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An investigation of the economic potential of Short Rotation Forestry in Ireland

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Declaration:

No element of the work described in this dissertation has been previously submitted for a degree at this or any other institution. The work in this thesis has been performed entirely by the author except where otherwise acknowledged.

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Abstract

An investigation of the economic potential of short rotation forestry in Ireland

Ana de Miguel Muñoz

An increase in Short Rotation Forestry (SRF) in Ireland is expected in response to the increasing demand for fibre products and wood energy. SRF is the practice of cultivating fast growing tree species mainly for the production of biomass, through a rotation length of less than 20 years in Ireland. Although forest policy is promoting SRF, currently establishment is limited. This thesis aims to investigate the potential financial value of practicing SRF and evaluate whether SRF should be financially managed to allocate a range of assortments to diverse markets or supply a single market only.

The work included: 1) Quantification of above ground biomass by dry matter content, merchantable volume and energy content from four SRF stands, two of *Eucalyptus* spp. and two of *Populus* spp.; 2) A market survey identifying pallet producers and the wood energy sector as most willing to use SRF material; 3) Benchmarking conditions that facilitated market development in Oregon with current conditions in Ireland, identifying: large scale plantations; high value product market development; and, investment in research, education and marketing, as key conditions; 4) Development of a unit conversion tool to quantify and value wood resources by volume, weight and energy parameters for market segment comparison and 5) Determination, from the landowner's perspective, of the optimal financial value of SRF and finding maximum returns were for eucalyptus stands used for diverse markets, mainly small sawlog for pallet production. Contrary to policy objectives, SRF will not contribute significant biomass to fibre and fuel markets, under current financial and market conditions. Policy promoting SRF must be long term, and supported by industry, research and education to gain landowners acceptance. Further research on SRF wood properties and yield models will be necessary to underpin SRF development in Ireland.

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A	Ash content
BD	Bulk density as received
BD_d	Bulk density dry
BEF	Biomass Expansion Factor
C	Carbon content
C_{tot}	Total Carbon
CO_2	Total CO_2 sequestrated
CTL	Cut to length harvesting
CLT	Cross Laminated Timber
D_d	Basic density
DP	Dynamic Programming
D_w	Gross density
E	Energy Content
EAA	Equivalent Annual Annuity
f	Volume Weight Factor
H	Hydrogen content
IN	Integrated harvesting
M	Moisture Content
m_d	Dry matter
m_w	Total Mass
N	Nitrogen Content
NPV	Net Present Value
O	Oxygen Content
$q_{gr,d}$	Gross calorific value dry
$q_{gr,daf}$	Gross calorific value dry ash free
$q_{net,d}$	Net calorific value dry
$q_{net,m}$	Net calorific value as received
SRC	Short Rotation Coppice
SRF	Short Rotation Forestry
SVF	Solid Volume Factor
V_b	Bulk volume
V_s	Solid volume
WT	Whole tree harvesting

Chapter 1: Introduction

Chapter 1: Introduction

Forests are an increasingly important source of wood-based products and renewable energy. As a response to both the growing demand for wood fibre products and renewable fuel for energy targets, an increase in short-rotation woody crops for fibre and energy is expected in the Republic of Ireland (Teagasc, 2014a). This silvicultural system is called Short Rotation Forestry (SRF) and is defined by Christersson and Verma (2006) as "the silvicultural practice under which high-density, sustainable plantations of fast-growing tree species produce woody biomass on agricultural land or on fertile but degraded forest land". SRF have mainly been used by the energy, cellulose and fibre boards industries worldwide (Elias and Boucher, 2014). However, other products have been also produced such as furniture, flooring, veneers and fibre boards (Sepliarsky, 2007).

Demand for wood biomass is increasing globally as concerns about the environmental impacts of fossil fuel use and of carbon-intensive, non-renewable materials continue growing. SRF has the potential to contribute in meeting this global demand for wood biomass while helping to reduce pressure on natural forests and providing an alternative income for rural communities (Foroughbakhch *et al*., 2017). In fact, rapid forest expansion is identified as having the potential to sequester atmospheric carbon and reduce greenhouse gases (Erb *et al.*, 2018; Bastin *et al.*, 2019; Doelman *et al.*, 2020)

Demand for wood biomass for energy is now seen as another market competing with forest products as the global efforts to reduce greenhouse emissions continue increasing (EFI, 2014a). An increase on the use of wood biomass to meet renewable energy targets is expected and this will increase the competition between assortments used for wood fuel and fibre, thus an increase of price of these assortments (Johnston and van Kooten, 2016).

SRF has been researched extensively as an alternative to fossil fuels (Adams *et al*., 1977; Malinen *et al*., 2001; Hinchee *et al*., 2011). For instance, research in Italy found poplar plantation residues had lowest environmental impact producing heat and electricity compared to three other scenarios including the current production from natural gas (González-García and Bacenetti, 2018). Furthermore, the use of poplar (*Populus* ssp.) to produce liquid biofuels for the aviation industry as an alternative to petroleum-based fuel was investigated concluding that it will contribute to the reduction of fossil fuels use and global warming (Budsberg *et al.*, 2016).

In addition, SRF has the potential to displace more environmentally intensive materials such as those used in construction, ie. concrete or steel. For instance, the use of SRF to produce cross laminated timber (CLT), an engineered timber product made by orthogonally glued layers composed of boards (Brandner *et al.*, 2016), has been researched as a potential option to obtain a higher value than on the fibre or energy markets (Thomas and Buehlmann, 2017). Research on eucalyptus grown in China (Liao *et al.*, 2017), Brazil (Pereira and Calil Junior, 2019), and Australia (Pangh *et al.*, 2019) found eucalyptus wood had good mechanical properties of resistance and stiffness, to produce CLT. However, research on hybrid poplar (*Populus* spp.) found it may meet the strength requirements for CLT but it may not meet the stiffness requirements, so it would be recommended to combine poplar with other denser wood to produce CLT (Kramer *et al.*, 2014).

The use of SRF for ecosystem services has also been investigated. Poplar used for biosolids and wastewater management was demonstrated to have a high uptake capacity for nitrogen and metals (Houda *et al.*, 2016). While decontaminating water, timber and biomass can be sold to cover the cost of management (Miller *et al.*, 2018). Thus, ecosystem services could be the additional motivation for the establishment of SRF. However, development of a convincing business model would be the key driver for landowners to establish poplar SRF for biomass feedstock and at the same time provide ecosystem services such as wastewater management and floodplain management (Hart *et al.*, 2018).

Indeed, economic motivation has been identified as the main driver for the development of SRF, for both landowners and markets (Munn *et al.*, 2018). Landowners need to reduce uncertainty on the returns on their investment through securing a SRF products pay and benefit comparison with the any competing land use option (Schulze *et al.*, 2017; Soliño *et al.*, 2018). On the other hand, markets need to be assured of a secure supply of raw material (Munn *et al.*, 2018).

It is more probable that SRF will be established on marginal land (Acuña *et al.*, 2018; Munn *et al.*, 2018), so it reduces concerns about competition with agricultural crops but if agricultural product prices are very low, SRF could displace food production on higher productivity sites also (Schulze *et al.*, 2017). However, profitability of SRF on marginal lands may depend on a reduction in current management costs, availability of higher subsidies and higher biomass value (Schulze *et al.*, 2017; Acuña *et al.*, 2018; Soliño *et al.*, 2018).

The Republic of Ireland (from here simply referred as to Ireland) has only 11% forest cover, compared to the EU average of 38% (Forest Service, 2017). One of the aims of Ireland's forest policy is to encourage afforestation by private landholders in order to achieve a forest cover of 18% by 2046. Increasing Ireland's forest cover will contribute to 1) timber and fibre production; 2) carbon sequestration, thus mitigating climate change; and 3) meeting renewable energy targets (Teagasc, 2014a).

Ireland's 100% State aid funding for forestry for the period 2014 to 2020 is summarised in the Irish Forestry Programme 2014-2020 (DAFM, 2014). A new grant premium category was proposed for forestry for fibre in this programme, with the objective of meeting the supply-demand gap for wood for energy and panel board applications that is forecast to arise over the next two decades (DAFM, 2014). In particular, SRF has the potential to help to meet Ireland's renewable energy targets set by the European Directive EU 2018/2001, which will increase to 32% by 2030, from only 9.5% in 2016 (NREAP, 2017). The planting target for fibre and energy within the forestry programme is 3,300 ha by 2020 (DAFM, 2014).

All the proposed species covered by the Forestry for Fibre grants are broadleaved species capable of high productivity over a short rotation, hence Short Rotation Forestry. The proposed species are certain eucalyptus species (*Eucalyptus* spp.), Italian alder (*Alnus cordata*), hybrid aspen (*Populus tremula x tremuloides*) and a list of specific clones of poplar (*Populus* spp.). The establishment of these fast-growing broadleaf plantations will also contribute to increasing the biodiversity in Ireland considering that currently 75% of the Irish forest area is covered by conifers, with Sitka spruce (*Picea sitchensis*) making up 51.1% of the forest area (Forest Service, 2017).

However, SRF is still very limited and its development is at a very early stage in Ireland (Teagasc, 2014a). Although private landowners are targeted to expand Ireland's forest area and financial support is provided by the Government, planting is still very slow (DAFM, 2019), partially because of a lack of clarity on the return on the investment. Economic goals have been a key factor for Irish private landowners to make the decision of turning their land into forestry (Dhubháin and Gardiner, 1994; Carroll *et al.*, 2011; Howley, 2013). While maximising their profit is not the main objective of all forest owners and other motivations such as landscape, environmental, recreation, intrinsic values have been identified (Carroll *et al.*, 2011; Duesberg *et al.*, 2014a; Duesberg *et al.*, 2014b), forest owners need to at least be confident they can make a satisfactory return (Duesberg *et al.*, 2013). Consequently, for the Forestry for Fibre grant scheme to be applied and SRF to become more common in Ireland, financial returns to the forest owner must be clear.

It is important to understand the market opportunities for SRF in order to assess the financial returns to the grower. A market survey is a research method to investigate market development of a product and define the market parameters of a business (Bryman and Bell, 2003; Entrepreneur, 2016). Inductive qualitative approach is used when there is very little known about the topic researched and often interviews are used to collect high quality information and to guarantee a high percentage of responses (Burnard et al., 2008). Grounded theory is a method often used to analyse interviews that involves the identification of the main emergent themes, grouping them into categories, testing with further interviews and giving direct quotes to illustrate the themes identified (Denscombe, 2003). NVivo (QSR International Pty Ltd., Australia) is a software developed for the analysis of qualitative, particularly it can be used facilitate the grounded theory approach (Hutchison et al., 2010). In forestry, NVivo has been used to analyse emergent forest markets in recent years such as the forest biomass energy market (Silver et al., 2015) and the forest carbon market (Thompson et al., 2012).

Besides the market opportunities, productivity rate is a key factor on the forest economics. SRF and particularly *Eucalyptus* and *Populus* genera are fast growing trees with high productivity rates. Yields of 33 m^3 ha^{-1} yr^{-1} were achieved in eucalyptus plantations in Brazil increasing to 62 m^3 ha^{-1} yr^{-1} with fertilisation and 83 m^3 ha^{-1} yr^{-1} with fertilisation and irrigation (Stape *et al.* 2010). In Britain yields between 11 and 30 m^3 ha^{-1} yr^{-1} were recorded (Leslie *et al.*, 2012) while in Ireland eucalyptus trials produced between 23 and 32 m^3 ha^{-1} yr^{-1} (Thompson *et al.*, 2012).

Poplar plantations in Denmark reached yields between 9 and 12 m^3 ha^{-1} $yr^{-1,}$ or an average of 3.6 odt ha^{-1} yr^{-1} and it was confirmed the selection of hybrid poplar species have a very strong influence on biomass productivity (Nielsen *et al.* 2014). In Britain productivities in poplar plantations ranged between 6 and 10 odt ha^{-1} yr^{-1} (Cannell, 1980) and poplar trials in Ireland had potential yields between 7 and 11 odt ha^{-1} yr^{-1} (Keary, 2003).

In addition, wood and fuel properties influence quantification and suitability for the potential markets. Basic density, the dry weight per green unit of volume, influences the structural, fibre and energy markets (Bowyer *et al.*, 2007). There are differences in SRF species basic density, for instance eucalyptus have a higher basic density, 450 to 500 kg m^{-3} (Leslie and Purse, 2016) than poplar, 300 to 390 kg m^{-3} (Balatinecz *et al.*, 2001).

Furthermore, moisture content, calorific value and ash content are important properties for the use of biomass as a fuel. Moisture content, the percentage of water contained in the material just after felling, varied from 43% to 68% in different studies of eucalyptus and poplar SRF (Lyons *et al.*, 1986; Lausberg *et al.*, 1995; Zhang et al., 2003; Zanuncio *et al.*, 2013). Calorific value is defined as the energy amount per unit mass (MJ kg^{-1}) or volume (MJ m^{-3}) released on complete combustion (ISO 16559:2014). Gross calorific value of stem wood of eucalyptus varied from 19.10 MJ kg^{-1} to 20.16 MJ kg^{-1} (Kumar *et al.*, 2010) while foliage reached 23.48 MJ kg^{-1} (González-García *et al.*, 2016; Viana *et al.*, 2018). In poplar, a range of gross calorific values between 15.79 MJ kg^{-1} and 24.28 MJ kg^{-1} for stem, including bark and wood, was recorded (Klasnja *et al.* 2002). Ash content is the inorganic residue remaining after combustion and is usually expressed as a percentage of the dry matter (ISO 16559:2014). Quantification of ash content and its chemical composition are important for the biomass boiler design as the latter determines ash melting behaviour which can cause slagging (Vassilev *et al.*, 2010). Ash content of SRF poplar and eucalyptus ranged from 0.4% for stem wood to 7.1 for bark (Lyons *et al.*, 1986; Klasnja *et al.* 2002; Perez *et al.*, 2006; Kumar, 2010; Perez *et al.* 201; Viana *et al.*, 2018).

Accurate measurement of the productivity and properties described above is essential in the forest and wood energy sectors (Laurila and Lauhanen, 2011). However, woody biomass is quantified using many different units and it is not always clear the units to use and the conversions between these units (Kofman, 2010). There are three different ways to quantify woody biomass: weight based, volume based and energy content based measurements (Lindblad *et al.*, 2010). The use of each of these methods depends of the step of the supply chain and the market. Relevant organisations (e.g. UNECE/FAO), standards (EN and ISO) and research networks (Fonseca *et al*., 2010; CEN, 2016; COST Action FP0902 *et al.*, 2016) have attempted to solve this confusion and to achieve harmonisation and accuracy in the quantification of woody biomass. Furthermore, many conversion tools have been developed to be able to convert between different units (Austrian Energy Agency, 2008; Forestry Commission, 2009; Forest Business Network, 2011; Nylinder, M., & Kockum, F., 2016; Kofman, P. & Murphy, G., 2019; FPInnovations, 2020) In Ireland there are currently two publicly available wood price indices: 1) Standing sale prices in solid volume expressed in € m^{-3} (Teagasc, 2018) and 2) Wood fuel energy price, that included wood fuel expressed in € kWh^{-1} (SEAI, 2018).

Net value recovery is the financial return the forest owner will gain from the sale of forest products once all the costs have been subtracted and operational and marketing constraints have been met (Murphy, 1998). Optimal net recovery value will be reached when volume and value are maximised while cost is minimised (Twaddle and Goulding, 1989). Bucking is the activity of cutting tree stems into shorter logs with specific diameter ranges and length. Optimised bucking seeks to recover the maximum harvested product value. Three different levels of bucking optimisation have been identified: stem, stand and forest levels (Laroze, 1999). The best situation for the forest owner is the stem level because it means the value of each individual stem is maximised as the market will take the amount of each log type produced (Murphy et al., 2004). This situation is called supply constrained market. Dynamic programming (DP) has been the most popular optimisation algorithm at stem level in a supply constrained market. The DP approach to bucking divides the merchantable stem into potential positions where each crosscut could be made (Briggs, 1989). The number of cutting locations is limited by constraints from market requirements on log lengths and diameters. Market price variations decide the optimal cut. The first DP stem level bucking optimisation algorithm was developed by Pneumaticos and Mann (1972) and other algorithms have been proposed since then (Briggs, 1980; Sessions, 1988; Wang *et al.*, 2004; Arce *et al.*, 2004). A variety of commercial software has also been developed to solve the bucking optimisation problem: Valmax (Murphy, 2008), Atlas (Atlas Technology Integral, 2014), YTGEN (Interpine Group Ltd, 2018), Optware (Optware Solutions LLC, 2019) and Halco (Sotware Systems Ltd., 2020).

VALMAX is an optimal log-making simulation software (Murphy, 2008) that combines market prices and product specifications with stand data to optimally allocate wood products from the standing timber. VALMAX allows the analysis from the point of view of the landowner, at stem level and uses a DP algorithm. This software has been used worldwide in several analyses. For instance, it was applied to assess tree value and log product yields of radiata pine in Australia (*Pinus radiata*) (Acuna *et al.*, 2009) and of SRF poplar (*Populus* spp.) plantation in Oregon, U.S. (Murphy *et al.*, 2011; Barnett, 2012).

Collecting the above information on markets, stands productivity, wood and fuel properties and carrying out a bucking optimisation exercise will help to bring clarity to landowners, their advisors and policy makers on the economic sustainability of SRF in Ireland. Focusing on the above issues, the research question of this dissertation is: *What is the financial value of SRF plantations in Ireland?* This broad research question was tackled by dividing it into smaller questions:

1) What are the most suitable markets for SRF in Ireland?
2) How can SRF biomass be quantified for payment purposes by different markets?
3) How can the financial value of SRF in Ireland be maximised through the optimal allocation of products to markets?

These questions have been answered by:

1) Assessing the potential markets for SRF plantations in Ireland, analysing in particularly the: a) price paying potential, b) species suitability, c) material requirements, d) market scale, e) infrastructure and exploring the Irish industry's knowledge and perceptions of SRF. Furthermore, an established SRF industry was analysed. A case study was carried out in the Pacific North West region (U.S.A.) in order to learn from others' experiences and gather

indications on how to best develop this land use in Ireland. This case study allowed for a deeper understanding of the SRF market sector. (Chapters 2 and 3. Both of these chapters have been published as peer-reviewed papers).

2) Assessing SRF productivity and quantifying above-ground biomass distribution in four mature SRF stands in Ireland. Additionally, developing a unit conversion tool to quantify wood resources for different markets, making the direct comparisons between product values possible (Chapters 4 and 5).
3) Maximising the financial value of the SRF plantations in Ireland from the point of view of the landowner, through a modelling exercise on the optimal allocation of above ground biomass to different SRF potential markets, using the VALMAX model (Chapter 6).

This PhD project is part of the ShortFor Project, funded by the Department of Agriculture, Food and the Marine (project number 13/C/498) which aimed at researching the potential of short rotation forestry to contribute to biomass production and renewable energy targets in Ireland. ShortFor was a collaboration between five research-performing organisations in Ireland: University College Dublin, Trinity College Dublin, University of Limerick, Teagasc and Waterford Institute of Technology, with UCD as lead partner. The ShortFor project has investigated the current SRF resource in Ireland, sites and species suitability, economic and environmental sustainability of SRF silvicultural systems. Among others, the species proposed for grant-aid under the forestry for fibre Grant and Premium Category (GPC) within the Irish Forestry Programme 2014-2020 have been investigated within this project.

This thesis focused on the economic sustainability of SRF in Ireland. As such, this work will help to reduce uncertainties about the financial return from the point of view of short rotation forest owners and will inform forest policy on how to lead the growth of this silvicultural practice.

Some of the stands data collected by the Shortfor Project and the supply chain cost investigated by the same were inputs of this PhD.

The experience gained by the PhD candidate during a six-month residence in Oregon (U.S.A.), thanks to a World Forestry Institute Fellowship, supplemented and completed the candidate's work done in Ireland.

This dissertation is divided into seven chapters, including the current chapter. The other chapters are summarised as follows.

Chapter 2:

Market opportunities for Short Rotation Forestry were investigated by surveying the current Irish wood processing and solid biofuel sectors.

Chapter 3:

A comparison of market opportunities for Short Rotation Forestry in Ireland and Oregon (U.S.A.) was carried out. Potential challenges to SRF market development in Ireland were identified and opportunities that could facilitate this market expansion were recognised by comparing the Irish conditions to those in Oregon, where a SRF market had been developed over the last 40 years.

Chapter 4:

Four Short Rotation Forestry stands (two *Eucalyptus* spp. and two *Populus* spp. plantations) were characterised for total above ground biomass and energy content.

Chapter 5:

A woody biomass unit conversion tool was developed in order to allow quantification of the forest resource for different markets, which use different measurement units for quantification and valuation. A case study of the use of the tool applied to Short Rotation Forestry in Ireland was also carried out, using the data gathered in Chapter 4.

Chapter 6:

Optimal log product yield and financial returns from the landowner's perspective of the short rotation forestry *Eucalyptus* spp. and *Populus* spp. stands were investigated using optimal bucking software, VALMAX. Data inputs from the SRF stands, markets and supply chains were collected and described in Chapters 2, 4 ,5 and annexes A and B.

Chapter 7:

The main findings of this study and conclusive remarks were summarised in this chapter. Limitations of this dissertation and suggestions for future research were also included.

A graphical summary of this work is presented in Figure 1.1 which describes the framework of this study.

