked as tightly on the forwarder bunk.

The same premise is true for the smaller scale extraction methods: ATV and horse extraction are labour intensive operations. The operator is on the ground, physically handling logs most of the time, and experience will heavily influence productivity. These manually intensive extraction methods should preferably be used on small sized sites, whereas for longer extraction distances the effectiveness of the forwarder has been shown in the results presented.

Interestingly, the tractor and grapple had a comparable cost to the forwarder at the Mullinavat site. Even though the tractor and grapple was slower per unit volume for driving empty, driving full, and unloading, it was much faster at loading than the forwarder. The slow drive time of the tractor indicates that as extraction distance increases, this method's cost effectiveness will drop far below the forwarder. A crucial benefit of the tractor and grapple system over other small-scale extraction methods is that, if presentation of logs by the harvesting crew is correct, the operator does not need to leave the cab of the tractor.

4.2.5 FIREWOOD PROCESSOR PRODUCTIVITY

The firewood processors trialled had very different operational methods from one another. These affect the cost associated with their operation. The main cost is the resource required for operation. The saw bench relied solely on one chainsaw operator. The *Bilke* required one operator with a tractor to power it. The *Hawk* was self-powered with a petrol engine but required two operators. The Posch also required two operators.

The other consideration in the productivity of the machines is log size capacity. The *Bilke* was highly productive in producing firewood from first thinning size material. The cost of production was 25% that of the other processors, and 50% that of the saw bench. This is mainly due to the *Bilke* being specifically designed for small-sized material. The other processors have a capacity to handle bigger logs, and work at a slower speed to do so. As processor speed is independent of log size, small logs will under-utilize some machine makes' production potential.

4.2.6 TERRAIN CHIPPING PRODUCTIVITY IN BROADLEAVES

Wholetree terrain chipping costs were consistently lower than the other methods of producing woodfuel from broadleaf first thinnings. Operation costs are lower as they are spread over a greater volume, due to the maximum capture of biomass from the wholetree assortment. Broadleaf plantations are generally situated on better land than conifers. The *Silvatec* terrain chipping system is designed to work in conifer plantations, as such these machines will have little trouble operating in Irish broadleaf plantations.

4.3 MOISTURE CONTENT AND BULK DENSITY OF WOODFUELS

4.3.1 MOISTURE CONTENT OF WOODFUELS

The mean moisture content of freshly felled Sitka spruce shortwood was 61%. The energy wood and wholetree assortments were lower, at 60% and 57% respectively, indicating that the moisture content in branches is lower than in the main stem. Freshly felled ash assortments had significantly lower moisture contents, with the shortwood assortment ranging from 36-43%, depending on whether trees were felled in winter or summer. The ash wholetree assortment moisture content averaged 44%.

Conifer shortwood stacks were all covered prior to seasoning, with the exception of one stack left uncovered at Woodberry as a comparison. Shortwood dried down from 61% to 50% after one summer on average. The mean moisture content was slightly further reduced to 46% after a second summer seasoning, but this was not statistically significant and there was wide variability in moisture content, largely due to the covers disintegrating, allowing water to lodge in the stacks. At Woodberry, there was a significant improvement in drying in both years due to the presence of the cover, when compared with the uncovered stack.

The conifer energy wood assortment did not dry to the same extent as the shortwood assortment. Energy wood contained branch stubs and some green material that had the effect of allowing more water to lodge in the stack where stacks were uncovered and to hasten the disintegration of the covers by snagging and tearing on the branch stubs. In fact, due to the high variability in moisture content samples, it could not be determined if there was any significant reduction in moisture content in the energy wood assortment, with the exception of Woodberry. On that site, the energy wood assortment dried at a broadly similar rate to the roundwood assortment seasoned on the same site.

Conifer whole trees dried significantly over one summer when left in-situ on the forest floor but did not dry significantly any further over the second summer. An average moisture content of 49% was achieved after one summer's drying. Conifer whole trees that were selectively felled and left standing dried to an average 45% moisture content after one summer, they tended to be small trees and in some cases already dead or dying from suppression and had an initially lower moisture content. Chemically thinned whole trees reached an average moisture content of 39% after two treatments and two summers. It would appear that drying is improved of the trees remain standing in the canopy rather than lying on the ground in the extraction rack, probably due to greater air flow.

Broadleaf whole trees dried slightly, but statistically significantly over one summer season. More interesting in the case of broadleaves was the significant difference in moisture content of freshly felled trees related to the time of year. Ash roundwood felled in winter had a mean moisture content of 36%, whereas when felled in summer it had a mean moisture content of 43%.

Both conifer and and broadleaf firewood assortments dried significantly and consistently over a range of storage conditions. A mean moisture content of less than 30% was achievable for both conifer and broadleaf firewood using only ambient air drying when stored in a shed or under top cover outdoors. Conifer firewood took more time than broadleaf firewood to season, mainly as the initial moisture content was much higher. Broadleaf firewood could season over one summer period, or as little as four months. Conifer firewood took longer, at over 12 months on average.