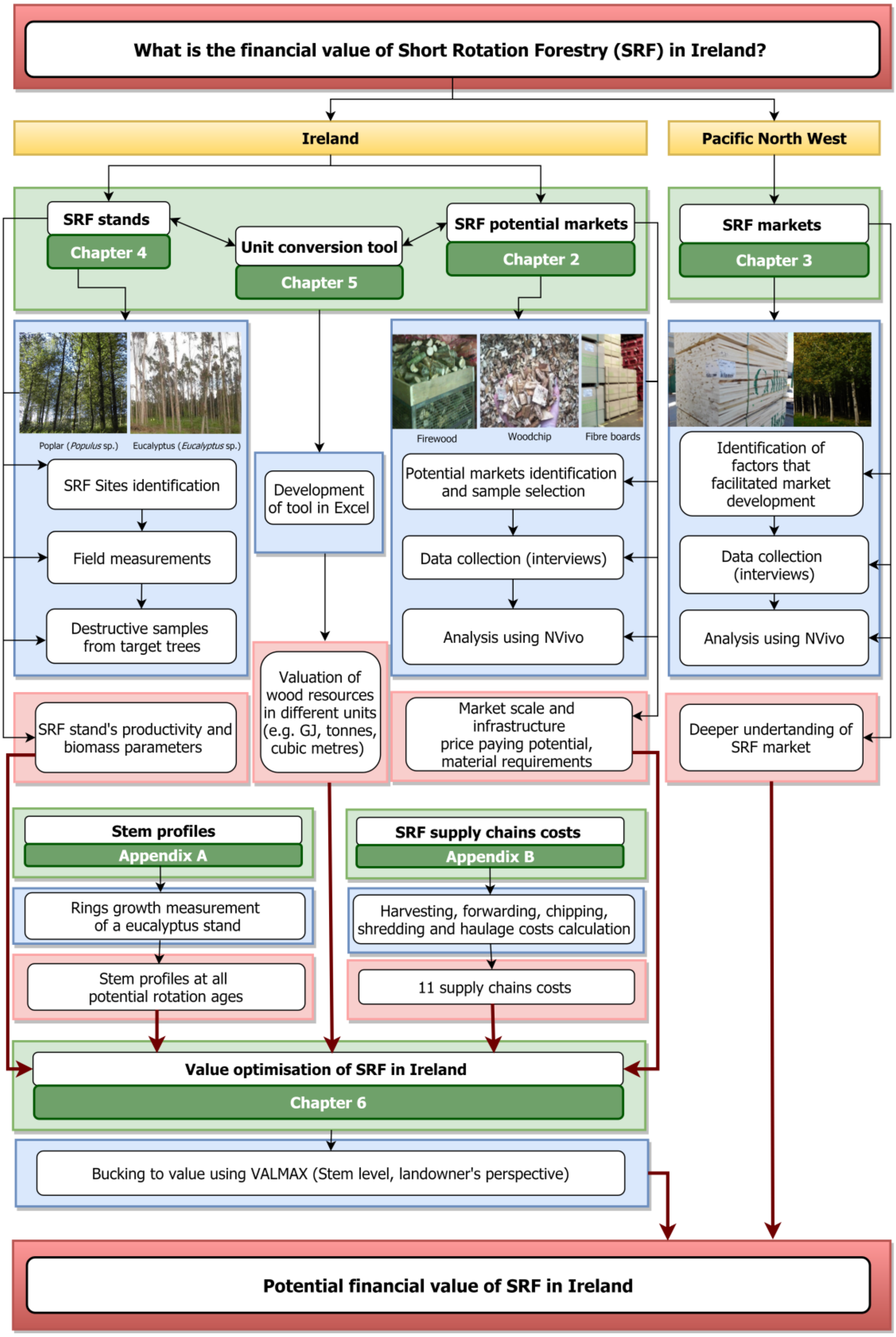

Figure 1.1. Conceptual framework of the dissertation.

Chapter 2: Exploring market opportunities for Short Rotation Forestry in the current Irish wood processing and solid biofuel sectors

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Chapter 2: Exploring market opportunities for Short Rotation Forestry in the current Irish wood processing and solid biofuel sectors

Abstract

Short Rotation Forestry (SRF) is expected to increase in Ireland in response to the increasing demand for fibre products and fuel for renewable energy targets. A survey was carried out of 30 companies in the energy, fibre and sawmills sectors to assess their perceptions on the suitability of SRF species as a raw material. Also data was gathered on current company production, scale, material requirements, species used, price paid and source of supply. The objective was to identify market opportunities, if any, for growers of SRF.

The raw material intake for interviewed companies ranged from 400 to 650,000 t yr-1 and the price they paid at the mill gate for softwood roundwood varied from €34 to €108 t^{-1}, with price aligned with piece size but not quality. Most of the interviewees (76%) were not familiar with SRF, however 30% of companies were favourable towards using SRF material, for wood fuel and for pallet manufacture. A further 34% were negative about the suitability of SRF as a raw material, with the other 36% expressing no opinion. Information gaps were identified in wood and fuel properties, drying rate and particularly the scale of supply that would become available. Views were mixed regarding forecasted gap between roundwood supply and demand, with sawmills reporting a shortage of sawlog. Instead, the wood energy sector indicated plentiful supply but insufficient market development, which may indicate renewable energy policy targets, will be missed without support measures.

2.1 Introduction

Demand for wood products is expected to increase internationally and forecasts show that demand for wood based products such as fibre boards, wood fuel and paper, supplied from fast growing plantations, will increase even faster than other wood products (Elias and Boucher, 2014). The silvicultural practice of producing woody biomass from sustainable fast-growing plantations on agricultural land or suitable forest land on a reduced rotation length is known as Short Rotation Forestry (Christersson and Verma, 2006). SRF management (e.g. tree density, fertilization, harvesting cycles, etc.) is less intensive than conventional agricultural crops or Short Rotation Coppice (SRC) but more intensive than conventional forestry, which means that SRF occupies a niche between the highly productive systems and conventional forestry (Teagasc, 2014a). SRF rotation length is usually between 8-20 years, longer than the 2 to 5 year cycle of SRC (Crops for Energy Ltd, 2015). SRF has advantages as single stemmed trees can be planted in areas unsuitable for SRC, and all operations are performed using conventional forestry equipment whereas SRC requires specialised machinery (Biomass Energy Centre, 2016).

A wide range of products are manufactured worldwide from SRF, although these fast growing plantations are mainly used to produce cellulose, energy, and fibre boards (Elias and Boucher, 2014). In recent years wood production from SRF has increased, due to increasing environmental constraints on harvesting native forest (Sánchez Acosta *et al.*, 2008). Globally, Eucalyptus (*Eucalyptus* spp.) are the most common species used for fast growing plantations and have the potential to help to meet world demand for wood (Laclau *et al.*, 2013). Eucalyptus plantations, grown in a short rotation (10-16 year rotation), have been mainly used by the cellulose industry in the past decades in the Iberian Peninsula (Ruiz and López, 2010). Other uses for Eucalyptus, such as furniture, flooring, veneers and fibre boards, increased from local use to international markets since 2000 (Sepliarsky, 2007). Poplar plantations in Italy, also grown in a short rotation (10-18 year rotation), have been traditionally used for plywood, pallets, crates and paper pulp (Coaloa and Nervo, 2011).

The current area of SRF in Ireland is very limited. Keary (2003) estimated that there were 80 ha of hybrid poplar plantations in Ireland, and it is unlikely that this area increased as poplar was not an approved species under the Afforestation Grant Scheme until 2014. Coillte have established plantations of Eucalyptus species since

2008 on reforestation sites, particularly in the south and east, expanding on field trials laid down in 1993/94 (Thompson *et al.*, 2012). An unpublished survey of the Coillte inventory carried out in November 2014 by WIT indicated that there were 333 ha of eucalyptus on 53 sites, established over the previous 6 years.

The main wood industry sectors in Ireland are the panel boards mills and sawmills, with the wood energy sector emerging recently (IFFPA, 2015). The panel board mills used a total of 1.38 million cubic metres of wood fibre (pulpwood, woodchips, sawdust and used wood) in 2014 and this is forecast to increase to 1.6 Mm^3 by 2020 (COFORD, 2015). In 2014, a total of 1.95 Mm^3 of roundwood was used by the sawmills, including large sawlog or sawlog, mainly used for construction sawn timber and small sawlog, use'd for pallets, fencing, packaging and small dimension construction timber. All Irish roundwood was used indigenously and due to shortfall, additional logs were imported from Scotland (IFFPA 2015). Also demand for wood biomass for energy is forecast to increase from 0.99 Mm^3 in 2014 to more than 1.87 Mm^3 in 2020 (COFORD 2015) to help to meet Ireland's renewable energy targets, which are set to increase to 16% of total energy supply by 2020 (European Directive 2009/28/EC). The percentage of renewable energy contributing to the Irish Gross Final Energy Consumption in 2013 was 7.8%, almost half of the 2020 target (Howley, et al. 2014). Across all forest industry sectors, COFORD (2015) predicted a gap of 0.9 Mm^{-3} between supply and demand by 2020.

Irish forest policy is promoting SRF afforestation through targeted support measures to contribute to meet this forecasted supply-demand gap for fibre, energy and other wood products (Phillips, 2011; COFORD, 2015). A new grant premium category for Forestry for Fibre was included in the Irish Forestry Programme 2014-2020 (DAFM, 2014). The planting target for fibre and energy within the programme is 3,300 ha by 2020. The species selected under this scheme are specific Eucalyptus species (*E. glaucescens* Maid. and Blakeley, *E. gunnii* Hook. f., *E. nitens* Dean and Maid. Maid., *E. rodwayi* A.T. Baker and H.G. Sm. and *E. subcrenulata* Maid. and Blakeley), Italian alder (*Alnus cordata* (Loisel) Desf.), hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) and a list of specific clones of hybrid poplar (x *Populus* spp.) (ibid.). All the proposed species covered by the Forestry for Fibre grants are broadleaved species, capable of high productivity over a short rotation.

A market survey is “a research method for defining the market parameters of a business” (Entrepreneur, 2016), used to investigate market development and marketing opportunities (Bryman and Bell, 2003). The nature of market surveys is often qualitative and associated with emergent research design. Particularly, when there is very little theory, structure or framework in the research area, inductive qualitative approach is chosen (Burnard *et al.*, 2008). Emergent research design uses the data collected to develop the structure of analysis. This means that the sample selection and size cannot be decided at the beginning as this will depend on the course of the research (Denscombe, 2003).

Interviews are frequently used in qualitative research to secure a maximum number of responses, collect high quality information, and to contextualise the responses and the relations between them. Interview study usually involves thematic content analysis. This type of analysis is generally known as grounded theory (Denscombe 2003) and is based in identification of the main emergent themes from the qualitative data collected following these steps:

- First broad coding of the data in different categories or themes.
- Identification of the main themes and relations, so categories are grouped or merged.
- These themes and groupings are then tested by further collected data.
- Finally, more and less popular responses on different themes are identified and direct quotes from a wide range of participants are chosen to illustrate those themes (Burnard *et al.*, 2008; Anderson, 2010).

Market surveys have been carried out in the forestry sector to identify market development (Perkins *et al.*, 2005; Mendell *et al.*, 2007), and marketing of alternative and not well-known timber species (Venn and Whittaker, 2003; Nicholas and Garner, 2007). Some studies have used NVivo (QSR International Pty Ltd., Australia), specialised software developed for qualitative data analysis, and used in academia, government, business and social science research. In forestry, this tool has been used to analyse opinions of stakeholders and forest owners on emergent forest markets in recent years: for example in the forest biomass energy market (Silver *et al.*, 2015) and the forest carbon market (Thompson *et al.*, 2012).

Current Irish forest policy measures promote SRF as a means to bridge the predicted gap in wood biomass supply and demand. The success of this policy will depend in part on the readiness of the wood industry in Ireland to use SRF as a source of raw material. The objective of this study was to explore the Irish industry's perceptions and knowledge of SRF, and identify if there are real market opportunities in Ireland for raw material that SRF growers could supply in the future.

The study, carried out in the form of a survey, aimed to research species suitability for particular market segments, price, material specifications (e.g. dimensions, certification, moisture content), market scale and infrastructure. This type of information is useful in order to study the economic sustainability of this land use, which is a key principle of sustainable forest management, as well as aid in determining return on investment to growers of SRF relative to other land uses.

2.2 Materials and methods

A survey was carried out on market opportunities for SRF of the Irish wood processing and solid biofuel sector between October and December 2015. The methodology used in this survey is summarised in Figure 2.1.

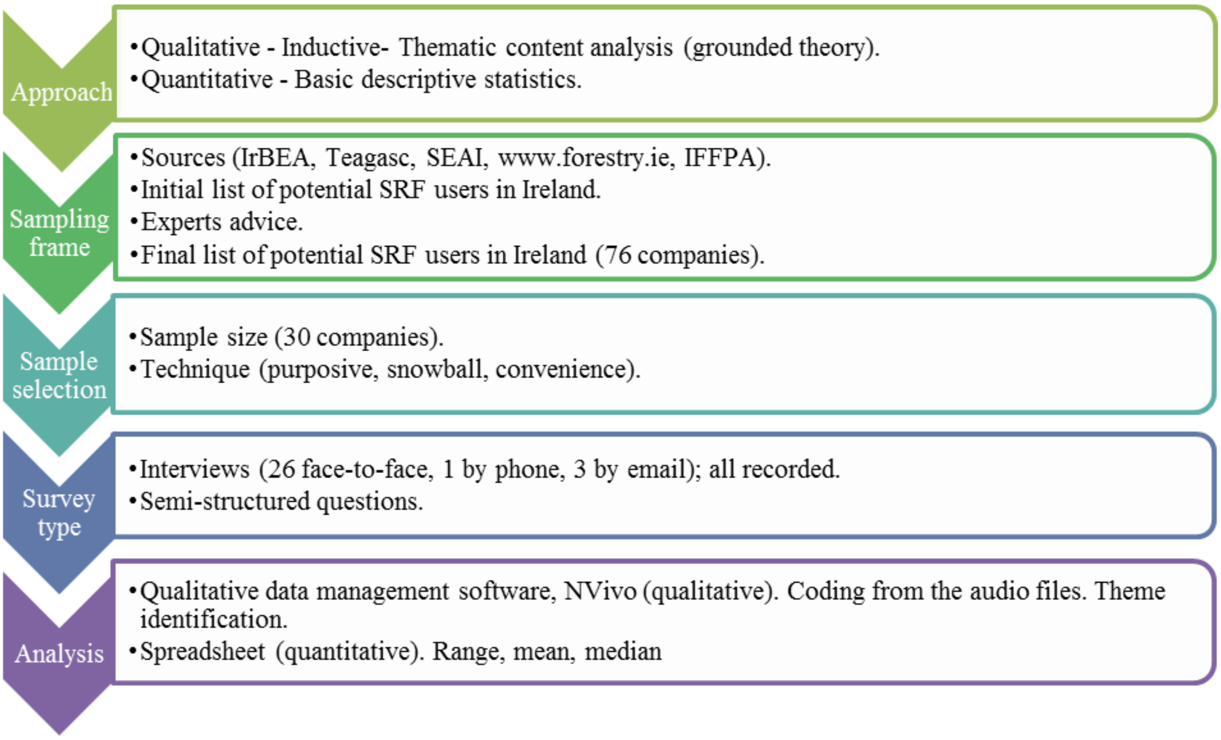

Figure 2.1. Outline of the methodology used for the market survey.

2.2.1 Approach

Qualitative analysis was used to collect the range of industry views concerning short rotation forestry as these perceptions could not be captured with an absolutely quantitative approach. Due to the novelty of SRF in Ireland an inductive qualitative approach was chosen. A thematic content analysis or grounded theory was used to analyse this qualitative data. In addition, some quantitative information was sought from the interviewed people (price, raw material amount and dimensions) and basic descriptive statistics were applied to the data.

2.2.2 Sampling frame: List of potential SRF users

The main sources used to develop the initial list of SRF potential users for energy were the catalogue of Irish wood fuel companies produced by the Irish Bioenergy Association (Irbea, 2013) and the SEAI List of Known Wood Fuel Suppliers (SEAI, 2015), supplemented by work done by Mockler and Kent (2014).

Other potential users of SRF were identified by online search and in databases such as the contact list for timber buyers and contractors developed by Teagasc (2014b), and the forestry directory (Forestry.ie). Also the annual overview of the Irish forestry and forest products sector produced by the Forestry and Forest Products Association (IFFPA, 2013) was used to identify companies.

The main survey focused on companies that use raw material from the forest. However, a number of secondary users were interviewed also to get a better insight into woodflow in the Irish market. Furthermore, some of the interviewees were not only users of raw material from the forest but also forest owners or harvesting companies. This broadened the scope of the survey and helped to get a more comprehensive understanding of the market.

After an initial list was finalised, the following experts on the Irish timber and wood fuel markets and fast growing species were contacted for advice on the survey scope and company contact list: Noel Gavigan, Irish Bioenergy Association; Eoin O'Driscoll and Gordon Knaggs, authors of the annual Woodflow in Ireland COFORD report; and Kevin J. Hutchinson, expert on eucalyptus (Thompson, et al. 2012). On advice from the experts, the sawmill sector was included in the survey, in order to consider the possibility of using SRF for pallet and fencing material. This idea of looking for higher value products was supported by literature. Other countries first introduced SRF with the target of producing pulpwood for the cellulose and energy sectors and higher value markets developed later once SRF became established. Experts also helped to identify companies that were no longer in business and to add missing companies to the list.

This final list was revised and updated again throughout the interview process as new companies were nominated by the interviewees (see sample selection). The final list was composed of a total of 76 companies, representative of the Irish energy, fibre and sawmills sectors.

2.2.3 Sample selection: technique and sample size

Purposive sampling, snowball sampling and convenience sampling were the techniques used to select the interview sample. The sample size and selection were decided throughout the interview process due to the emergent research design nature of the survey. Purposive sampling was used because it was planned to interview people among the different sectors from those who showed interested in being interviewed in a first phone call contact. Snowball sampling refers to some of the interviewees providing new contacts interested in participating in the survey. Convenience sampling was required because interviews were scheduled in order to meet several companies in the same region on the same day due to time and cost constraints.

From the total of 76 companies that were identified, 30 were successfully surveyed. More companies were first contacted (53) but some were excluded for different reasons:

- did not answer the phone after several calls in several days,
- were not interested in participating in the survey,
- were too busy and could not commit to an interview.

The 30 surveyed companies were selected to represent all the target sectors and different regions of Ireland (

Figure 2.2). Through the survey process the main potential users of SRF were identified as the firewood, woodchip, panel boards, pallet and fencing sectors. Other potential users of SRF were also explored and interviewed: construction timber, specialised sawmills, bark and woodchip for landscaping, animal bedding, pellet producers and power plants.

The identified and interviewed companies were mapped, so a spatial distribution of the identified and sampled potential users is shown in
Figure 2.2.

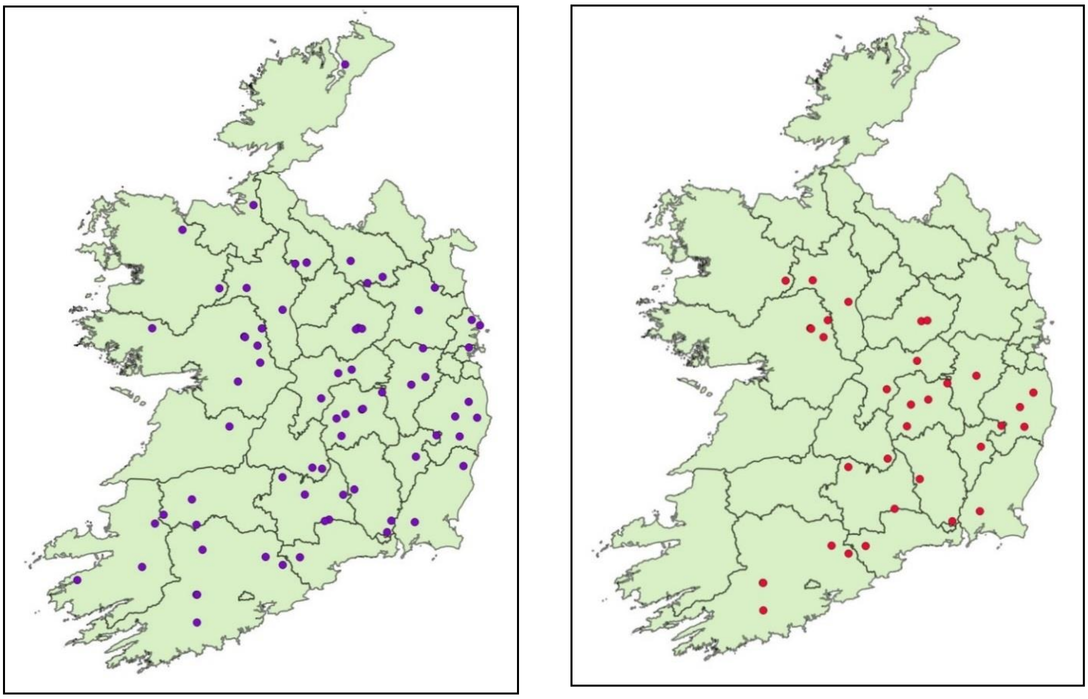

Figure 2.2. Left: Potential SRF user companies in Ireland. Right: Companies that were sampled (interviewed).

2.2.4 Survey type

Companies were surveyed by interview. Questions focused on perceptions and current knowledge on Short Rotation Forestry as a potential raw material (e.g. What can you say about SRF? And about the new grants for forestry for fibre? Do you know of any SRF plantations? Would you consider using SRF material?), availability now and into the future of forest resource (e.g. Do you think there is balance between supply and demand?), the raw material used by the company (e.g. Where do you source your raw material? how much you pay for it?, What are the maximum and minimum diameters and lengths you can use? Any other requirements?).

The interview was semi structured, in that, a clear list of questions was generated but there was flexibility to allow the interviewee to come up with related ideas and speak more broadly about the topic.

Most of the interviews, a total of 26, were face to face in order to get better quality information. However, three companies preferred to be interviewed by email and one by phone. The face to face interviews and interview by phone were recorded using the free, open source, cross-platform audio recorder software Audacity (found at: audacityteam.org). All the participants were asked for consent of recording before the interview and all accepted it. A unique identifier (company ID) was allocated to each company in order to keep the data anonymous. The average duration of the interviews was 40 minutes, ranging from 16 to 78 minutes.

2.2.5 Analysis

Survey responses were evaluated with NVivo, while a spreadsheet was used to compile the quantitative data. The method used for analysis of the qualitative data was grounded theory. This involved identifying themes, and detailed examples of those themes, emerging from the data collected.

2. 3 Results

The results from the interview analysis were described, including direct quotes from the interviews to illustrate the qualitative analysis and tables to report the quantitative analysis.

2.3.1 Business products

There was a tendency for some companies to be involved in more than one product or even sector. Table 2.1 shows that nine companies were involved in two products and four in three products. Some products were very seasonal so a complementary product was needed: “The main reason we went into the firewood is because the fencing is very quiet into the winter”. Also, companies sought to make the most of the material they bought, for instance sawmills often sold or used their own residues as wood fuel.

Table 2.1. Companies interviewed by sector and sub-sector.

Market sector	Sub-sector	Number of companies interviewed	Company ID
Wood energy	Firewood	10	A, D, E, F,G, H, I, J, K, L,M
Wood energy	Woodchip	8	D, E, F, L, W, X, Y,Z
Wood energy	Power plant	2	S, AA
Wood energy	Pellet	2	B, DD
Fibre	Panel boards	2	BB, CC
Sawmill	Pallet	9	Saw: B, K, R, S, V Pre-cut[a]: M, N, O, P
Sawmill	Fencing	5	Saw: B, C, R, V Pre-cut: I
Sawmill	General	3	S, U, V
Sawmill	Cut to order	2	Q, T
Other fibre users	Woodchip landscape	2	A, Y
Other fibre users	Bark	1	A
Other fibre users	Animal bedding	1	N

[a] Pre-cut: Did not purchase roundwood

2.3.2 Perceptions of Short Rotation Forestry

Most of the participants (76%) were not familiar with SRF defined as single stem plantations, on 8-20 year rotations. Seven of the interviewees thought of short rotation coppice willow instead. “My vision of SRF is willow and for those crops to be successful you need good fertilizer”

Just 6 out of the 30 interviewees were aware of the forestry for fibre afforestation grant scheme.

In spite of the majority not being familiar with SRF terminology, 37% had experience using eucalyptus or poplar wood and a further 27% had heard of these species (total 64%). However, these participants confirmed that their current knowledge was limited. Forty percent of the participants were able to say something about the wood properties of these species: “eucalyptus looks like softwood, it’s very pale…burns ok…poplar is too hard to dry”; “eucalyptus cracks…it is very difficult timber to deal with, very difficult to dry…but when you saw is beautiful, great pattern”; “poplar, eucalyptus…I wouldn’t say is very strong…”; “poplar doesn’t burn very well it gets black and people think firewood isn’t dry”.

Almost a third (30%) of the participants, all of whom knew or had experienced using SRF wood, would consider using this material. Most of them were from the wood energy sector (86% of that), while two small-medium size sawmills expressed interest in using SRF to produce pallet material. These two sawmills had less advance technology so they stated that they could adapt easily to different species and volumes. However, all the larger sawmills were not favourable toward SRF. The main reasons for that seemed to be the large volume required in order to change the manufacturing process and make the production effective:

> We just don't have the volume in this country...if we were setting up the sawmill for hardwoods...it's a completely different plant it's a completely different market and we don't have the species on the ground, we don't have the hectares planted…we could change the plant and even there would not be material to run one day.

Within the wood energy sector, the firewood sub-sector and the power plants were the most positive. The woodchip sub-sector was less enthusiastic. It might be because they think the purchase price would be too high as SRF species are hardwoods, and the current prices for hardwoods are prohibitive for the woodchip suppliers: “…(we take) any softwood, preferably hardwoods, but you can't buy hardwoods, it is too expensive...you can't compete with the firewood”

The fibre board mills were negative toward using SRF. There was a general perception among all sectors that SRF is just a crop for fuel: “These are crops for biomass production; they will not be suitable for sawn products.”

A set of concerns towards SRF were revealed in the interviews, around the perceived risk due to past experiences of unsuccessful new crops: “…be careful because Miscanthus was fantastic 10 years ago, now nobody wants it.”

Another concern of using alternative species was that customers complain about species different to Sitka spruce: “If I took in Douglas, it’s a better timber but the customer would complain, they just don´t know it´s a better timber, they just see a piece of timber of a different colour and they'll say, oh, an issue, problem.";"…because our customer's requirements...we can't afford to take the chance, we have to keep our quality up and to keep the quality up, we need spruce."

Seven of the interviewees expressed the view that it would be better to plant more Sitka spruce instead of SRF. Although they admitted species diversification was needed, their point of view was that Sitka spruce is the best species to grow in Ireland:

> Rather than growing short rotation crops for fibre or biomass, this land could be used for growing Sitka spruce on a 35 year rotation...the benefit is a strong saleable product, which has high demand, that can be put into years of service, as construction products, locking up carbon for potentially hundreds of years, before finally being available for fibre or biomass. We have a massive natural advantage to growing Sitka spruce in Ireland, the problem is, we are not growing enough of it!

There was also a repeated opinion of planting more Sitka spruce and using harvesting residues for energy instead of establishing energy crops as there was a perception of plenty of forest waste material available for energy:

> I don't see the sense in SRF, I think we should be pushing forestry, planting trees and using the branches of the trees, and we are doing two jobs: we are supplying logs to sawmills and we are supplying energy rather than the energy crop just being energy…we grow very good Sitka spruce…

The perceived difficulty to convince landowners and industry to change species was another concern: "The industry that is in the country at the moment is based on Sitka spruce…if somebody is thinking of changing species they should put a lot of consideration into it."

Users who had experience using eucalyptus and poplar were mainly negative about their use due to problems with drying and sawing processes. On eucalyptus concerns about the bark were also identified:

> Although the quick yield was great and the timber quality was good, we had huge problems with the bark of the tree. This created a lot of problems in our production process as it blocked chutes and conveyors and wrapped itself around pulleys which stopped conveyors.

In spite of this, they agreed SRF had potential once the appropriate management, drying and sawing techniques are clear.

Participants affirmed they would need more information about SRF in order to consider using it and highlighted the importance of clarifying uncertainties about SRF for market development to proceed. Interest was expressed in more information on:

- Financial return and market for SRF, 13 interviewees
- Combustion properties such as calorific value, chemical composition and boiler reaction, 9 interviewees
- Moisture content and how long it takes to dry, 4 interviewees
- Wood properties e.g. straightness, 4 interviewees
- Availability, 4 interviewees

2.3.3 Raw material: quantity, suppliers, distance

The range of raw material intake by companies was from 400 to 650,000 t yr^{-1} with a median of 5,000 t yr^{-1} (Table 2.2).

Table 2.2. Annual raw material intake and price paid relative to specification.

	Annual raw material intake (tonnes[a])			Price paid relative to specification (€ t^{-1} softwood at mill gate)		
Sub-sector	Min	Max	Median	Min	Max	Mean
Firewood	170	5500	1852	34 (55[b])	42 (85[b])	40 (52[b])
Woodchip	600	50000	9012	34	42	39
Pallet and fencing	35000	150000	114167	40	65	52
General sawmill	100000	350000	216667	70	96	84
Bark	20000	20000	20000	23	23	23
Cut to order	3000	5500	4250	100	130 [b]	108
Power plant	500000	500000	500000	-	-	-
Panel boards	500000	650000	575000	-	-	-

[a] *Assumed conversion between cubic metres and tonnes was 1* m^3 *= 1 t*

[b] *Hardwood price*

Interviewed companies purchased raw material from a variety of sources: Coillte, forest management companies, sawmills and private forest owners. Just 20% of companies relied on one source only. Half of interviewed companies purchased material from 2 sources and 30% purchased from three sources. Coillte (the Irish semi-state forestry company) supplied raw material to 18 of the 30 companies, but only 2 companies relied solely on Coillte. There were 4 companies that purchased from sawmills only, but a further 4 companies bought from sawmills in addition to Coillte, forest management companies or private forest owners. Forest management companies entirely supplied 6 companies and partially supplied a further 14 companies. Only one company purchased all raw material from private forest owners but another 9 companies were partly supplied by private forest owners.

However, the amount of raw material sourced directly from private forest owners was very limited. Interviewees reported that they preferred dealing with forestry companies than directly with forest owners:

> …it's hard to deal with farmers and get a good rate and then in the long run it nearly costs you more by the time you have the guys in and the licence got, it just takes too long so it's easier for someone else than for ourselves.

Furthermore, if interviewees dealt directly with forest owners, they had to organise the transport. They were also negative about buying from private forest owners due to the small properties, observing that a lot of work was required for a small amount of raw material.

> They (private landowners) are very nervous and demanding… it's more work for me and if I am dealing with the landowner I might have 10 ha, and then that's a lot of work for 10 ha, if I am dealing with a forestry company is the same amount of work for maybe 200 ha.

Most of the interviewees sourced their raw material from anywhere in Ireland. Mainly sawmills imported some of the material because of the short supply in Ireland (Table 2.3). Some of the woodchip and firewood suppliers tried to only buy locally (50 km maximum) to save transport costs, but they were finding this difficult:

> Normally within an hour of the yard, 40-50 km of where it has to be processed, it should be the maximum, it should be moving biomass, but the way it is happening at the moment, there is very few outlets for the product… the market at the moment for pulp is small, it is big for board mills but take

the price…they use a lot of pulp from the South of the country going to the North at the moment, you talking about 150 miles…

Table 2.3. Source of raw material by distance and by sector.

Sector	Anywhere in Ireland	Anywhere in Ireland and imported	Locally (<50km)
Wood energy	10	2	5
Sawmill	5	7	1
Fibre	2	0	0

2.3.4 Requirements of raw material: dimensions, species and others

Table 2.4 summarises roundwood dimensions required by each sub-sector, where the specifications include the minimum, maximum and median allowed dimensions. The most common assortments in Ireland are: sawlog from lower section of the stem, usually with a small end diameter down to 20 cm; small sawlog, from the stem mid-section, usually 20 cm large end diameter and down to 14 cm; pulp, from the stem top section, usually with a minimum diameter of 7 cm; and residues are the top, below 7cm diameter, and the branches.

Table 2.4. Roundwood assortment dimension requirements by sub-sector.

Sub- sector	Length (m)	Top diameter (cm)	Bottom diameter (cm)	Assortment
Firewood	1.8- 6.7 (3.0)	5.0- 25.0 (8.0)	20.0-100.0 (45.5)	Pulp
Woodchip	3.0- 4.9 (3.0)	7.0- 14.0 (9.0)	40.0-100 (62.5)	Residues & Pulp
Panel Board	3.0- 3.0 (3.0)	7.0- 7.0 (7.0)	35.0-50.0 (42.5)	Pulp
Pallet	2.4- 7.7 (3.1)	13.0- 18.0 (14.0)	30.0- 120.0 (40)	Small sawlog
Fencing	1.6- 3.8 (3.0)	7.0- 16.0 (13.0)	16.0- 40.0 (23.0)	Pulp & small sawlog
General sawmill	2.5- 7.3 (4.9)	14.0-16.0 (15.0)	35.0- 150.0 (57.5)	Sawlog & small sawlog

Regarding species, the Irish wood industry is softwood based (58% of the participants use softwood only). The predominant Sitka spruce (*Picea sitchensis*

(Bong.) Carr.) was the industries preferred species (60 to 100% of the total raw material intake) because of availability, price and wood properties:

> Alternative species are probably not there for us…now we get a bit lodgepole…is very bad timber species, it breaks when you are peeling…the product you are dealing with is still a low value product (round posts for fencing) so, if we are going to hardwood they (customers) wouldn't pay to do it.

Another 27% used mainly softwood but occasionally some hardwood. They also confirmed that they used mainly Sitka spruce. Other softwoods used were Norway spruce (*Picea abies* (L.) H.Karst.), larch (*Larix* spp.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), lodgepole pine (*Pinus contorta* Dougl. ex Loud).

Just 15% of the companies, all from the firewood sector, use mainly hardwood: "The hardwood is much better: it burns twice as long but you pay more".

Hardwood species used were quoted as being: ash (*Fraxinus excelsior* L.), beech (*Fagus sylvatica* L.), oak (*Quercus robur* L. & *Quercus petraea* (Mattuschka) Lieblein), alder (*Alnus glutinosa* (L.) Gaertn.) and birch (*Betula* spp).

Another set of requirements emphasised were

- Straightness (10 interviewees)
- Appearance (e.g. colour, smell) (6 interviewees),
- Moisture content and the time wood required for seasoning (5 interviewees),
- Cleanliness from branches (5 interviewees)
- Sufficient supply volume (4 interviewees)
- Combustion characteristics (calorific value, chemical composition, dry matter and ash) (3 interviewees)

2.3.5 Purchase: price, point of purchase, units

The prices paid by the surveyed companies varied from €20 to €80 m^{-3} roadside (€34 to €96 at mill gate), with prices aligned with roundwood piece size but not quality. Companies reported prices in tonnes and cubic metres interchangeably. The cheapest raw material was bark (€23 m^{-3} delivered in, i.e. at mill gate) and the most expensive was timber from old and big size hardwoods used in specialist mills that saw to order (€130 m^{-3} delivered in). There was no data collected from power plants and panel boards due to confidentiality (Table 2.2).

Most prices were given delivered-in (17 out of 23 responses). Some interviewees gave a haulage rate, averaging €15 t^{-1}, and ranging from €5 t^{-1} to €30 t^{-1}, with prices aligned with distance (€30 approximately 250 km). It was also common to buy roadside (6 out of 23 responses), but standing sales were unusual (no responses).

Prices were mostly given in weight units (tonnes) by the private sector and in volume (cubic metres) by the state company. Furthermore, 30% of the interviewees did not use the metric system when describing dimensions. It was very common for lengths and diameters to be reported in feet and inches.

2.3.6 Balance supply-demand: currently and in the future

Interviewees, by market sub-sector, had different perceptions on availability of, and demand for, raw material. Demand for woodchip and bark for horticulture was reported to be increasing, so more material was requested by this sector. The woodchip for energy sub-sector has the opposite opinion: demand for woodfuel had not developed in recent years, but the raw material supply is readily available, and increasing:

> Getting timber is fine, there is no problem with it, getting rid of it is the problem. It is fine for us because we have our customers already,...there is no order, there is no more development going on, the grants are gone which is a killer, ...we are waiting for, there is talks about bringing the tariff from England over to here.

The latter companies pointed out the necessity of grants, such as the Renewable Heat Incentive in the UK, to develop the woodfuel sector and they highlighted the price of oil as the key determinant for this sector's future. Firewood participants viewed the supply-demand as being in balance at the moment. However, some of the sawmills expressed strongly that there was lack of timber in the country at the moment: "…now every sawmill in Ireland is fighting over the raw material. There is more capacity in this country than there are logs…", while others thought there is balance between supply and demand at the moment.

There were different opinions between and within sectors regarding the availability of raw material in the coming years. Some of those surveyed thought there would be enough wood resources: "…there will be, there was a lot planted 20 years ago,…it's flying in, it's coming on." Other opined that there would be lack of supply as demand was going to increase: "If the business happens the way it is supposed to happen there will not be enough timber, there isn't enough planted".

2.3.7 Potential market for SRF in Ireland

A basic analysis of the survey results indicated that the thirty companies had a combined annual raw material requirement of 3,126,120 m^3, or 98% of the Irish total annual demand of 3.2 Mm^3.

Of the surveyed wood energy companies and sawmills that confirmed that SRF material could potentially be used, the sawmills required 52,500 m^3 of small sawlog, 3.1 m in length and 13-120 cm diameter, purchased at mill-gate on average at €52 m^{-3}. The wood energy companies had a total annual requirement of 512,120 m^3. However, this value was dominated by a single large power station, and included approximately 50% imported non-woody biomass and an amount of indigenous biomass, such as Miscanthus and forest residues, amounting to an estimated 300,000 m^3. The remaining 212,120 m^3 could be characterised as pulp logs, typically 3 m in length, 5-100 cm diameter, with an average mill-gate price of €40 m^{-3}. In all cases except the large power station, these companies sourced material only within Ireland and 2 companies preferred local supply.

2.4 Discussion

Currently, the cellulose and veneer industries that use SRF wood internationally are absent from the forestry sector in Ireland. However, the current wood industry in Ireland (panel boards mills, wood energy sector and perhaps the sawmills) have the potential to use SRF as these same sectors use short rotation species such as poplar and eucalyptus internationally. This survey confirms that SRF is considered an acceptable raw material by the majority of the wood energy sector and some sawmills. The international experience (Sepliarsky 2007) suggests that additional wood industry sectors will include SRF in their raw material mix as it becomes increasingly available.

While the negative views expressed towards SRF by some industry sectors may be partially attributed to attachment to Sitka spruce, there were valid technical issues raised on the difficulties of sawing, drying and debarking of SRF species. Also, the reason participants were not familiar with SRF might be partly due to lack of awareness of this terminology (Silver, et al. 2015). Also in literature, there are different definitions for SRF (Christersson and Verma 2006, McKay 2011) and these plantations are often treated as fast growing species harvested every 8-20 years. Confusingly, SRF is often applied by authors to short rotation coppice systems (Pannacci *et al*. 2009, Tullus *et al.* 2013)

Although potential SRF users prefer local supply to reduce transport cost, most took material from anywhere in Ireland, so the location of SRF plantations should not be limited to areas adjacent to particular end users. On the other hand, the transport cost and value of SRF will determine maximum viable distance to market. The SRF products identified as suitable by this survey are pulp and small sawlog and these assortments are lower in value compared to large sawlog, so shorter haulage distances may be more economic.

These assortments are also smaller in average dimensions, indicating a smaller mean tree volume compared to current norms. This suggests short rotation length, higher tree stocking rates or a mix of both could be used to affect target tree volume. However, the tendency of wood-using companies to be involved in more than one sector will require SRF growers to ensure production suitability for diverse markets, rather than targeting a single end use. Furthermore, wood property requirements indicated by sawmills, such as straightness and small knot size, would need to be investigated in SRF wood.

A further point of concern for SRF growers was the clear preference SRF potential users expressed for purchasing raw material from Coillte and private forestry companies rather than small forest owners. This suggests that growers should organise themselves and join a producer group co-operative or sell through a forest management company.

There were diverse opinions about availability and demand of wood resources. While the sawmills agree with the forecast of a shortfall of resources (COFORD 2015), the wood energy sector, and particularly the woodchip suppliers have the opposite opinion and state that demand would only increase with grant support. Ultimately, this represents industry feedback to policy makers that current energy policy has defined renewable energy targets for wood biomass but has not put in place the supports to ensure that these targets are met.

As shortfall of wood in Ireland was the main reason given by sawmills of importing sawlog, even if native material was preferred, SRF could be a real option if supply, quality and processing concerns were addressed. As also found in similar studies, availability of SRF and information on properties are prerequisites for market development (Nicholas and Garner, 2007).

Regarding quantity of raw material intake, market expansion will depend on the larger potential users (Venn and Whittaker 2003). However, this expansion is difficult as it incurs a significant risk (Perkins, et al. 2005) and smaller wood energy companies may first establish the market. In that case, development of SRF may depend on grants for the establishment of firewood and woodchip boilers or fixed rate tariffs on energy prices.

This study had several limitations including the relatively small sample due to the qualitative approach and the heterogeneous data responses from market sectors, scale of production, measurement units for payment, and species used. Results should be interpreted with caution and more research in this field is encouraged.

Companies interchangeably used price in tonnes and cubic metres, and these two different measurement units are perceived as being equivalent. This equivalence is only rarely accurate due to variation in basic density and in particular, moisture content. Currently, these companies pay depending on the raw material source: weight for the private forest sector and volume for Coillte. This interchangeable use of volume and weight units, in addition to using non-metric units to describe dimensions, promotes ambiguity and a lack of transparency in trade. Particularly, as raw material is being supplied increasingly from sources other than Coillte, there may be a need in the wood processing industry to articulate more precisely their raw material needs.

The survey captured a point sample of roundwood prices for the surveyed market sectors. These prices are indicative only as there is no SRF material supply yet and wood prices vary throughout the year. However, this data gives a reference of how much potential users of SRF are willing to pay, so sets a ceiling on the price SRF material should meet to compete in the market. Knowledge of this price paying potential is a necessary input to evaluate the economic sustainability of SRF in Ireland.

2.5 Conclusions

Nine of the companies (30%) indicated that SRF material would be a suitable raw material, and they had an annual roundwood requirement of 264,620 m^3 each year. The wood energy sector was the most favourable toward SRF and the other sectors agreed the main use of SRF would be energy. Two sawmills indicated that SRF could also be suitable for pallet manufacture.

Other companies had reservations against SRF, including preference for conventionally produced Sitka spruce, poor drying characteristics and other doubts about the wood properties of SRF species and the large volume required for the biggest companies in order to make the production effective. The technical capacity of these wood market sectors to use SRF in production should also be investigated.

Seventy percent of the interviewed companies identified need for SRF research and education. Evidence of the potential production scale of SRF species in Ireland, in addition to information on wood properties and fuel parameters, and suitability to different markets is needed to inform potential users on the suitability of SRF for their market sector. Current research, under the SHORTFOR project, may provide some of the required information but further research, development and dissemination actions will be required.

As evidence of this, only 20% of the companies were aware of the Forestry for Fibre grant premium category described in the Afforestation Grant Scheme, supporting SRF afforestation. However, this study confirms there is a potential market for SRF material grown under the scheme. The mixed views on wood biomass supply and demand gap represent a challenge to policy makers. In particular, wood energy producers' insistence that there was raw material oversupply and insufficient market development of renewable energy from biomass suggests that policy targets on renewables may not be met without support measures to stimulate the investment in wood energy.

Chapter 3: A comparison of market opportunities for Short Rotation Forestry in Ireland and Oregon

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Chapter 3: A comparison of market opportunities for Short Rotation Forestry in Ireland and Oregon

Abstract

Short Rotation Forestry (SRF) is the practice of cultivating fast-growing tree species mainly for the production of biomass. In Ireland, SRF rotation lengths are less than 20 years. SRF forest cover is expected to increase in response to the increasing demand for fibre products and renewable energy targets set by the European Union. Although Irish policy supports the establishment of SRF, prior research identified Irish forest industry concerns over the market opportunities for SRF, which may limit its establishment. A SRF market was successfully established in Oregon, U.S., mainly based on hybrid poplar (*Populus* spp.). A survey was carried out there and its results were supplemented by US-based literature. The objective was to benchmark conditions that facilitated market development in Oregon with current conditions in Ireland, to identify and describe gaps and opportunities that can be applied for growers and potential users of SRF in Ireland.