4.3.2 BULK DENSITY OF WOODFUELS

Bulk density (as received) was directly related to moisture content. Therefore bulk density (as received) does not distinguish the amount of fuel present from the amount of water. Bulk density (dry matter), free of moisture, gives a better indication of the actual fuel bulk density. Bulk density (dry matter) can be used to recalculate bulk density (as received) to a specified moisture content.

The mean bulk density (as received) of 403 samples of Sitka spruce shortwood woodchip was 277 kg/m^3, with a mean moisture content of 39%. The mean bulk density (dry matter) was 156 kg/m^3. Sitka spruce wholetree woodchip bulk density (as received) was similar, with a mean of 275 kg/m^3. However, the mean moisture content was higher at 47% and the mean bulk density (dry matter) was lower at 144 kg/m^3. Sitka spruce energy wood woodchip had a mean bulk density (as received) of 310 kg/m^3 and a mean moisture content of 46%. This resulted in energy wood woodchip having a higher bulk density (dry matter) than wholetree or shortwood woodchip, at 160 kg/m^3. Ash wholetree woodchip had a mean bulk density (as received) of 308 kg/m^3 and mean moisture content of 38%, resulting in a mean bulk density (dry matter) of 192 kg/m^3.

Bulk density varied significantly between species. Broadleaves, particularly ash, birch and sycamore had significantly higher mean bulk density compared with Sitka spruce and lodgepole pine. Bulk density varied significantly between seven Sitka spruce trial sites. This may be largely explained by variation in the basic density of Sitka spruce between sites. Further, bulk density varied between harvested assortments of Sitka spruce:the wholetree assortment had, on average, lower bulk density than the shortwood or energy wood assortments. This may be due to the presence higher proportions of bark and leaf material, of lower density, in the first two assortments. In addition, the wholetree assortments were mainly chipped using the *Silvatec* terrain chipper, which produced a woodchip of higher mean particle size and broader particle size distribution compared with other chippers trialled. The mean bulk density of shortwood woodchip from five chippers was compared and little difference could be determined.

4.3.3 BULK/SOLID VOLUME CONVERSION FACTORS

Bulk/solid volume conversion factors were determined for woodchip and firewood in both conifers and broadleaves. A number of factors were determined for woodchip produced from different species and assortments. The overall factor for Sitka spruce woodchip was 2.9, whereby 1 m^3 solid volume is equal to 2.9 m^3 bulk volume. The overall factor for ash wholetree woodchip was 3.2. The bulk/solid volume conversion factor for loosely stacked split firewood from ash and Sitka spruce was estimated at 2, whereby 1 m^3 solid volume is equal to 2 m^3 bulk volume.

These factors can be used to quantify woodfuel production from solid volume, to calculate transportation and storage requirements, to derive the solid volume required to satisfy a stated bulk volume of woodfuel, and a number of other conversions used to facilitate effective and fair trade of woodfuels. The estimated margin of error associated with the factors as presented should be noted and may be used for sale and purchase purposes. The Sitka spruce woodchip conversion factor estimate of 2.9 had a margin of error of ± 17%, while for the ash wholetree woodchip conversion factor of 3.2 it was ± 10%. The firewood conversion factor of 2 had a margin of error of ± 10%. Further determinations from a broader range of woodfuels will be required to improve the precision and accuracy of these estimates.

BIBLIOGRAPHY

The Technical Specifications quoted in this report were valid at the time of use, but have since been upgraded to full European Standards (EN). The Technical Specifications are as such no longer current.

CEN/TS 14588: *Solid Biofuels - Terminology, Definitions and Descriptions*. NSAI, Dublin.

CEN/TS 14961: *Solid Biofuels - Fuel Specifications and Classes - Part 1: General Requirements*. NSAI, Dublin.

CEN/TS 15103: *Solid Biofuels - Determination of Bulk Density*. NSAI, Dublin.

CEN/TS 14780: *Solid Biofuels - Methods for Sample Preparation*. NSAI, Dublin.

Brinker, R. W., Kinard, J., Rummer, B. and Lanford, B. 2002. *Machine rates for selected forest harvesting machines*. Circular 296. Auburn Agricultural Experimental Station, Auburn University, Auburn, Alabama, USA.

Forestry Commission, 2006. *Forest mensuration, a handbook for practitioners*. Forestry Commission, Edinburgh.

Kofman, P.D. and Kent, T. 2007. *Harvesting and processing forest biomass for energy production in Ireland - The ForestEnergy 2006 programme*. COFORD, Dublin.

Serup, H., Kofman, P.D. et al. 2005 Wood for energy production, Irish Edition, COFORD, Dublin

Short, I. And T. Radford, 2007. *Silvicultural Guidelines for the Tending and Thinning of Broadleaves*. Teagasc, Dublin.

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