The key success factors in growing and marketing SRF in Oregon were large-scale plantations, local supply chains, consistency of supply, FSC certification and the targeting of high value products. Small scale plantations and low value product systems were unsuccessful in Oregon. However, liquid biofuels and payment for ecosystem services are new opportunities currently in development. These options could also be applied in Ireland to motivate SRF development and improve the sustainability of these plantations.

3.1 Introduction

3.1.1 Historical development of hybrid poplar in Oregon

In 1893 the first poplar plantation was established in the Pacific Northwest (PNW) (Bourque *et al.*, 2014). The potential of combining western black cottonwood (*Populus trichocarpa* Torrey & A. Gray), a native poplar in the PNW, and eastern cottonwood (*Populus deltoides* W. Bartram ex Marshall) was realised by tree breeders in this region in the early 1970s (Carlson and Berger, 1998). Located in the PNW, where many Irish forest species originated, Oregon State invested significantly in research and commercialisation, so that new markets were developed in hybrid poplar production and processing. Hybrid poplar was first used as a fuel (Hansen *et al.*, 1983) and then planted to meet the forecasted shortage in pulp for the paper industry (Figure 3.1). Initial stocking of 1500 trees per ha could produce 62 to 100 odt ha^{-1} of clean chips and additionally from 22 to 33 odt ha^{-1} of residue biomass on a 7 to 10 year rotation (Stanton *et al.*, 2002).

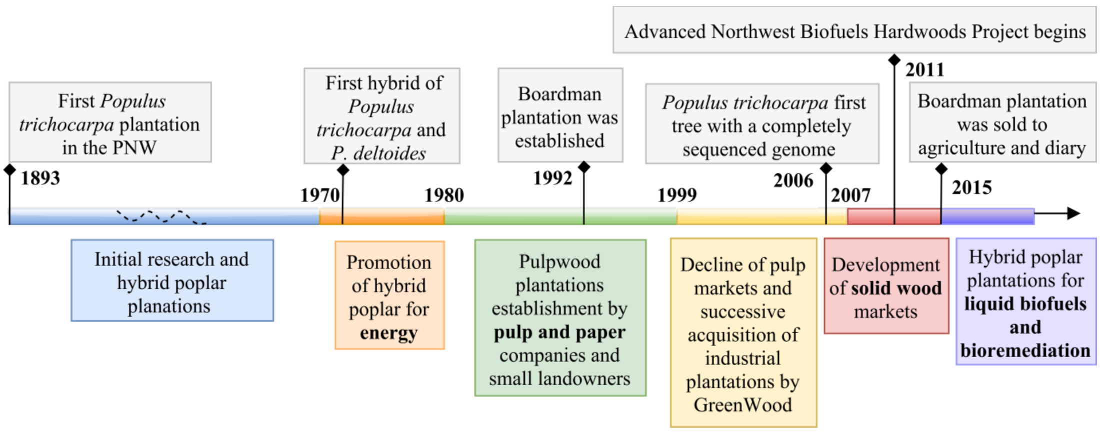


Figure 3.1. Timeline describing the use of hybrid poplar in SRF systems in the Pacific Northwest.

Farmers established hybrid poplar plantations motivated by the potential profits indicated by research and supported by the paper mill markets. Although there were no specific grants for afforestation with hybrid poplar, some landowners could avail of cost sharing funds from the Agricultural Stabilization and Conservation Service if rotations were over 10 years (Heilman *et al.*, 1990) in order to enhance the environmental benefits resulting from a longer rotation. Small landowners' plantations ranged from a few hectares up to 100 ha (Figure 3.2.).

Figure 3.2. Whole-tree harvesting of a 12-year-old 60 ha hybrid poplar plantation belonging to a small landowner in the Willamette Valley, Oregon in 2004. (Photography credit Don Wirth).

Also in the eighties and nineties, 5 pulp and paper mills established significant poplar plantations (a minimum of 3,000 ha each) with the aim of supplying material for their own production (Bourque *et al.*, 2014). In 2002 it was estimated that there was over 20,000 ha of hybrid poplar in the PNW (Stanton et al. 2002). However, markets did not develop as the forecasts had predicted. The decline of the paper industry and low pulp prices forced the closure of plants and the sale of plantations resulting in a reorganisation of the ownership structure.

3.1.2 Boardman plantation

An example of the industrial development of hybrid poplar SRF in Oregon is the poplar plantation in the Boardman region of eastern Oregon. Although this is a very dry area, the land has water rights from the Columbia River so the poplar plantation was irrigated. Established in 1992 for the pulp and paper mill, this 7,000 ha plantation and on-site chip mill were acquired in 2007, by GreenWood Resources, a timber investment and asset management company, with the aim of finding new markets for higher-value products from hybrid poplar (Rinaldi, 2015). GreenWood invested in research and innovation on silvicultural practices and clonal material to improve productivity and disease resistance (Stanton 2005, Stanton 2011) and to develop expertise in hybrid poplar management.

In 2008 a sawmill was built in the middle of the plantation (Figure 3.3) while in 2013 a veneer mill to manufacture plywood was established next to the sawmill. Products such as wine boxes, ceilings, pencils, and interior frames for furniture were made from boards produced from the sawlogs. The plywood was used mainly to produce cabinets. The residues were used for pulp for the paper industry and for energy. The poplar plantation increased to over 10,000 ha through subsequent acquisitions (Rinaldi 2015). However, in 2015 the plantation was sold and is now in the process of being converted to agriculture. GreenWood still owns another 2,000 ha of poplar in west Oregon that is mainly used for pulp, paper and veneer production.

Figure 3.3. Boardman poplar plantation and sawmill. Oregon, August 2016.

3.1.3 New opportunities for SRF in Oregon

The $40 million Advanced Hardwoods Biofuels project run from 2011 to 2019 (AHB, 2019), funded by the U.S. Department of Agriculture, investigated how to develop a renewable transportation fuels industry by growing and converting hybrid poplars into liquid biofuels. Poplar for biofuel use is grown in a coppice system on a three year rotation (Figure 3.4).

Poplar is a suitable feedstock for energy generation due to: 1) its ability to coppice and accumulate biomass quickly, 2) its suitability to grow strongly on marginal lands and 3) wood composition is adequate for the energy conversion process (Budsberg *et al.*, 2016). However, low fossil fuel prices and lack of economic incentives for renewables make the viability of biofuels a challenge. Furthermore, poplar plantations will need to be of sufficient scale to fuel biorefineries all year round and be located near the refineries to reduce transport cost. The production of plant derived biochemicals (such as paints, plastics, packaging, and cosmetics) is being investigated as a way to improve financial viability (Crawford *et al.*, 2016).

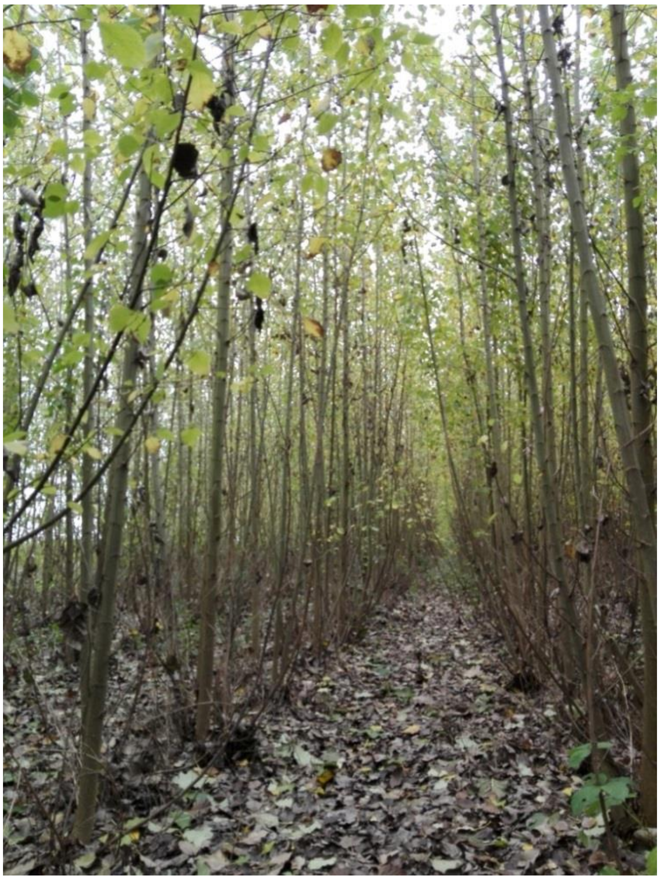


Figure 3.4. A three-year old second rotation hybrid poplar coppice plantation, ready for harvesting, chipping and converting in liquid biofuel for energy generation in Jefferson, Oregon. October 2016.

Another option for poplar being explored in Oregon is the payment to forest owners for the provision of ecosystem services such as carbon storage or remediation of pollution (Figure 3.5). There is increasing interest and approximately 5,000 ha of poplar plantations are grown primarily for environmental services in the PNW, although still only 2% of municipalities have applied this system (Gustafson, 2016).

Figure 3.5. Hybrid poplar at the Biocycle Tree Farm in Eugene, Oregon. This plantation recycles wastewater treatment by-product from two cities, Eugene and Springfield. Trees are harvested every 10 years with a view to generate revenue to balance against operating expenses. Back: 8 years old stand. Front: stand replanted a few months before the photo was taken, October 2016. (Photo credit Rick Zenn).

In addition, hybrid poplar wood has been tested for engineered wood product manufacture such as Cross Laminated Timber (CLT). While initial tests indicated it met strength requirements, it did not pass stiffness specifications. Mixing poplar wood with higher density species had the potential to improve stiffness results (Kramer *et al.*, 2014).

An exploration of the market opportunities for SRF in Ireland was carried out by de Miguel et al. (2016). This study aims to benchmark the conditions in Ireland identified by that publication with those that facilitated market development in Oregon. Benchmarking design and analysis involves identification of good practice cases, rigorous study of one's own practices (e.g. using site visits and interviews), and development of recommendations for potential implementation (Garvin, 1993; Hothorn *et al.,* 2005). This methodology has been applied in various forestry sectors, such as for the development of clone propagation methods (Pilbeam, 2004), forest certification (KCBS, 2006), forest biodiversity (European Commission 2011) and the wood products industry (Mitchell, 2012).

The main objectives of this study are 1) to identify the conditions in place in Oregon that facilitated the successful implementation of SRF and 2) to identify gaps between Irish and Oregon conditions that may deter development of SRF in Ireland, and to suggest ways to address such issues. Previous work revealed the Irish wood energy sector and pallet industry may be favourable towards using SRF, but other market sectors were negative about SRF citing doubts about wood properties and lack of sufficient supply of raw material (de Miguel et al. 2016). That survey identified the need to provide the industry with the following information: wood properties of SRF-grown species; suitability as a wood fuel; the current afforestation grant supports for SRF. This survey of the Oregon SRF sector aimed to reveal perceptions on the suitability of SRF material for different products in Oregon and to discover the drivers that initially gave industry confidence to use SRF systems. The survey aimed to investigate the availability and importance of information on the characteristics of the raw material. The scale of annual raw material production required in Oregon, and balancing of supply and demand, will be described, as this was considered an important prerequisite by the Irish processing sector in potentially using SRF material.

3.2 Methods and Materials

Benchmarking analysis was the process used to understand and learn from good practice case studies of SRF hybrid poplar production in Oregon. A survey of the hybrid poplar industry chain in Oregon was completed by semi structured interviews of industry stakeholders, following the same methodology described in de Miguel *et* *al*. (2016). Fourteen interviews were carried out between August and October 2016 in Oregon. The sample was chosen mainly by the snowball technique; whereby new survey participants were nominated by some interviewees. As the target was to compare the survey results to those previously described for current Irish conditions, purposive sampling was followed; so markets not currently in Ireland, such as pulp and paper mills were ignored. Seven users of SRF-grown material in Oregon, made up of primary and secondary wood processors, were identified and interviewed. To develop a comprehensive understanding of the case study, it was necessary to capture perspectives of people from different points of view so poplar growers were also interviewed. These other interviewees were two small forest landowners, two university extension officers advising hybrid poplar growers, and three managers of larger scale plantations (Table 3.1 and Figure 3.6).

Table 3.1. Numbers of survey participants and their categories.

Target group	**Sector**	**Number of participants**	**Type of interview**
SRF users	Primary wood processors (sawmill and chips mills, veneer mill and biomass power plant)	**3**	Face-to-face
	Secondary wood processors (sawlog users, plywood and briquettes)	**4**	Face-to-face (2) Phone (1) Email (1)
SRF growers	Managers	**3**	Face-to-face
	Small landowners	**2**	Face-to-face
	Extension agents	**2**	Face-to-face

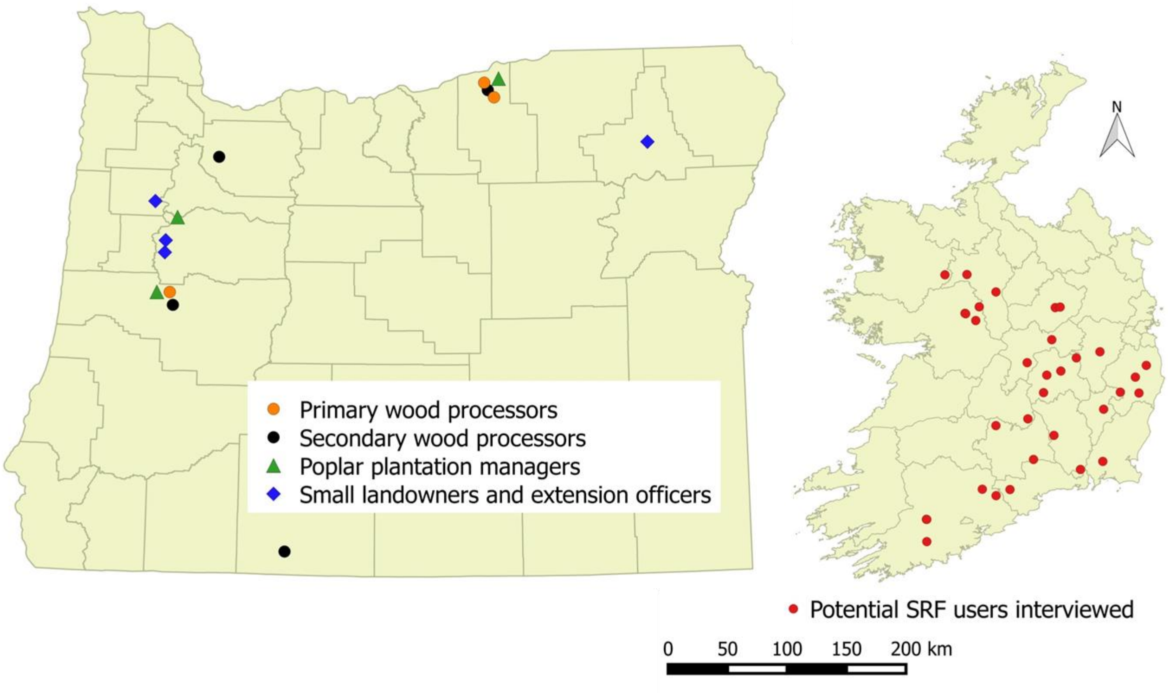


Figure 3.6. A scaled comparison between Oregon (left) and Ireland (right) showing the locations of participants in the survey. Oregon has a land area of 25.5 million ha and 48% forest cover whereas the Republic of Ireland covers an area of 7 million ha and forest cover 11%.

The triangulation method, meaning validation of the survey responses from other sources, was used to verify the data collected in the interviews (Patton 1999, Carter *et al.* 2014). Three researchers involved in hybrid poplar development in Oregon confirmed the information supplied by the interviewees, filled in gaps and provided additional background information. Also, relevant literature including harvest reports, market survey reports, marketing materials, and sawmill technology information, were reviewed and included in the analysis. Consistency in general patterns was expected. However, when there were contrasting findings from different sources, reasonable explanations were given and in this way they contributed to the overall credibility of the results (Patton 1999). Another difference to the study in Ireland was that survey results focused on qualitative analysis only as the objective was to identify conditions that facilitated SRF development. Questions focused on perceptions of using hybrid poplar in SRF, specifications of raw material, supply-demand balance, and source of the raw material. Interviews were transcribed and the software N-Vivo (QRS International Pty Ltd., Australia) a qualitative data management tool, was used to analyse them.

Results from the Oregon study were compared to results from a similar survey carried out previously in Ireland (de Miguel *et al.* 2016). This comparison was carried out using the benchmarking potential analysis methodology (Garvin 1993) that involves the identification of good practice cases and the development of recommendations for potential implementation. Oregon good practices and strategies for success were identified and recommendations for gaps and weaknesses recognised in the Irish survey were developed.

3.3 Results

The number of interviews was smaller than for the survey in Ireland, but more homogeneous since all interviewees were directly involved in the SRF hybrid poplar sector.

3.3.1 Perceptions of Short Rotation Forestry in Oregon

Although nowadays hybrid poplar and its wood properties are well-known in Oregon, there was an initial lack of knowledge within the industry prior to using it. Information needs were satisfied by university research and extension, and companies carrying out their own research and testing. Wood processors confirmed that this information was an important factor in enhancing confidence to use SRF hybrid poplar: "We knew it was difficult to machine but I guess it was [required] a lot of testing and trial and error"; "…marketing materials that talked about the properties of the wood, so that you could compare to other species; ultimately you just have to try it. You just have to run it and see how it does."

Specifically, it was important to compare poplar wood property values with those of the most common species used at the time and to define expected poplar grades.

> …this [wood properties information] was very important early on when we were introducing the species to the customers; they said what are they like? What are the properties? Compared to pine, compared to alder? So this was really useful early on.

In addition to the lack of knowledge on wood properties, hybrid poplar suffered from a bad reputation in the forest industry, which was another barrier to its introduction. Industry had preference for other species or specifically preferred not to use poplar. Initially, the majority of the sawn board production was exported to Asia but subsequently it was accepted in the PNW and markets were developed locally.

Hybrid poplar wood became a competitive commercial species in the PNW and there was potential to increase plantation area. One of the marketing strategies was to rebrand poplar wood as Pacific Albus to eliminate negative perceptions about poplar and cottonwood (Figure 3.7).

> Pacific Albus grows only in that plantation in Boardman....since the plantation closed, we are looking at other sources of poplar in other parts of the world…but it would not be Pacific Albus, it would be some other types of poplar.

Figure 3.7. SRF hybrid poplar is promoted as Pacific Albus wood, here showing different board grades.

Regarding willingness to use SRF, all the companies interviewed would like to continue using poplar. Users of poplar from the plantation in Boardman were very disappointed that their log supply would cease as they saw many advantages on using hybrid poplar: "there were many, many positives for us; it is very disappointing that it is going away…I was sorry to see it go"; "We have loved Pacific Albus for our market. We will really miss it!" Managers at Greenwood confirmed the strong demand from processors, and expressed disappointment that the plantation was being sold for conversion to agriculture.

However, small forest landowners were not willing to establish hybrid poplar. Although hybrid poplar for liquid biofuels is currently being promoted, they had some concerns to establish new poplar plantations due to previous difficulties in marketing poplar to end-users.

> Now cottonwood [hybrid poplar] has come back in the last few years: the excitement has been for biofuels...they have been asking us and they haven't been getting a lot of enthusiasm from us.

3.3.2 Raw material: quantity, suppliers, distance

The majority of the hybrid poplar raw material sold in Oregon came from the Boardman plantation which grew >10,000 ha of SRF. However, a third of the plantation had already been harvested at the end of 2016 and the land was converted to agriculture. The amount of hybrid poplar from this plantation will be significantly lower in the coming years until the SRF plantations have been completely cleared. In future harvested roundwood will only be used to produce veneer, as the sawmill has already been closed. Although there is an obvious gap in supply, owners of smaller scale plantations think they will still have difficulties in marketing hybrid poplar timber. The reasons provided seem to be the small volumes individual forest owners can produce and the long distance to supply to markets, particularly for low value products.

> [The veneer mill] was happy. They took the poplar and made some plywood sheets out of it.....later on he [the veneer mill] said: you know, we buy so much volume that this is actually more hassle…then I realised we were pretty small fish in a big pond here in terms of wood products."

Companies confirmed they did not like dealing with small landowners as they needed consistency in supply.

> We need a lot of quantity, that's why we like the Boardman plantation because it was a large plantation with specific quality. We are not interested in buying a few poplar here and there, because the quality varies a lot with location; so we try to work with large plantations as they can supply us quite a bit of wood on a regular basis for the long term.

3.3.3 Requirements of raw material

Supply consistency seems to be an essential requirement for SRF users. Boardman material users highlighted the advantages of a secure supply and also the uniformity of the material as it came from the same plantation: "In general for people who want to use poplar they like large plantations because they want the consistency of the supply but also the quality”.

Price was another characteristic that made hybrid poplar attractive: “…very economical price-wise…stains well to look like other premium hardwoods, looks like solid maple, but a lot less money.”

The particular appearance of hybrid poplar wood, light colour and weight were also considered advantages for sawn timber products: “The nice thing about hybrid poplar is a very light colour, so if you start with a light colour you can make every colour, if you have alder, walnut, you can't make it lighter”; “One of the nice things of Pacific Albus is the light weight…most of the time what happens is it gets used internally in a product, with the exception of the wine boxes, but our customers like the look.”

Among the other advantages of using hybrid poplar from the Boardman plantation was its FSC (Forest Stewardship Council) certification status, a particularly appreciated aspect in the marketplace.

> …even though it was a lower quality wood, the fact that it was certified helped it to be accepted by some of our customers. We are looking now at some certified woods to replace Pacific Albus because there is a need for it.

Other plantations also confirmed certification was required for them to market SRF poplar for sawn timber or veneer: “If we can grow the stuff and meet their expectations, and we are FSC certified, without that there really doesn’t seem to be anything doing...”

On the other hand, there were some challenges regarding wood properties of hybrid poplar, partly because of the change of market, from pulp production to the sawn-board market. For instance, clones with higher yield for pulp production presented problems with straightness for sawn timber or with distortion during the drying process. Industry solved these problems by adapting their production technology and processes to these particular wood characteristics.

> We said ok you got a curvy tree, we solved by using curved log scanning technology… if you trying to follow the log curvature you are going to reduce your slope and grain, you are going to have a better quality piece of lumber, better recovery...the long term was to try to grow the tree straight

Secondary producers also found some challenges at first working with poplar wood including: the roughness of the finished products; learning how to stain it; and the type of fasteners to use; but again they adapted to poplar wood properties.

> The biggest problem was the poplar makes a fuzzy, a very rough surface, so it requires different tooling, more steps, sometimes sanding maybe. We had to assume that we were able to make it work, but definitely that was challenging. A bit more difficult to work than other woods.

Hybrid poplar wood fuel was used in biomass power plants and sawmill residues were also used to produce briquettes. Some challenges identified for using hybrid poplar as a wood fuel were moisture content, contamination due to leaf content and inability to meet the prices achieved in other poplar wood markets such as the pulp and paper.

> …it is worth about twice as much in the form of chips [for pulp and paper] as what we can pay bringing in to burn in our facility. Poplar has a relatively high moisture content and that is a problem when it comes to renewable cogeneration power…if we could get the whole tree yes, but my concern would be that it would be a very expensive fuel for us at that time...if they couldn't sell it to the pulp mills then yeah.

3.3.4 Balance of supply and demand

Regarding raw material for pulp and paper, contrary to the forecasts, production in this sector decreased as demand for paper declined so there was no longer a raw material shortage and pulp prices reduced. In addition, not as many landowners as expected planted hybrid poplar. Those that did had difficulties in selling the timber and in some cases they have not harvested or have harvested at a loss just to convert the land to agriculture.

> What got me into it was we live in a world of poplar here. I just thought there was going to be a shortage of pulp and there is fewer mills than there was...I ended up with those of them that didn't sell so I had 40 acres that I burned.
> There is a couple of growers in the region who had some history of it and at some point they said I am getting out and there is a couple that weren't as involved and left it, like the guy who called me the other day: there is a 30 years old stand, giant, I don't know what he is going do with it.

Before the Boardman plantation was sold in 2015, demand for sawn timber and veneer was increasing and expansion of hybrid poplar growing was required as some businesses were planning to expand.: “I have felt that demand has grown beyond supply, as it relates to the Superior Grade [clearest grade]”; “I would say it was pretty well balanced, but there were times, some times when we wanted some of the higher grade material and we couldn't get it.”

After the large Boardman plantation was sold there was a gap in supply and users have concerns about how to replace the poplar wood that has been the mainstay of some of their products and that they were basing expansion around. They had to look for other species to replace poplar as there was not enough poplar in Oregon to replace the amount that was produced by Boardman: “We are looking into different species: finding poplar is very difficult”; “Yes, a big concern. We need to find a replacement for Pacific Albus now. We are not sure what we will do.”

3.3.5 Potential markets

Liquid biofuels, payment for ecosystem services such as carbon and bio-remediation, and engineered products such as CLT are options currently being explored for poplar plantations. However, managers and landowners think these potential markets will still take some years to develop, so they need to find some replacement markets until then: “Being optimistic but also being realistic, probably 20 years down the road the stuff becomes biofuel feedstock. We need to create some markets in between and build up the amount of poplar that is being grown.”

The variability in the price of crude oil plays an important role in the viability of biofuel refinement from biomass.

> Back in 2011 oil was up over $100 a barrel and at that point making fuels from feedstock was pretty economically viable, but since then the price of oil has dropped down to about $40 a barrel, which makes it very difficult to compete with making fuels and chemicals from biomass sources.

3.3.6 Benchmarking potential analysis

Results described above were compared to the results from the previous survey in Ireland. The parameters evaluated were land use classification of SRF, availability of grants, availability of information e.g. wood properties, initial level of knowledge about SRF, reputation, willingness to use, past experiences, quantity of raw material, industry preferred source of raw material, distance of supply, requirements of raw material and potential markets identified (Table 3.2). The same requirements that had been recognised in the survey in Ireland (e.g. supply consistency) were then evaluated in relation to poplar in Oregon.

Table 3.2. Benchmarking potential analysis of SRF in Ireland compared to Oregon where SRF plantations and markets were established and well developed.

Parameters	Ireland	Oregon	Key factors for development of SRF in Oregon
SRF land use	Forestry	Agriculture (maximum of 12 years rotation)	Although no funding available, reduced risk as it was possible to revert to agriculture
SRF grants	Forestry for fibre afforestation grants	No afforestation grants specifically for SRF	
Information availability	70% identified gaps and needs	No information initially, now available	University and/or industry research and knowledge transfer through extension foresters
Initial knowledge	76% not familiar with SRF	Not familiar initially, now familiar	Dissemination by sawmill, university and extension
Reputation	Poor	Initially poor, now good	Marketing: renamed as Pacific Albus Proven processing experience and market
Willingness to use	30% favourable	100% of industry favourable, not initially	Research, own testing, marketing, repeat customers
Past negative experiences	*Miscanthus* and SRC willow	Hybrid poplar for pulp and paper	Marketing, testing and extension dissemination
Quantity of raw material	Targeted 3,300 ha from 2014 to 2020 (DAFM, 2014)	Industrial plantations (over 12,000 ha in 2015) plus small plantations	Large scale, 10,000 ha plantation
Industry preferred source of raw material	Not from small landowners	Not from small landowners	Large scale industrial plantation
Distance of supply	Anywhere in Ireland but no more than 50 km for wood fuel	Mills on site, secondary wood processors first in Asia, then in PNW	Locally sourced log supply
Requirements of raw material identified in the Irish survey and evaluated by wood processors in Oregon	▪ Supply consistency	✓ Advantage	Large plantation: volume and uniform quality
	▪ Cheap price	✓Advantage	Low cost and fast growing
	▪ Appearance	✓Advantage: light weight and colour	Find niche markets
	▪ Certification	✓Advantage	Allowed entry to new markets or survival in traditional markets
	▪ Straightness	× Challenge	Investment in suitable cutting technology and straighter clones
	▪ Low moisture content	× Challenge	Investment in moisture testing and drying technology
Potential markets	Solid biofuels and pallets	1980-1999: pulp and paper 2000-2015: solid wood products Future: Liquid biofuels and ecosystem services	Flexibility, adaptability and research (different clones better for specific products)

3.4 Discussion

Differences between Oregon and Ireland in policy issues such as land use classification and the process of change of use category were identified. While 12-year rotation SRF is considered agricultural land in Oregon, it is considered forestry in Ireland and should remain in forestry as specified in the Forestry Act (2014). Most of the small landowners who invested in SRF in Oregon went back to agriculture due to their inability to market the SRF produce. There were no specific grants for SRF in Oregon, unlike SRF afforestation incentives in Ireland. However, in Oregon landowners had the flexibility to try SRF and return land to agriculture after one rotation. The permanency of the requirement of staying in forestry may be one factor that will limit the establishment of SRF in Ireland.

In line with the findings of the Irish survey (de Miguel *et al.* 2016), growers and end-users in Oregon initially required information on SRF, particularly on wood and fuel properties. This appears to be an important gap to fill to start market development. Furthermore, product testing by researchers and industry was also needed in Oregon.

Negative perceptions by industry towards hybrid poplar wood were a barrier to the introduction of SRF for sawn products in Oregon and biases towards using SRF were also identified in Ireland. In Oregon this bias was overcome by the marketing strategy of branding the species with the name Pacific Albus, together with dissemination of wood property information and prepared samples. In Ireland, wood property information and product test samples are at least needed in order to counter industry preconceptions.

Skepticism of SRF viability was expressed by small-scale poplar growers. The promotion of hybrid poplar to fill the forecasted shortage in the pulp market, which did not happen, dampened Oregon growers' interest in the potential new market for poplar for liquid biofuels. Oil prices fluctuations also contributed to increase this reluctance. A similar situation was found in Ireland, where doubts were raised about the viability of SRF due to unsuccessful market development for other energy crops, e.g. elephant grass (*Miscanthus* spp) (Witzel and Finger 2015). Elephant grass. was previously extensively promoted in Ireland with a scheme from 2007 to 2010 providing establishment grants to landowners to produce biomass suitable for use as a renewable source of energy. A proven and consolidated market could be needed to get these growers investing in SRF.

Development of SRF in Oregon was based on a large scale industrial plantation of 10,000 ha. This was a successful model that ended only due to the plantation land being sold for agricultural development (Stanton *et al.*, 2016). Boswell et al. 2008 estimated that approximately 7,000 ha of hybrid poplar would be needed to develop a sustainable model, considering this the minimum volume to get cost effective production as well as to attract the added value processing infrastructure. However, only a total area of 3,300 ha is targeted to be afforested with SRF in the period 2014-2020 under the Irish forestry programme (DAFM, 2014). Similarities in the volume of raw material supply required by the Oregonian and Irish wood processing industries and reluctance to deal with many small suppliers (de Miguel *et al.,* 2016) indicate that large-scale plantations will be needed to develop markets in Ireland. Production scale may be achieved in two ways: 1) the industrial approach followed in Oregon by GreenWood; or 2) by forming effective producer groups of small forest owners with clustered plantations. However, this latter approach was not very successful in Oregon (Stanton *et al.*, 2002), as smaller forest owners could neither guarantee the consistency of supply or quality required by users. Distance from plantation to market was also a crucial issue and particularly when low value products were transported. Both in-situ mills and high-value products were needed for a successful supply chain in Oregon. As low-value products are the main goal for SRF in Ireland, an in-situ end-use or locally available supply would seem to be required.

Similarities were found between Oregonian and Irish companies' preferences for raw material requirements. In addition to security of supply, raw material price and appearance were identified as important to end-users in both surveys. Certification was also a requirement highlighted by the Oregonian sawn-timber industry and is increasingly required in Ireland. The requirement for straight logs for certain products was identified in Ireland. Research, testing and technology adaptability helped to solve these difficulties in Oregon and a similar approach could be adopted in Ireland.

Mixed views regarding the supply-demand balance were found in both cases. While sawmills found difficulties in sourcing their raw material in Oregon and Ireland, woodfuel producers in Ireland and small growers in Oregon found there was more raw material available than demand for it.

Policy requirements in response to environmental issues, e.g. the use of renewable energy, remediation of pollution and construction with renewable materials, were the drivers for development of new markets for hybrid poplar in Oregon and may be options to explore in Ireland. Meeting renewable energy targets provides a suitable reason for the State to heavily incentivise investors or growers to meet these targets. That would provide the impetus to develop a market, from which point ordinary market forces would ensure its success or failure. The wood energy sector was the most favourable to use SRF in Ireland, so developing biorefining to produce liquid biofuels could be an option to explore if sufficient scale of feedstock production was feasible and fossil fuel prices increased.

3.5 Conclusions

Oregon developed a model of growing and marketing SRF hybrid poplar based on large scale industrial plantations, in-situ processing mills, certification and high value product market development. However, small plantations and lower value products were not successful. Furthermore, there is now a shortage of hybrid poplar wood supply in Oregon that will increase to about 400,000 m^3 yr^{-1} when the Boardman plantation is completely converted to agriculture. However, such a shortfall in supply would not guarantee that an individual grower could secure a financially viable place in this market due to requirements for production scale and log quality that the processing sector demanded. Learning from the Oregon experience, Ireland must consider the importance of scale and management of quality, so the development of co-operative producer groups would be essential. Moreover, industry should provide clear guidance on pricing related to size and quality specifications.

Another lesson from the approach to SRF in Oregon was the need for flexibility to adapt to changing circumstances. Although the wood energy sector was identified as a potential market for SRF in Ireland and a future shortage of woodfuel is expected, market demands can change by the time plantations reach rotation age, as happened in the pulp sector in Oregon. Flexibility of management is an advantage of the SRF model proposed in Ireland, based on single stem trees and 10- to 20-year rotations, and with the possibility of conversion to conventional forestry systems. However, if other markets need to be targeted in the future, then different species, stocking and silvicultural practices may be required.

Although flexibility can help market development, there is a risk of a commercial supply chain ending even when successful markets have been developed. For instance, land competition from other higher value uses can hinder the development of SRF; e.g. another agricultural crop in Oregon or another Grant Premium Category of the forestry programme in Ireland. Research and dissemination actions together with marketing strategies were essential to the development of SRF in Oregon for both growers and markets; the same approach will most likely be needed in Ireland.

Although development of high value products was essential in Oregon, wood energy was the sector most favourable towards using SRF in Ireland. The Oregon experience highlights a series of possible challenges for economically sustainable energy feedstock supply:

- minimum production scale;
- locally available consistent supply of SRF for energy;
- requirement for as short a supply time (rotation length) as possible;
- consideration of coppice techniques to reduce establishment costs;
- need for higher value products to increase financial revenue for the grower.

Chapter 4: Quantification of total above ground biomass and energy content of SRF *Eucalyptus* spp. and *Populus* spp.

Chapter 4: Quantification of total above ground biomass and energy content of SRF *Eucalyptus* spp. and *Populus* spp.

4.1 Introduction

Eucalyptus and *Populus* genera include fast growing trees extensively used in commercial plantations and managed on short rotations. These plantations, although limited in extent and at an early stage of development, have been recently established in Ireland with the aim of reducing the shortage of pulpwood for the fibre and energy markets (DAFM,2014). However, very little is known about their productivity rates, their wood and fuel properties. Irish wood industry identified the lack of information on SRF particularly on wood and fuel properties and the need for it (Chapter 2). Furthermore, growers and end-users in Oregon initially required information on wood and fuel properties (Chapter 3).

Eucalyptus trials in Ireland produced mean annual increments (MAI) between 23 and 32 m^3 ha^{-1} yr^{-1} (Thompson *et al.*, 2012). In Britain yields between 11 and 30 m^3 ha^{-1} yr^{-1} and a mean basic density of 475 kg m^{-3} were recorded (Leslie *et al.*, 2012). This equates to 5 to 14 odt ha^{-1} yr^{-1}. A study on 7 eucalyptus species in Northern Spain found that *E. nitens* had the highest productivity with 7.7 odt ha^{-1} yr^{-1} (Pérez *et al.*, 2011). Along with other species of Eucalyptus, several trials of *E. delegatensis* and *E nitens* have been developed in Britain recording respectively mean DBHs of 48 cm at 28 years and 36 cm at 25 years (Leslie and Purse, 2016).

Poplar trials were also established in Ireland with the potential to produce between 7 and 11 odt ha^{-1} yr^{-1} (Keary, 2003). In Britain a study of poplar plantations revealed productivities between 6 and 10 odt ha^{-1} yr^{-1} and independency of stocking and productivity in fully-stocked plantations (Cannell, 1980).

Besides productivity, basic density, defined as the weight per unit green volume of dry wood, is a key factor to characterise wood for structural, fibre and energy uses (Bowyer *et al.*, 2007). Studies of basic density of eucalyptus in Britain produced values ranging from 450 to 500 kg m^{-3} (Leslie and Purse, 2016).

Poplars have relatively low basic density from 300 to 390 kg m^3 (Balatinecz *et al.*, 2001). Lyons et al. (1986) reported stem wood mean basic density of 315 kg m^3 in *P. trichocarpa x P. deltoides* “Rap” poplar clones and 361 kg m^3 in *x. P. trichocarpa* “Fritzi Pauley” poplar clones in Ireland.

Furthermore, other parameters influence wood quantification and suitability as a fuel: moisture content, calorific value and ash content. Very few studies exist on these parameters in eucalyptus and poplar in Ireland and Britain, for instance no studies on moisture content of eucalyptus were found.

Moisture content, the percentage of water contained in the material just after felling, was studied in *Eucalyptus urophylla* in Brazil with results of 43% and 53% for 2 different clones (Zanuncio *et al.*, 2013). Results of a study on *Eucalyptus nitens* in New Zealand reported a mean stem moisture of 57%, with a gradual decrease of the stem moisture content from breast height to the top of the tree (Lausberg *et al.*, 1995).

Lyons et al. (1986) studied moisture content of three year old poplar clones in Ireland and found stem wood mean moisture content of 51% in Rap clones and 54% in Fritzi Pauley clones. Zhang et al. (2003) found a large moisture content variation from 44% to 68% in a study analysing 371 stems of three years old poplar clones.

Calorific value is defined as the energy amount per unit mass (MJ kg $^{-1}$) or volume (MJ m $^{-3}$) released on complete combustion (ISO 16559:2014). A study carried out on *Eucalyptus globulus* in Portugal reported gross calorific values from 18.48 MJ kg $^{-1}$ for the stem bark to 23.48 MJ kg $^{-1}$ for the foliage (Viana *et al.*, 2018). Pérez et al. (2011) studied gross calorific values of 7 eucalyptus species in northern Spain and found also that foliage had the highest calorific values reaching 23.13 MJ kg $^{-1}$. Another study on *Eucalyptus globulus* and *Eucalyptus nitens* in the same area found that *E. nitens* had higher calorific value than *E. globulus* for all the tree partitions (Pérez *et al.*, 2006). González-García et al. (2016) reported gross calorific value of stem wood of *Eucalyptus nitens* of 19.54 MJ kg $^{-1}$ also in northern Spain. Kumar et al. (2010) tested the calorific value of stem wood from eucalyptus hybrids of different ages, 2 to 20 years old, in India. The study found that gross calorific value increased with age from 19.10 MJ kg-1 to 20.16 MJ kg^{-1}.

From the poplar trials in Ireland, Lyons et al. (1986) found a mean calorific value of 17.85 MJ kg^{-1}. A wide range of calorific values from 15.79 MJ kg^{-1} to 24.28 MJ kg^{-1} for stem, including bark and wood, was recorded by Klasnja et al. (2002), sampled from 1 to 12 years old *P.* x *euramericana* and *P. deltoides* poplar clones.

Calorific value is highly influenced by basic density and moisture content when expressed by volume. Freshly felled poplar (*Populus* spp.) has about half the calorific value of ash (*Fraxinus* spp.) due to the difference in basic density and moisture content (Biomass Energy Centre, 2010). Pérez et al. (2006) also concluded that the calorific value of eucalyptus could be doubled if the sample is dried prior to combustion.

Ash content is the inorganic residue remaining after combustion and is usually expressed as a percentage of the dry matter (ISO 16559:2014). Quantification of ash content and its chemical composition are important for the biomass boiler design as the latter determines ash melting behaviour which can cause slagging (Vassilev *et al.*, 2010). Viana et al. (2018) reported *Eucalyptus globulus* ash ranged from 0.4 to 2.88%. Among the 7 eucalyptus species studied by Perez et al. (2011), *E. globulus, E. gunni* and *E. viminalis* produced more ash, at about 3%. *E. nitens* ash content ranged between 1.1% for branches and 7.1% for bark (Perez *et al.*, 2006). In Kumar (2010), ash content of stem wood of *Eucalyptus* hybrids varied from 1.09% at 2 years old to 0.43% at 20 years old.

Poplar biomass ash content values reported in the literature are similar to those reported for eucalyptus. In the Irish trials it varied from 0.8% for the stem wood of Rap clone to 4.3% for bark of Fritzi Pauley, with the ash content of the other partitions in between (Lyons *et al.*, 1986). Klasnja et al. (2002) reported ash values from 0.5% for stem wood of a *P. deltoides* clone and 6.8% for bark of a *P. x euramericana* clone. The ash contents of branches and stem wood fell between those of the wood and bark partitions.

Quantification of forest biomass is a key factor to estimate timber, fibre and energy potential and carbon stock. Biomass expansion factors (BEFs) are defined as "multiplication factors that expand commercial round-wood harvest volume, to account for non-merchantable biomass components such as branches, foliage, and non-commercial trees" (IPCC, 2003) so they are simple conversion factors to estimate total biomass from stem data, in other words they are constant BEF. However, application of BEFs is sometimes inaccurate because they are based on local studies and also because there are several inconsistent BEF definitions (Somogyi et al., 2007). It has been observed that proportions of most biomass components vary considerably with age (Lehtonen et al., 2004). Therefore, BEFs are age and site dependent so there is a good correlation with stand variables, particularly diameter, top height, basal area and age (González-García *et al.*, 2013). BEF equations have been developed to include the influence of these parameters and therefore improve accuracy of constant BEFs (Teobaldelli *et al.*, 2009; Castedo-Dorado *et al.*, 2012). We did not find any previous reported BEF for poplar or eucalyptus in Ireland. BEF, defined as the ratio of the total biomass to the total volume, was identified for *Eucalyptus globulus* in Portugal and a model relating BEF to dominant tree height was developed with a constant BEF of 0.72 Mg m^{-3} for dominant height greater than 13.6 m (Soares and Tomé, 2012). BEF can be also calculated as the ratio of the total aboveground biomass to the stem biomass. A study on the OP42 poplar clone in Southern Scandinavia showed BEF values around 1.2 for trees with DBH greater than 10 cm (Taeroe *et al.*, 2015).

The purpose of this chapter was to quantify above-ground biomass and energy content of poplar and eucalyptus stands in Ireland. The analysis involved taking field measurements of standing trees, destructively sampling whole trees and dividing them into partitions to measure volume, weight and dry weight and taking laboratory samples to determine basic density, moisture content, calorific value and ash content.

4.2 Materials and methods

4.2.1 Study sites

SRF stand data were collected from four sites: two eucalyptus (*Eucalyptus* spp.) and two poplar (*Populus* spp.) stands.

The eucalyptus sites consisted of a *Eucalyptus delegatensis* stand in Kilbora, Co. Wexford (Figure 4.1, top left) and a *Eucalyptus nitens* stand in Cappoquin, Co.

Waterford (Figure 4.1, bottom). There was a considerable number of dead and windblown trees on both sites.

The poplar sites included a mixture of *Populus* clones from the species *P. trichocarpa,* and from hybrids of *P. deltoides x P. nigra, P. deltoides x P. trichocarpa* and *P. nigra x P. trichocarpa* (Table 4.1). The stands were established using a randomised block design. Originally 20 blocks with one tree of each clone per block were established but by the time this work took place parts of the original stands had been felled and the remaining number of clones were different in both stands. There was a total of 30 different clones but the Irish Forestry Programme 2014-2020 (DAFM, 2014) recommended particularly 8 of them that seemed to have better performance in Ireland.

Table 4.1. Poplar clones in the stands studied

Species	*Populus trichocarpa*	*P. deltoides x P. nigra*	*P. deltoides x P. trichocarpa*	*P. nigra x P. trichocarpa*
Clones	Trichobel* Balsam Spire Fritzy Pauley* Columbia River V.471xv.24('65)/34* 70036/14 71058/2* 70.038/67	Gibecq Gaver Ghoy	Boelare Beaupre Hoogvorst Hazendans Hunnegem Unal* Raspalje* 70045/1 69037/2 71009/2 71015/1 71009/1 71085/1 76004/10* 69038/1 5683/24 72030/7* 3681/84	Essene 2xv.24/19

*Clones recommended by the Irish Forestry Programme 2014-2020 (DAFM, 2014)

One of the poplar stands was in Ballyhaise, Co. Cavan (Figure 4.1, top right) and the other one in Kildalton, Co. Kilkenny.

Figure 4.2 shows the spatial location of the four sites and Table 4.2 summarises the main characteristics of the sites. The eucalyptus sites were owned by Coillte, the semi-state forestry company of Ireland, while the poplar sites were owned by Teagasc, the Agriculture and Food Development Authority of Ireland.

Figure 4.1. Top Left: Site EUC-WEX, Eucalyptus delegatensis. *Kilbora, Co. Wexford. Top Right: Site POP-CAV,* Populus *spp. Ballyhaise, Co. Cavan. Bottom. Site: EUC-WAT,* Eucalyptus nitens, *Cappoquin, Co. Waterford.*

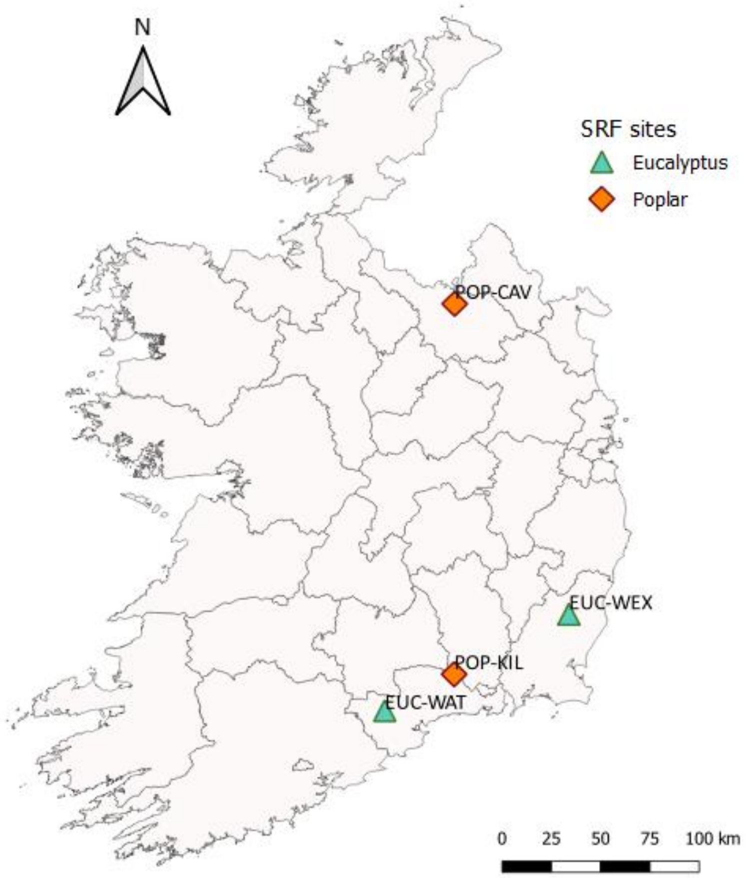


Figure 4.2. Map of the locations of the four SRF stands studied in this dissertation.

Table 4.2. Study site characteristics

Site	Location	Latitude/ Longitude	Area (ha)	Genera	Species sampled	Age (Growing seasons)
EUC-WEX	Kilbora, Co. Wexford	52°38'N/ 6° 26' W	1.28	*Eucalyptus*	*E. delegatensis*	22
POP-CAV	Ballyhaise, Co. Cavan	54°03'N/ 7°18'W	0.33	*Populus*	*P. trichocarpa* *P. deltoides x P. trichocarpa*	17
EUC-WAT	Cappoquin, Co.Waterford	52°11'N/ 7°49'W	2.46	*Eucalyptus*	*Eucalyptus nitens*	23
POP-KIL	Kildalton, Co. Kilkenny	52°21'N/ 7°19'W	0.58	*Populus*	*P. trichocarpa* *P. deltoides x P. trichocarpa*	19

4.2.2 Field work methodology

Before the biomass sample collection, a preliminary site assessment was carried out: accessibility to the site was assessed, stand boundaries were surveyed and stand inventory measurements were taken (Table 4.3). In the 2 eucalyptus sites, 8 plots of 200 m^2 were delimited and DBHs, stand top height and stems per ha were recorded. In the poplar sites, the DBHs of all the standing trees were recorded.

Table 4.3. Inventory measurements for the four sites: stocking and quadratic mean diameter at breast height (QMDBH).

Site	Stocking (trees ha^{-1})	QMDBH (cm)
EUC-WEX	436	35
POP-CAV	258	36
EUC-WAT	842	27
POP-KIL	291	30

The inventory data collected was used to calculate diametric distribution for each site by grouping the DBHs measurements into diametric classes. The total count of DBHs per diametric class was graphed in a histogram against DBH classes. To illustrate with an example, Figure 4.3 shows the diametric distribution of *Eucalyptus nitens* (site EUC-WAT).

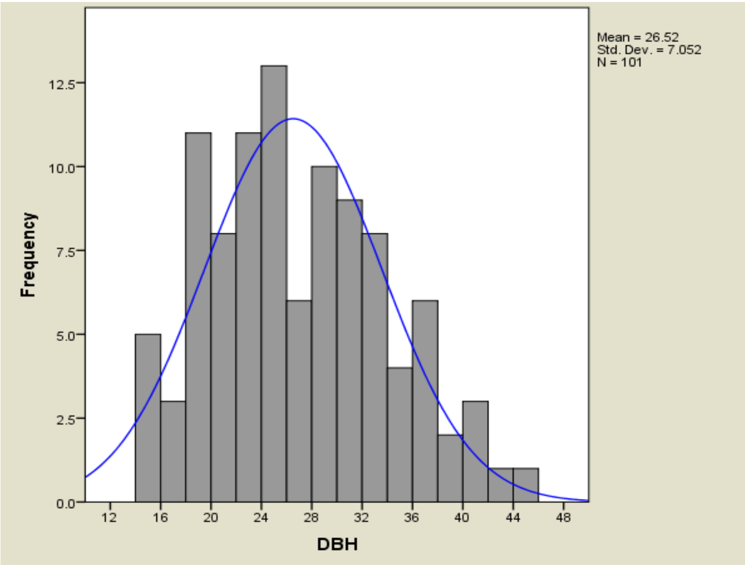


Figure 4.3. Diametric distribution of the site EUC-WAT. Eucalyptus nitens *stand in Cappoquin, Co. Waterford.*

Diametric distribution of the stands was used to identify sample trees that were a representative sample of the stand. A total of ten trees from sites EUC-WEX, POP-CAV and EUC-WAT and 14 trees from site POP-KIL were marked and used for destructive sampling by felling with a chainsaw. In the poplar sites only clones recommended by the Irish Forestry Programme 2014-2020 (DAFM, 2014) were sampled. In site POP-KIL, a total of 14 trees (4 more than in the other stands) were felled to include in the study all the recommended clones in the stand. Once the trees were on the ground, diameters were measured every metre along the stem (at 0.5 m, 1.5 m, 2.5 m, etc.) as in Figure 4.5.a. Diameter at 1.30 m height (DBH), total height and height up to 7 cm diameter were also recorded. Following the approach taken by Picard N. *et al.* (2012), trees were divided into 7 partitions as illustrated in Figure 4.3. There were 4 above ground biomass partitions: merchantable stem, top, live branches and dead branches. Top and live branches were grouped to determine the proportion of residues available for biomass assortments. A subset of the live branches was sampled to determine the proportion of leaves on the live branches and to determine leaf energy parameters; and a subset of the merchantable stem (the discs) were sampled to determine proportion of wood and bark and to determine wood and bark energy parameters. Dead branches were included in total above ground biomass but not in residues as they were assumed to be lost in the supply chain remaining in the forest after harvesting. The description of the partitions is as follows:

1. Stem: merchantable stem, meaning the part of the stem greater than 7 cm diameter, containing wood and bark;
2. Top: part of the stem with diameter smaller than 7 cm diameter, containing wood and bark;
3. Live branches: live branches containing wood and bark
4. Dead branches: dead branches containing wood and bark.
5. Foliage: leaves
6. Wood: merchantable stem without bark
7. Bark: only from merchantable stem

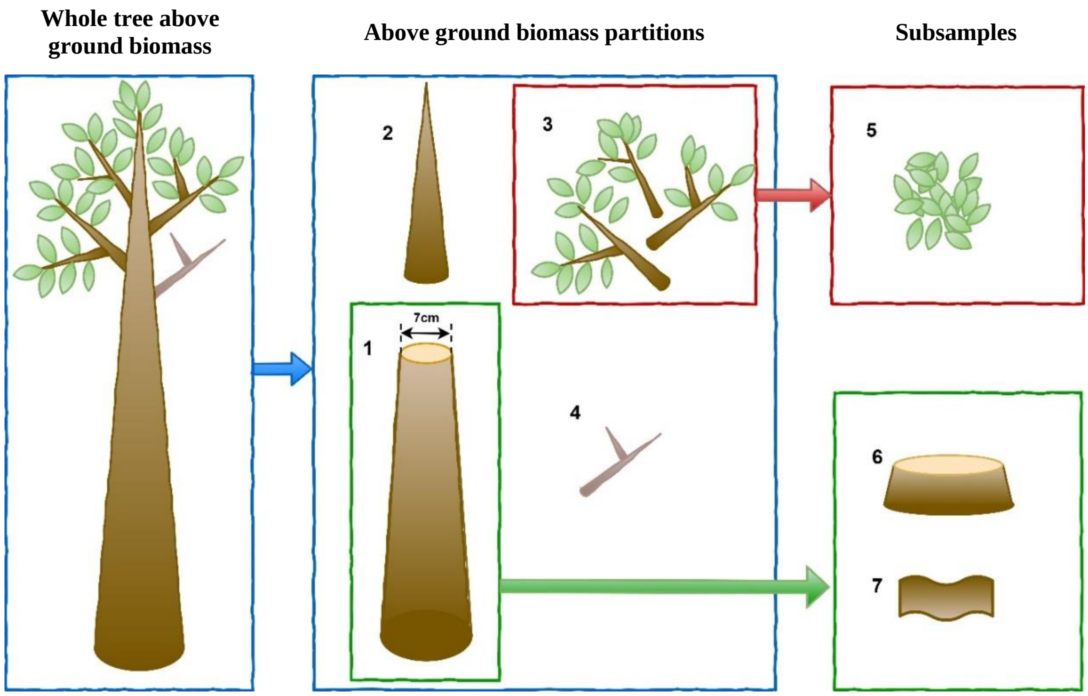


Figure 4.4. Diagram of sampling partitions. 1. Stem; 2. Top; 3. Live branches; 4. Dead branches; 5. Foliage; 6. Stem wood; 7. Stem bark

Discs were cut along the stem at intervals of 3 m and about 30 mm thickness. These discs were weighed in the field. Each disc was labelled with a tree identification number, collection height and field weight (Figure 4.5.b.).

Some of the sample trees in the poplar stands (POP-CAV and POP-KIL) presented forked stems of diameters greater than 7 cm. Discs were cut along these forks at intervals of three metres, and these were also weighed and labelled. The biomass of these forks greater than 7 cm also contributed to the total merchantable volume.

All the live branches from each tree were collected and weighed in the field (Figure 4.5.c.). The same procedure was carried out with the dead branches.

Tops and branches were chipped on the site with a Linddana TP200 chipper (Figure 4.5d). The chipped material was mixed and laboratory samples were taken from the mixture.

a. 

b. 

c. 

d. 

Figure 4.5. Field work in the Eucalyptus delegatensis site, Kilbora, Co. Wexford. June 2014. (Photos credit Enda Coates)

a. Measuring volumes. A diameter tape was used to measure diameters every metre along the stem and callipers for the smaller part of less than 7cm. A tape was used to measure merchantable and total height.

b. Stem discs were taken every three metres to bring to the laboratory to analyse moisture content, basic density and energy parameters.

c. Weighing live branches to obtain total above ground biomass.

d. Taking destructive sample of live branches to bring to the laboratory to analyse moisture content and energy parameters.

4.2.3 Laboratory methodology

The collected samples, made up of main stem and fork discs and branch samples and chipped material samples were brought into the lab and were dried in an oven at 105 °C for a minimum of 48 hours to remove all moisture. The samples were weighed immediately after being taken out of the oven to determine dry matter content, the amount of material after removal of moisture, i.e. dry weight.

Disc volume was measured by immersion in water until saturation and then using Archimedes' principle to measure the volume of water displacement as first done by Keylwerth, cited by Smith (1954).

Representative subsamples of each partition were ground into dust samples and tested for calorific value and ash content in the laboratory, after testing these subsamples again for moisture content because of the hygroscopic property of wood. Determination of the moisture content was carried out in accordance with the Solid Biofuels Standards (EN 14774-3:2009).

There were a total of six samples for each of the seven partitions per site. Three from a sample tree chosen randomly and three from a mixture of all the trees for each partition.

Calorific value is usually expressed per unit mass and although it can be presented in different units the most common and the one used in this study is Megajoules per kilogramme, MJ kg^{-1}. Determination of calorific value was carried out in accordance with (EN 14918:2009). Samples for calorific value determination were pressed into a pellet with a 2811 Pellet Press and then combusted under controlled conditions with a Parr 6300 automated isoperibol bomb calorimeter (Parr Instrument Company, IL, US). Gross calorific value as received was automatically calculated and printed by the instrument.

Ash content of sample material was determined in accordance with the Solid Biofuels Standards (EN 14775:2009) by total combustion at 550˚ C in a Carbolite OAF 11/1 muffle furnace.

4.2.4 Calculations

4.2.4.1 Volume

The volume of each section of the stem over-bark was estimated using Huber's formula (Eq 4.1) Volume of each one metre section was calculated individually and merchantable stem volume was the sum of each one metre section volume:

$$V_{stem} = \frac{\pi}{4}\left(\sum_{j=1}^{n} l_j \times d_m^2\right)$$

(Eq. 4.1)

where

V_{stem}, merchantable stem volume of a sampled tree;

d_m, diameter at half length of the section *j;*

l_j, length of the section *j;*

n, total number of sections of merchantable stem.

The destructive sample trees were classified by DBH ranges so proportionality of each sample tree out of the total stand was calculated. Volume of the sample trees according to their proportion to the diametric distribution was then used to calculate mean tree size. Volume per ha of each stand was calculated by multiplying inventory stocking per hectare by mean tree size.

4.2.4.2 Moisture content

Moisture content is the amount of water in a fuel. Wet and dry weights of stem disc and branches sampled were used to calculate moisture content on a wet basis by using the equation:

$$M\ (\%) = \frac{m_w - m_d}{m_w} \times 100$$

(Eq.4.2)

where

M, is moisture content percentage on a wet basis;

m_w is the initial weight measured just after trees were felled;

m_d is the dry matter weight.

4.2.4.3 Basic density

Basic density is defined as the ratio of the mass on dry basis and the solid volume on green basis (ISO 16559:2014). The basic density of each stem disc was calculated as

$$D_{dj} = \frac{m_{dj}}{v_j},$$

(Eq. 4.3)

where

m_{dj} is the dry weight of the disc *j;*

v_j is the volume of the water saturated disc.

The mean basic density of the stem was calculated as:

$$D_{d,stem} = \frac{m_{\ d,stem}}{V_{stem}}$$

(Eq. 4.4)

where

$m_{d,\ stem}$ is the dry matter weight of the stem;

V_{stem} is the volume of the stem.

4.2.3.4 Dry matter

The total dry matter of the merchantable stem was calculated as the sum of dry matter of stem sections as:

$$m_{d,stem} = \sum_{j=1}^{n} \frac{D_{dj} + D_{dj+1}}{2} \times v_j$$

(Eq. 4.5)

where,

D_{dj} is basic density of disc at the bottom of section *j;*

D_{dj+1} is basic density of disc at the top of section *j;*

v_j is the volume of the section *j.*

Tops' and live branches' dry weights were combined as residues to present the results. The dry matter of the residues (tops and branches) was calculated as:

$$D_{d,i} = m_{w,i}\left(1 - \frac{M_i}{100}\right)$$

(Eq. 4.6)

where

$D_{d,i}$ is the dry matter of the partition i, i.e. live branches;

$m_{w,i}$ is the wet weight of the partition i measured on the field;

M_i is the moisture content of the partition i, calculated as an average of the moisture of the samples taken for each partition.

The total dry matter per hectare was calculated, similarly to the volume per hectare, by multiplying the mean tree dry matter from the sample tree by the stocking per hectare of each stand.

4.3.4.5 Biomass expansion factors

Biomass expansion factors were calculated as the ratio of the total aboveground biomass to the stem biomass.:

$$BEF = \frac{m_{d,ag}}{m_{d,stem}}$$

(Eq. 4.7)

where,

$m_{d,ag}$ is the total above ground biomass dry matter or the sum of dry matter from merchantable stem, top, dead branches and live branches;

$m_{d,stem}$ is the dry matter contained in the merchantable stem.

4.3.4.6 Calorific value

The gross calorific value on a dry basis including ash, $q_{v,\,gr,d,}$ was calculated using the moisture content values tested in the lab and the gross calorific value as received determined by calorimetry:

$$q_{v,gr,d} = q_{v,gr} \times \frac{100}{100 - M}$$

(Eq. 4.8)

where

$q_{v,\,gr,d}$ is the gross calorific value at constant volume of the dry (moisture-free) fuel;

$q_{v,\,gr}$ is the gross calorific value at constant volume of the fuel as analysed;

M is moisture content wet basis in expressed as a %.

Ash content was then calculated using the following equation:

$$A = \left(\frac{m_3 - m_1}{m_2 - m_1}\right) \times 100 \times \left(\frac{100}{100 - M}\right)$$

(Eq. 4.9)

where

A is the ash content expressed as %, dry weight;

m_1 is the mass of the empty dish;

m_2 is the mass of the dish plus the test sample;

m_3 is the mass of the dish plus ash;

M is moisture content on a wet basis, expressed as a %.

4.3 Results

4.3.1 Volume of sample trees

Table 4. 4 shows a summary of the sample tree attributes per site. DBHs of the sample trees ranged from 17 to 53 cm with an overall mean of 36 cm while total height ranged from 21.2 to 35.8 m with an overall mean of 27.9 m. Mean merchantable volume per tree was greater than 1 m^3 for all the sites, and the largest volume was 2.65 m^3 from a tree sampled in site POP-KIL.

Table 4.4. Sample tree characteristics summarised per site. Mean tree and range in parenthesis.

Site	DBH (cm)	Total Height (m)	Merchantable Volume (m^3)	Top Volume (m^3)
EUC-WEX	34 (21- 47)	28.2 (25.4-31.1)	1.026 (0.346-2.001)	0.003 (0.001-0.005)
POP-CAV	40 (24- 48)	25.0 (21.2-28.2)	1.278 (0.299-2.189)	0.006 (0.004-0.007)
EUC-WAT	30 (17- 46)	30.7 (22.0-35.8)	1.044 (0.202-2.408)	0.008 (0.001-0.018)
POP-KIL	39 (24- 53)	27.7 (23.1-32.3)	1.482 (0.428- 2.650)	0.010 (0.005-0.018)

4.3.2 Dry matter of sample trees

Allocation of dry matter in the merchantable stem, residue and dead branch partitions of the sample trees are presented in table 10. Merchantable stem mean dry matter ranged from 394 to 446 oven dry kg per tree in sites 2 and 1 respectively while residues mean ranged from 27 to 117 oven dry kg, also in sites 2 and 1 respectively. Percentage of dry matter allocated to the merchantable stem was higher than 90% in both eucalyptus stands (sites 1 and 3) while a lower percentage of c. 80% was allocated to merchantable stem in poplar sites (2 and 4) respectively with 18% and 21% allocated to other partitions (Figure 4.6).

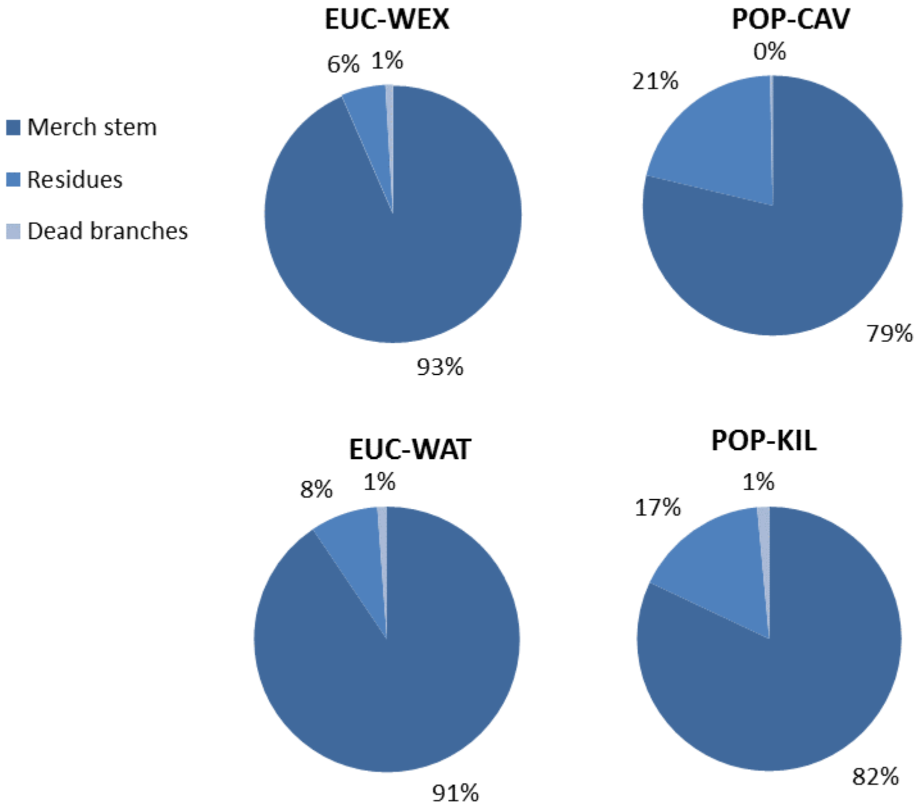


Figure 4.6. Allocation of dry matter in the partitions of the tree.

4.3.3 Calorific value of sample trees

Gross calorific value of the stem ranged from 19.2 MJ kg^{-1} in the *Eucalyptus nitens* site (EUC-WAT) to 19.6 MJ kg^{-1} in the *Eucalyptus delegatensis* site (EUC-WEX), with intermediate values for the poplars. In both eucalyptus sites the highest calorific values were found in the foliage: 22.3 MJ kg^{-1} and 23.1 MJ kg^{-1} in sites 1 and 3 respectively; while the lowest was in the bark at 19.0 MJ kg^{-1} and 16.5 MJ kg^{-1} respectively. In the poplar sites (POP-CAV and POP-KIL) calorific values were more uniform between the different partitions.

Table 4.5. Mean gross calorific value, dry basis by partition expressed in Megajoules per kilogramme. Standard deviation in parenthesis.

Partition	Gross Calorific Value, $q_{gr,d}$ (MJ kg^{-1})							
	EUC-WEX		POP-CAV		EUC-WAT		POP-KIL	
Stem	19.6	(0.05)	19.4	(0.12)	19.2	(0.09)	19.5	(0.15)
Tops	20.0	(0.10)	19.8	(0.18)	20.0	(0.03)	19.5	(0.12)
Live branches	20.0	(0.10)	19.2	(0.81)	20.0	(0.12)	19.5	(0.12)
Dead branches	19.6	(0.03)	19.6	(0.07)	19.5	(0.07)	19.5	(0.16)
Foliage	22.3	(0.04)	20.1	(0.26)	23.1	(0.18)	19.1	(0.19)
Stem wood	19.7	(0.04)	19.4	(0.17)	19.3	(0.10)	19.3	(0.08)
Stem bark	19.0	(0.11)	19.6	(0.10)	16.5	(0.25)	19.6	(0.13)

4.3.4 Ash content

Ash content of the stem varied from 0.39% in site EUC-WEX to 1.21% in site POP-KIL. The bark and leaves had higher ash content, particularly the foliage of the poplar stands (sites 2 and 4) with values of over 10%.

Table 4.6. Mean ash content by partition expressed as a percentage of dry mass. Standard deviation in parenthesis.

Partition	Ash Content (%, dry weight)							
	EUC-WEX		POP-CAV		EUC-WAT		POP-KIL	
Stem	0.39	(0.03)	1.05	(0.08)	1.21	(0.11)	0.88	(0.10)
Tops	1.72	(0.06)	1.72	(0.15)	2.08	(0.18)	2.01	(0.13)
Live branches	1.72	(0.06)	1.70	(0.11)	2.41	(0.16)	2.48	(0.92)
Dead branches	0.79	(0.07)	2.62	(0.46)	1.09	(0.13)	1.40	(0.08)
Foliage	3.02	(0.01)	10.59	(0.16)	3.54	(0.11)	10.24	(0.33)
Stem wood	0.21	(0.04)	0.52	(0.04)	0.51	(0.20)	0.70	(0.09)
Stem bark	1.96	(0.03)	6.37	(0.43)	9.84	(1.37)	5.74	(0.03)

4.3.5 Biomass Expansion factors

Constant Biomass Expansion Factors were calculated for each site and are shown in Table 4.7. There was a strong correlation between stem dry matter and total above-ground biomass of the sample trees (Figure 4.7), with all the R^2 values higher than 0.96. Biomass Expansion Factors of eucalyptus ranged from 1.04 to 1.19 and poplar from 1.11 to 1.40 (Table 4.7). The higher poplar BEF were due to the higher proportion of dry matter allocated to the branches in this species.

Table 4.7. Descriptive statistics of the sample tree dry matter in oven dry kg and BEF (dimensionless).

Site	Statistic	Merch stem	Residues	Dead branches	Total aboveground biomass	BEF
EUC-WEX	Mean	445.9	26.8	4.4	476.2	1.06
	SD	210.8	19.2	5.1	227.3	0.03
	Range	(149.6-895.5)	(6.6-64.6)	(1.1-16.6)	(158.1-946.8)	(1.04-1.13)
POP-CAV	Mean	393.7	118.6	1.5	499.9	1.27
	SD	163.8	85.1	1.8	212.2	0.09
	Range	(84.2-685.9)	(20.3-293.1)	(0-5.1)	(106.7-867.4)	(1.11-1.40)
EUC-WAT	Mean	414.8	37.9	5.3	456.9	1.11
	SD	321.8	36.6	3.8	356.7	0.05
	Range	(81.5-1017.7)	(9.8-107.2)	(0.7-11.2)	(97.2-1116.6)	(1.06-1.19)
POP-KIL	Mean	422.4	91.2	7.6	519.6	1.20
	SD	218.2	62.5	10.1	277.9	0.07
	Range	(117.8-846.1)	(5.7-204)	(0.3-36.1)	(129.4-1056.7)	(1.05-1.29)

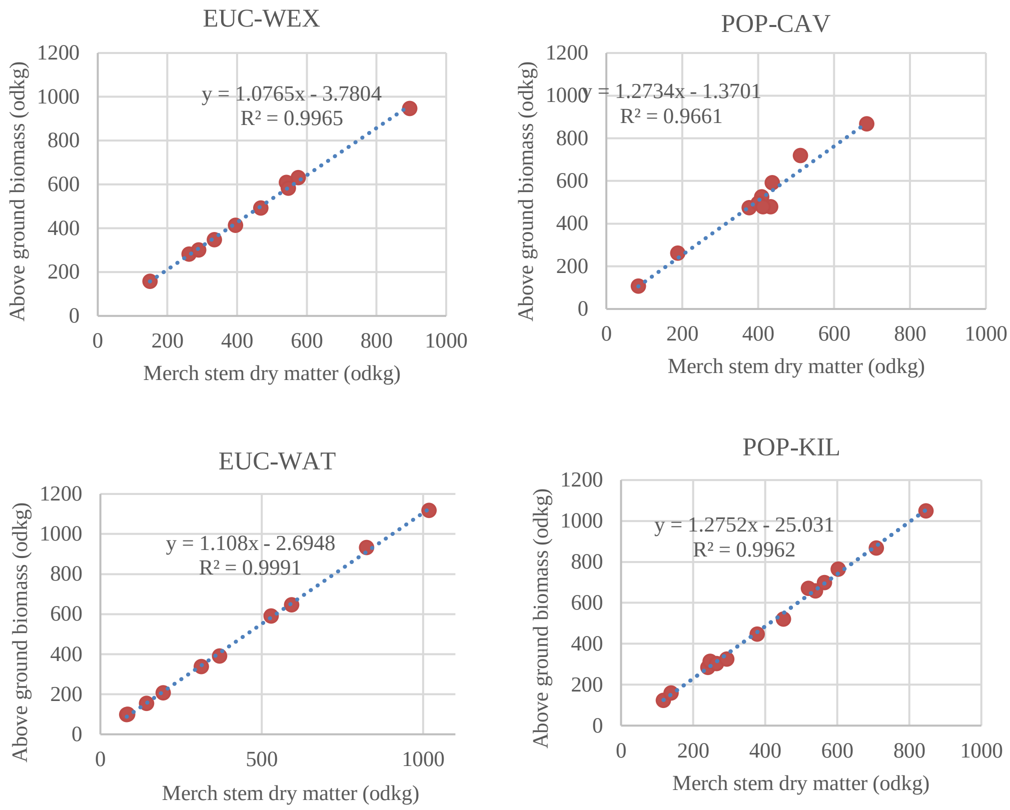


Figure 4.7. Relationship between dry matter of merchantable stem and total above ground dry biomass.

4.3.6 Moisture content

Stem moisture content values ranged from 48% to 63%. The higher values of moisture were in site EUC-WAT, *Eucalyptus nitens* in Cappoquin, where the mean was 60%. The other three sites presented similar mean moisture of the stem, between 52 and 54%. The general pattern of moisture content along the stem was to decrease with height but this trend was more pronounced in the 2 eucalyptus sites (Figure 4.8 and Table 4.8). Within each site, variability of moisture content between trees, and at each sample height class, was small, with coefficients of variation of the mean below 10% for all the sites.

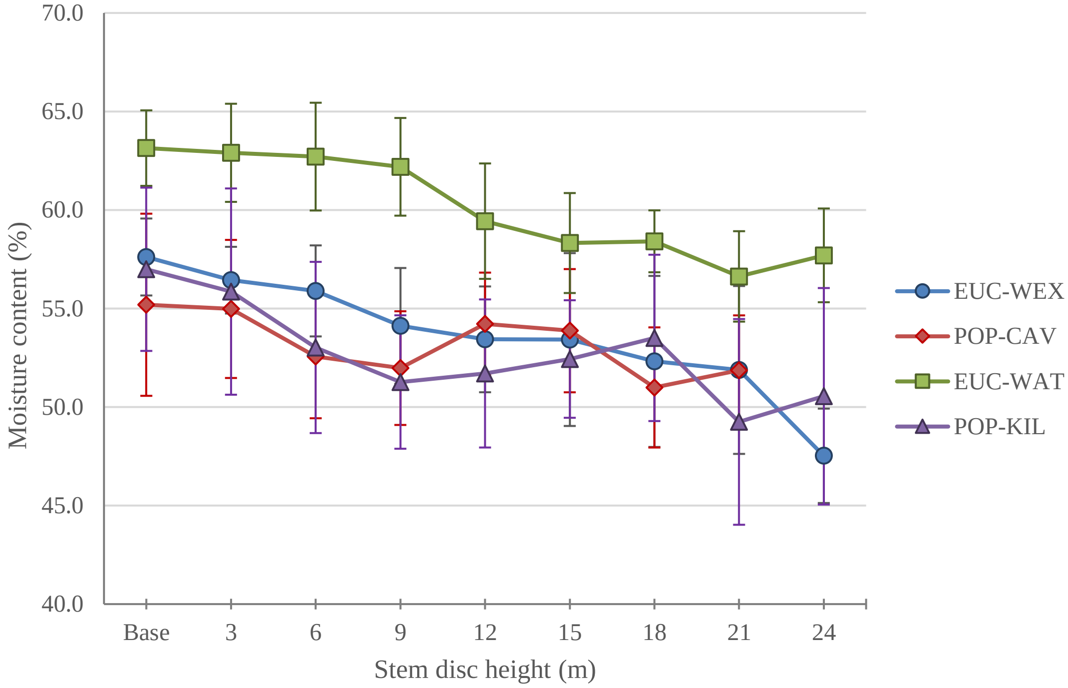


Figure 4.8. Variation of moisture content along the stem of 4 SRF sites in Ireland. Mean of 10 trees per site and standard deviation.

Table 4.8. Mean moisture content of stem at different heights expressed as % of total weight, wet basis. Range (minimum and maximum values) in parenthesis.

Disc height (m)	EUC-WEX M%	POP-CAV M%	EUC-WAT M%	POP-KIL M%
0	57.6 (54.5-60.9)	55.2 (49.4-64.8)	63.3 (60.2-68.7)	57 (51.9-64.7)
3	56.4 (53.0-58.8)	55 (48.6-61.1)	62.9 (57.5-67.1)	55.9 (47.1-64.2)
6	55.9 (52.7-59.5)	52.6 (45.8-59.7)	62.7 (57.2-66.7)	53 (44.6-60.7)
9	54.1 (47.0-58.1)	52 (47.2-57.5)	62.2 (56.2-66.2)	51.3 (46.8-57.5)
12	53.4 (48.0-58.4)	54.2 (47.1-57.0)	59.4 (52.8-65.6)	51.7 (46.7-59.6)
15	53.4 (43.1-58.2)	53.9 (47.9-60.0)	58.3 (51.9-61.3)	52.4 (47.8-57.6)
18	52.3 (42.7-58.2)	51 (45.2-54.5)	58.4 (54.6-60.4)	53.5 (45.0-59.8)
21	51.9 (41.2-56.7)	51.9 (47.1-55.7)	56.6 (52.8-59.2)	49.2 (40.6-58.4)
24	47.5 (44.1-50.0)	-	57.7 (54.5-60.5)	50.5 (42.9-57.9)

Moisture content appears to be correlated to the different tree partitions as results show, in table 4.9. Residues presented a lower moisture content compared to the stem in all the sites. All the sites presented higher variability in dead branches moisture between samples compared to the other partitions.

Table 4.9. Mean moisture content of different partitions expressed as % of total weight. Standard deviation in parenthesis.

Site	Merchantable stem	Residues	Dead branches
EUC-WEX	53.6 (2.0)	44.5 (1.6)	17.4 (2.5)
POP-CAV	54.2 (3.1)	42.6 (2.0)	32.5 (10.7)
EUC-WAT	61.4 (2.0)	51.9 (3.4)	38.2 (5.8)
POP-KIL	53.9 (4.1)	47.2 (1.9)	23.9 (6.2)

4.3.7 Basic density

The eucalyptus stands presented higher basic density than the poplar stands (Table 4.10). Generally, basic density increased in all stands from the base to the top of the trees (Figure 4.9). However, with the exception in the poplar site EUC-WEX, basic density decreased in the first part of the stem, from the base disc to the 3m disc. Variability of wood density between trees within a site was small with coefficients of variation of the mean below 10% except for site POP-KIL, where variability was higher and reached a maximum coefficient of variation of 18% at 6 m height. Furthermore, variability of basic density along the stem for each site was not higher than 10% for all sites except 4, where the coefficient of variation was 12%.

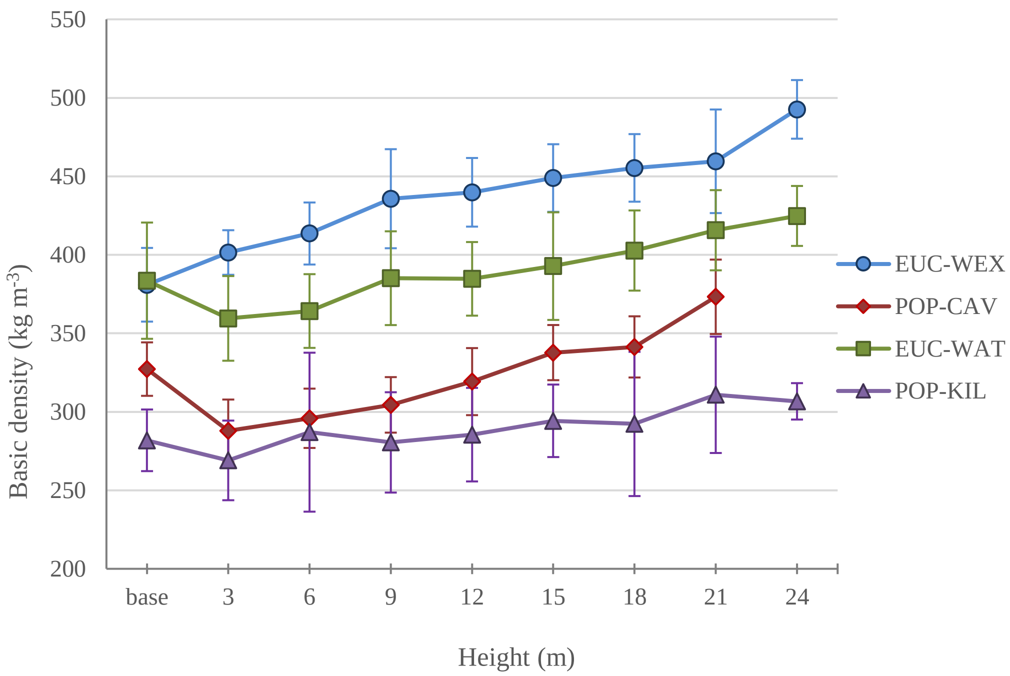


Figure 4.9. Variation of basic density along the stem of 4 SRF sites in Ireland. Mean of 10 trees per site and standard deviation.

Table 4.10. Basic density of the stem at different heights expressed in kg m^{-3} of eucalyptus (sites EUC-WEX & EUC-WAT) and poplar (sites POP-CAV & POP-KIL). Mean and range in parenthesis.

Disc height (m)	EUC-WEX Basic density (kg m^{-3})	POP-CAV Basic density (kg m^{-3})	EUC-WAT Basic density (kg m^{-3})	POP-KIL Basic density (kg m^{-3})
0	380.9 (349.8-418.3)	327.2 (298.0-360.4)	382.2 (337.6-463.9)	281.8 (253.1-323.9)
3	401.5 (383.6-425.7)	287.9 (256.8-327.8)	359.5 (322.7-421.0)	269.0 (223.6-316.0)
6	413.6 (377.1-439.2)	295.9 (265.1-323.1)	364.2 (326.9-405.1)	287.0 (230.5-399.4)
9	435.7 (392.5-518.4)	304.4 (272.5-331.6)	385.1 (351.9-451.9)	273.1 (244.7-310.2)
12	439.8 (402.5-477.0)	319.2 (289.4-349.2)	384.7 (355.9-440.4)	288.4 (213.3-376.2)
15	448.9 (413.2-472.5)	337.7 (298.3-361.1)	392.8 (338.3-481.3)	294.3 (258.0-336.0)
18	455.4 (424.4-491.2)	341.3 (311.5-369.7)	402.7 (367.7-451.0)	293.4 (145.4-334.0)
21	459.6 (416.6-538.3)	373.3 (336.7-393.8)	415.7 (364.1-453.5)	311.7 (276.8-401.5)
24	492.6 (464.2-519.2)	-	424.8 (390.5-460.5)	306.7 (284.9-316.7)
Stem	435.4 (405.3-450.8)	311 (286.1-334.6)	387.9 (353.6-422.6)	282.7 (263.7-329.0)

4.3.8 Productivity of the four short rotation forestry stands

The results presented above were used to calculate productivity per ha (Table 4.11). Site POP-CAV presented the lowest productivity at 128 odt ha $^{-1}$ or a mean productivity of 7.5 odt ha $^{-1}$ yr $^{-1}$ while site EUC-WAT presented the highest productivity, doubling site POP-CAV values and reaching 315 odt ha $^{-1}$ and a mean of 13.7 odt ha $^{-1}$ yr $^{-1}$.

Table 4.11. Productivity of the study sites.

Site	Merchantable volume (m^3 ha $^{-1}$)	Merchantable stem biomass (odt ha^{-1})	Residue biomass (odt ha^{-1})	Aboveground biomass (odt ha^{-1})	Productivity, aboveground biomass (odt ha^{-1} yr^{-1})	Energy (GJ ha^{-1})
EUC-WEX	413	180	9	190	8.6	2,971
POP-CAV	330	101	26	128	7.5	2,016
EUC-WAT	743	287	24	315	13.7	4,508
POP-KIL	428	123	26	151	7.9	2,324

4.3 Discussion

Values of productivity were in the ranges of other studies of eucalyptus and poplar in the literature. Annual Eucalyptus productivity, of 8 and 13 odt ha^{-1} is similar to the results presented by Leslie (2012) and annual poplar productivity 7.5 and 7.9 odt ha^{-1} yr^{-1} are in the lower extreme of the potential range suggested by Keary (2003). This could be due to the relative low stocking in the 2 poplar sites: if fully stocked perhaps higher values as suggested by Keary might be achieved. The poplar site productivity is similar to that found by Cannel (1980) in fully-stocked sites. Although the poplar sites had greater mean tree volume than the eucalyptus sites, EUC-WAT site had the highest productivity due to the higher stocking. Differences in stocking between the 4 sites influenced the productivity results. Further trials at different stockings have been established as part of the SHORTFOR project and could be useful to identify the effect of density on productivity if any and to compare with Cannel's results that demonstrated independency between stocking and productivity in young hardwoods. Although POP-KIL site had a slightly higher merchantable volume than EUC-WEX site, the total above ground biomass and energy content per hectare was higher in EUC-WEX site mainly due to the higher basic density. It seems for the fibre and energy markets eucalyptus would produce more biomass dry matter from the same amount of volume than poplar. However, in terms of merchantable volume for sawlog use, poplar seems to achieve a higher mean tree size in a shorter time although this needs to be investigated further due to the differences on the 4 site's conditions, i.e stocking and site factors.

Allocation of dry matter showed a higher proportion allocated to residues and a lower total above ground biomass in the poplar sites than in eucalyptus. This suggests that eucalyptus will be a better choice when maximising quantity of merchantable stem is the main objective.

BEF of the poplar sites were similar to those found by Taeroe (2015), at around 1.2. Literature on constant BEF for eucalyptus was not found to compare with the ones developed in this work. However, future research should develop BEF equations for eucalyptus in Ireland, so influence of site and age variations are also considered as in the eucalyptus BEF equations developed in Portugal and Spain (Castedo-Dorado *et al.*, 2012; Soares and Tomé, 2012).

Gross calorific value dry basis values were in the same ranges of the other studies for both eucalyptus (Perez *et al.*, 2006; González-García *et al.*, 2016; Kumar *et al.*, 2010) and poplar (Klasnja *et al.*, 2002). They are also within the range of the typical values for wood biomass quoted in European standards (EN 14961-1, 2010). The higher calorific value of eucalyptus leaves was also found in previous studies (Pérez *et al.*, 2011; Junior *et al.*, 2017; Viana *et al.*, 2018).

Ash content values of eucalyptus samples were in the range of those described in other studies (Perez *et al.*, 2006; Pérez *et al.*, 2011; Viana *et al.*, 2018) and the typical values quoted in the European standards (EN 14961-1, 2010). Poplar ash content values were also mainly in the ranges of other studies (Lyons *et al.*, 1986; Klasnja *et al.*, 2002) and the European standards (EN 14961-1, 2010). The exception was poplar foliage which presented very high values in both sites, triple the ash values of the foliage on the eucalyptus sites. This suggests that poplar leaves should be excluded from woodfuel, due to the large amount of ash produced. Ash melting behaviour has not been measured but will need to be studied to determine if this material will be suitable for boilers without damaging them through formation of clinker.

There was a gradual decrease in moisture of the stem as height increases in the eucalyptus sites. This trend was consistent with Lausberg *et al.* in their study of eucalyptus in New Zealand (1995). *Eucalyptus delegatensis* site (EUC-WEX) moisture content just after felling were similar to previous values reported from Ireland by Leslie (2013), while *Eucalyptus nitens* site (EUC-WAT) had a higher moisture. Although both sites were sampled in the summer months, site and weather variability could have influenced these results. Moisture content of *Populus* measured in this study were consistent with values from Ireland. (Lyons *et al.*, 1986). Moisture content was lower in residues than stem for the four stands as also found in previous studies (Quilhó and Pereira, 2001).

Eucalyptus sites had higher basic density than poplar sites, an average of 412 kg m^{-3} compared to 297 kg m^{-3}. Both basic density of poplar and eucalyptus sites were in the ranges of the literature reviewed (Lausberg *et al.*, 1995; Beaudoin *et al.*, 1992). Although sprouts and younger trees tend to have lower density, a study in Ireland had slightly higher values of basic density in younger trees (Lyons *et al.*, 1986) than the ones found in this study.

The tendency of increasing basic density with height along the stem agrees with other studies in poplar and eucalyptus (Lausberg *et al.*, 1995). Taeroe et al. (2015) found this tendency in poplar and suggested that the increase on basic density on the upper part could be due to the increase knots formed by branches. However, Quilhó and Pereira (2001) suggest the increase of basic density in eucalyptus from the base to the top of the stem due to the increase of fibre wall thickness and changes on vessel sizes and percentage. The decline of basic density in the first three metres presented in three of the sites was also found in other studies in *Eucalyptus globulus* (Quilhó and Pereira, 2001) and in *Eucalyptus nitens* (Lausberg *et al.*, 1995).

4.4 Conclusions

This study showed that short rotation forestry plantations in Ireland have potential yields between 7.5 and 13.7 odt ha^{-1} yr^{-1}, which compares well with values from other countries and suggests that SRF has good growth in Ireland. However, due to the lack of plantations from 7 to 16 years of age in the time when the field work was carried out, the productivity for the most likely harvest ages could not be estimated. Further research on the potential rotation ages is recommended when the SRF plantations resource is available.

Eucalyptus sites compared to poplar sites presented: 1) higher basic density and 2) higher proportion of biomass allocated to the merchantable stem out of the total aboveground biomass. Therefore, eucalyptus would be more efficient in terms of 1) producing more fibre and energy in the same amount of volume and 2) maximising merchantable stem biomass, particularly useful if markets are not taking the residues.

The energy parameters studied were in the range of typical values suggested by the European solid biofuel standards with the exception of the ash content of the foliage of the poplar sites. This indicates poplar leaves should be excluded in woodfuel. Calorific value of residues is higher in eucalyptus than poplar, while similar caloric value was found in the eucalyptus and poplar stems. The partition with the highest calorific value in the eucalyptus is the foliage suggesting it would be useful to optimise the production of leaves. However, this study did not include any chemical analysis, so it cannot be concluded on the possible occurrence of excessive amount of some compounds such as chlorine, that can damage boilers (Demirbas, 2005; Khan *et al.*, 2009). Such chemical analysis should be carried out before recommending inclusion of foliage in wood fuel. Similarly, the ash melting behaviour must be studied as it can produce serious problems of slagging on the boilers.

Moisture content of the stem ranged from 48 to 63% and decreased from the tree base to the top. However, basic density increased from the bottom to the top of the stem with exception of the first few metres.

This work developed constant BEFs for the four stands studied. This is a first attempt to measure BEF of eucalyptus and poplar in Ireland, but BEF is site and age specific. Development of BEF equations more accurate to sites with different quality and stand age would be recommended if these plantations are developed in Ireland, particularly for energy and carbon quantification purposes.

Chapter 5: Development of VEWTOOL, a volume-energy-weight conversion tool for woody biomass, and application to Short Rotation Forestry in Ireland

Chapter 5: Development of VEWTOOL, a volume-energy-weight conversion tool for woody biomass, and application to Short Rotation Forestry in Ireland

Abstract

Woody biomass is quantified using a variety of weight, volume and energy-based definitions. This generates confusion on which quantification units to use and on the conversion between them in different market areas. Many conversion tools have been developed to clarify this problem but lack flexibility or transparency. This paper describes the development of a unit conversion tool capable of 1) quantifying wood biomass resources in a variety of weight, volume and energy units for different markets, and 2) permitting direct comparisons between the valuations applied to the different market sectors. The tool has been developed to be educational, universal, flexible, accessible and simple. To implement the tool, parameters for quantifying wood biomass were identified, and a methodology to convert different weight, volume and energy-based wood units was developed. The conversion tool was applied to a case study using field measurements and lab analysis of destructive samples of Short Rotation Forestry stands in Ireland.

5.1 Introduction

Woody biomass is quantified using many different units. Even though accurate measurement is essential in the forest and wood energy sectors (Laurila and Lauhanen, 2011), there is often substantial confusion about which quantification units to use and the conversions between these units (Kofman, 2010). Both producers and users of forest biomass may lack important information required for a transparent market (Krajnc, 2015). Furthermore, while a wide range of quantifying units is available in the wood biomass literature, it is difficult to compare values from different sources due to the diverse measurement units used. Relevant organisations (e.g. UNECE/FAO), standards (EN and ISO) and research networks (Fonseca *et al.*, 2010; CEN, 2016; COST Action FP0902 *et al.*, 2016) have attempted to solve this confusion and to achieve harmonisation and accuracy in the quantification of woody biomass. Improving the quantification of woody biomass together with expanding the knowledge of units and unit conversions is essential to: 1) properly describe this material; 2) understand the variety of markets and the different units they use; 3) have better communication and understanding between buyer and seller in all stages of the supply chain; and 4) make woody biomass trading more transparent increasing trust in the fairness of prices (Philp, 2010; EFI, 2014a; b).

There are three different ways to quantify woody biomass: weight based, volume based and energy content based measurements (Lindblad *et al.*, 2010). Each of these approaches has advantages and disadvantages, which vary at each step of the supply chain. Wood is usually measured per tonne (t) or per cubic metre (m^{-3}) solid volume by the forest owner and forest manager; harvesters instead record production in terms of cubic metres over bark solid volume of roundwood; wood chip is expressed in cubic metres bulk volume, while the amount of energy is calculated per unit volume / weight (energy density / calorific value). The amount of energy is the most important variable when trading biomass fuels, and it varies greatly depending on the moisture content (Kofman, 2010). Biomass researchers frequently use oven dry weight as a common unit to present biomass, but dry weight is not used for valuation purposes. Forest owners or sellers generally prefer to be paid by weight or volume promptly after harvesting. On the contrary, payment based on energy content is preferred by users or buyers in the wood energy sector, because fuel quality at time of combustion is most important to them (Lindblad *et al.*, 2010). Moreover, as Hagauer and Pasteneir (2008) stated, ‘there are many differences in wood fuel trading units not only between countries, but also at a national level’.

In Ireland, wood is traded by weight in the private sector, and in cubic metres from Coillte (semi-state company) forest. The Irish wood industry (mainly sawmills and fibre panel board mills) often interchangeably uses price per tonne and per cubic metre (de Miguel *et al.*, 2016). Furthermore, the European Union has renewable energy targets of 32% of total energy supply by (European Directive 2018/2001), being in Ireland only 9.5 in 2016 (NREAP, 2017). While forecast availability of wood biomass is forecast to increase from 1.8 million m^3 in 2016 to 4.2 million m^3 in 2035 (Phillips *et al.*, 2016), demand for wood biomass is forecast to increase from

0.99 M m^3 in 2014 to more than 1.87 M m^3 in 2020 (COFORD, 2015). To service this demand, the industry will require information on wood energy prices and quantification, as well as the conversion from energy quantification to traditional wood markets units and valuation. Currently there are only 2 publicly available wood price indices in solid volume (€ m^{-3}) and energy (€ kWh^{-1}): 1) Standing sale prices, limited to Coillte conifer sites (Teagasc, 2018) and 2) Wood fuel energy price, from Sustainable Energy Authority of Ireland who has included wood fuel expressed in € kWh^{-1} in its energy price comparison statistics since 2008 (SEAI, 2018).

A grant premium category for Forestry for Fibre was introduced in the Irish Forestry Programme 2014-2020 (DAFM, 2014). The objective of this grant is to promote the development of Short Rotation Forestry (SRF) to meet the supply-demand gap for fibre for energy and other wood products applications in Ireland. Short Rotation Forestry is defined by Christersson and Verma (2006) as “the silvicultural practice under which high-density, sustainable plantations of fast-growing tree species produce woody biomass on agricultural land or on fertile but degraded forest land”. Eligible species for these grants are broadleaved species, capable of high productivity over a short rotation (10 to 20 years).

Many conversion tools have been developed to solve the issue above about the many different units to quantify and value wood biomass. A review of the existing tools and VEWTOOL was carried out and summarised in Table 5.1.

The existing tools were evaluated and VEWTOOL tool was built with the aim of improving on previous tools presented in Table 5.1. The following characteristics were used as a guide to make it a complete and comprehensive instrument:

- Educational. Does this tool educate the user in the conversions? VEWTOOL aims at educating the user in the conversions. The user can see how the conversions are done and definitions of the parameters are provided too. Furthermore, it intends to show how gaps in knowledge can be filled with reference parameters.
- Universal. Can this tool be used anywhere? The definitions and the methodology used for the conversions, as well as the predefined values used

in VEWTOOL, are those provided by the EN & ISO Solid Biofuel Standards developed to describe woodfuel in an accurate and unambiguous way that can be applied internationality.

- Flexible. Can the user input their own values and select the start point? VEWTOOL clearly explains the essential input parameters required but maintains the flexibility to add more parameters when available. Moreover, the tool allows the user to start with different parameters and convert from these.
- Accessible. Is the tool available to everybody? VEWTOOL has been created in a common excel spreadsheet so it is available for users without the need to install any additional software or application.
- Referenced. Are the parameters and their predefined values used in the tool referenced? VEWTOOL indicates its source of information, the EN & ISO Solid Biofuel Standards so users can refer to them if more details are needed.

VEWTOOL focuses on biomass material quantification, while some other tools focus on end use. Furthermore, while none of the other tools reviewed include conversions to different forms of calorific value expression, VEWTOOL accounts for carbon content too. Although it is possible to use just a specific part the tool, the tool is also comprehensive and allows for all the conversions in the same spreadsheet. This paper also shows how the tool can be used to quantify the amount and financial value of wood biomass from a case study of short rotation forestry in Ireland.

Table 5.1. Literature review and comparison of woodfuel unit conversion tools

Tool name	Description	Educational	Universal	Flexible	Accessible	Referenced	Reference
FP Joule	Estimates the amount of energy contained in the biomass and the economic savings compared to other traditional fuels.	No	Yes	No, just prices not amount	Yes	Yes	FPInnovations, 2020.
RenSMART Calculators	Converts logs prices from volume to kWh to compare to other fuels, allows comparing oil price with other fuels' prices, calculates CO_2 absorbed by a tree and CO_2 released generating electricity.	No	Yes	No	Yes	Yes	RenSMART, n.d.
Wood Energy Toolkit	Include four modules that allow for cost comparison between wood fuels and calculation of cost of fuel as delivered at the customer.	Just comments but not definitions or equations	No	Yes	Yes	No	Kofman, P. & Murphy, G. for the DAFM, 2019
Green ton converter	Converts between wood green weight and dry weight, based on moisture content.	Yes	Yes	No	Yes	No	Forest Business Network, 2011
Wood Fuel Calculator	Converts between dry and green weight, solid and bulk volume and energy units, considering moisture content.	Just definitions but not equations	No	Yes	Yes	No	Nejc Kebe, 2014

Table 5.1. (Continued)

Tool name	**Description**	**Educational**	**Universal**	**Flexible**	**Accessible**	**Referenced**	**Reference**
EECA Business Calculator	Small and specific tools, such as a wet/dry basis converter, biomass calorific value calculator, biomass volume to mass converter, energy unit converter, CO_2 emissions.	Yes	No, just *Pinus radiata*	Yes	Yes	Yes	EECA Business, n.d.
WeCalc	Calculates conversions of weight, volume and energy units and prices per these units, for various forest biofuels considering the assortment they come from.	No	Yes	Yes	Yes	No	Nylinder, M., & Kockum, F., 2016
Spreadsheet for the calculation of parameters and prices of wood fuel assortments	Calculates the main parameters for different wood fuel assortments and prices expressing them in different units.	No	Yes	No	Yes	Yes	Austrian Energy Agency, 2008
Technical Development Tools	Estimates cost comparisons for different types of fuels, assesses the quantity of woodfuel required to meet defined heating requirement and estimate the increase in value of the product due to processing.	Just comments but not definitions or equations	Yes	No	Yes	No	Forestry Commission, 2009
VEWTOOL	Quantifies wood biomass resources in weight, volume and energy units and permits direct comparisons between the valuations applied to the different market sectors.	Yes	Yes	Yes	Yes	Yes	This dissertation

5.2 Methods

5.2.1 Approach and tool development

VEWTOOL was developed using an Excel spreadsheet in order to make it widely accessible and easily usable. The tool serves the purpose of expressing amount of wood and market value in different units. The tool is comprehensive and is targeted at different users including forest landowners, woodfuel suppliers, foresters, and researchers as well as for teaching purposes. A flow chart of its development is outlined in Figure 5.1. Examples of the tool use are presented for the quantification of Short Rotation Forestry (eucalyptus, poplar) in Ireland.

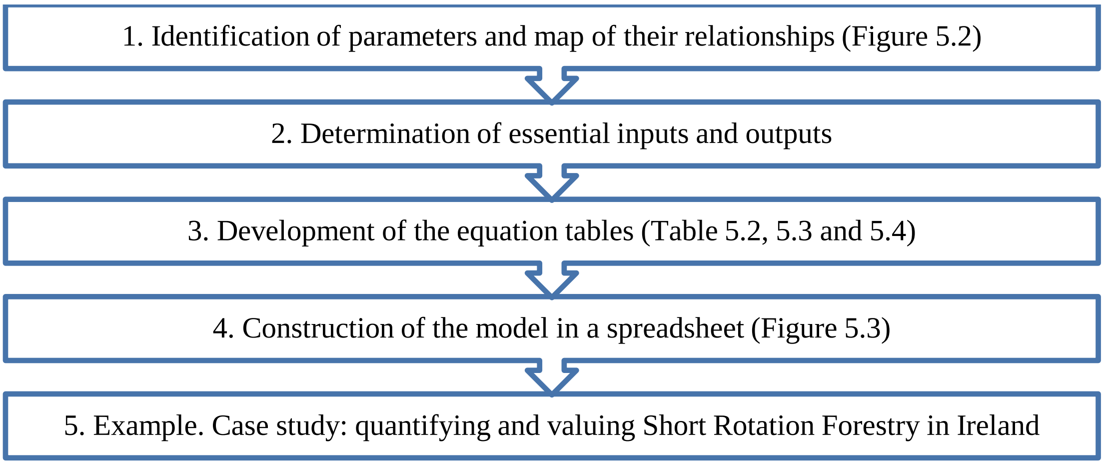


Figure 5.1. Development of the unit conversion tool workflow.

Although VEWTOOL is comprehensive and all the sub-routines are integrated (Figure 5.2), it is divided into its various components to allow for independent use of the sections of interest. Each tool section is outlined here:

- **Fuel Basic Parameters** includes the essential parameters required to carry out most conversions between measurement units (Table.5.2, green colour in Figure 5.2).

  There are two parameters to input: 1) moisture content, used to convert between total weight and dry weight, and gross calorific value and net calorific value; and 2) density, choosing from basic density, gross density, bulk density, used to define the wood volume-weight relationship and convert between these two variables. As moisture content and density are highly variable between species, partitions, conditions and treatment, no default values are provided by the tool. However, for the other essential parameters such as solid volume factor, calorific value in any of its forms, and ash content, default values are provided. Default values source are the solid biofuel standards for calorific value, ash, Hydrogen, Oxygen, Nitrogen and Carbon content (EN 14961-1, 2008) while solid volume factor from the Wood Fuels Handbook (Francescato *et al*., 2008). The user can displace the default parameter values with their own data, where that is available. Descriptive parameters (thus ID, assortment and fuel type) were also included with a list of default values.

- **Volume-Weight-Energy Converter** transforms the quantity of material to different units. The available options for conversion are: a) solid volume in cubic metres, b) bulk volume in cubic metres, c) total mass in tonnes, d) dry matter in oven dry tonnes, e) energy in Gigajoules and f) energy in Megawatts per hour (Table 5.3, red colour in Figure 5.2).
- **Financial Converter** allows for the expression of financial value in different units of volume, energy and weight. It calculates the value of the total amount of material according to the quantification unit in which it is expressed.
- **Calorific Value Converter** allows for the expression of calorific value or energy amount per unit mass released on complete combustion, to different bases. The tool includes default values for ash, Hydrogen, Oxygen, and Nitrogen contents, but allows the user to prioritise their own values if available (Table 5.4, yellow colour in Figure 5.2).
- **Carbon Converter** can be used to calculate the content of carbon contained in the input amount of biomass, and the equivalent CO_2 sequestered in this biomass. Default value Carbon content is provided but the user can displace the default value with their own data (Figure 5.2, blue cells and arrows).

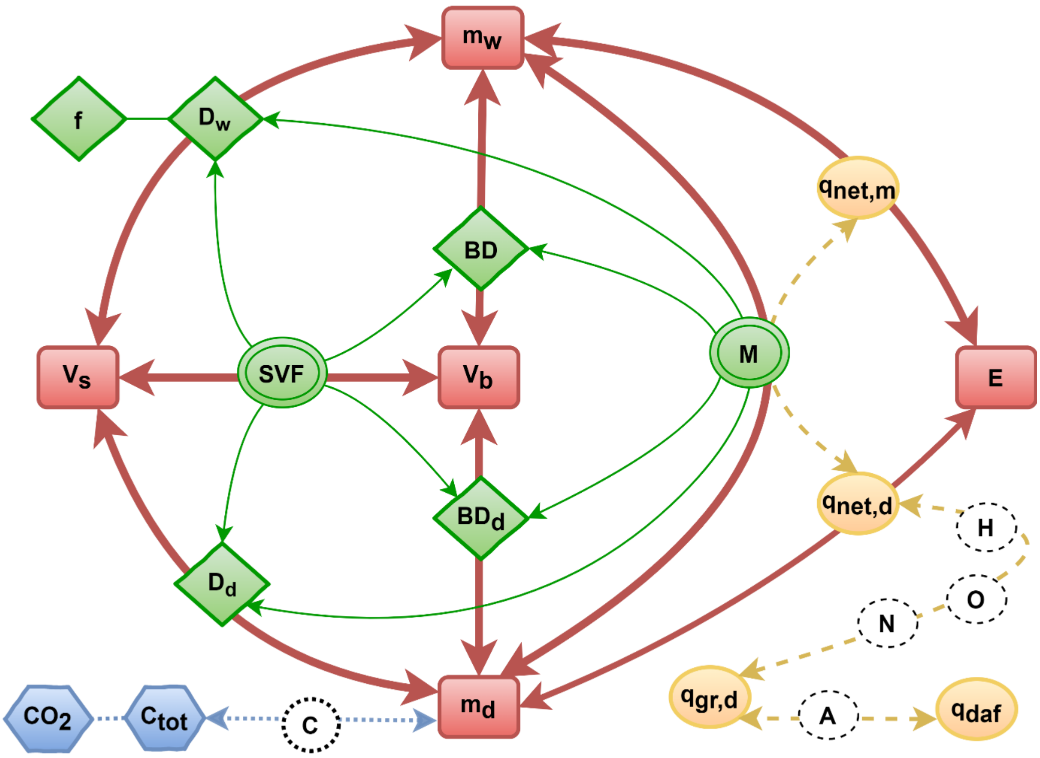


Figure 5.2. Unit conversion tool diagram. Parameters and their connections considered in the developed conversion tool. Legend:

Abbreviation	Parameter
A	Ash content
BD	Bulk density as received
BD_d	Bulk density dry
C	Carbon content
C_{tot}	Total Carbon
CO_2	Total CO_2 sequestrated
D_d	Basic density
D_w	Gross density
E	Energy Content
f	Volume Weight Factor
H	Hydrogen content
M	Moisture Content
m_d	Dry matter
m_w	Total Mass
N	Nitrogen Content
O	Oxygen Content
$q_{gr,d}$	Gross calorific value dry
$q_{gr,daf}$	Gross calorific value dry ash free
$q_{net,d}$	Net calorific value dry
$q_{net,m}$	Net calorific value as received
SVF	Solid Volume Factor
V_b	Bulk volume
V_s	Solid volume

Shape	Description
Square	Amount of material expressed in different basis
Diamond	Weight volume ratio
Continuous circle	Calorific value
Discontinuous circle	Parameters for calorific value
Double circle	Basic parameters for conversions
Dots circle	Carbon content
Hexagon	Carbon values
Thick arrows	Conversions between amounts of material expressed in
Narrow arrows	Conversions between weight volume ratios
Dashed arrows	Conversions between calorific values
Dotted arrow	Carbon conversion

Table.5.2. Volume-weight conversions

		Output parameter				
		Basic Density (kg m^{-3})	**Gross Density (kg m^{-3})**	**Bulk Density, dry (kg m^{-3})**	**Bulk Density, as received (kg m^{-3})**	**Volume Weight Factor (m^3 t^{-1})**
Input parameter	**Basic Density (kg m^{-3})**		D_d*(1-0.01M)$^{-1}$	D_d*SVF	D_d*SVC*(1-0.01M)$^{-1}$	10*(100-M)*D_d^{-1}
	Gross Density (kg m^{-3})	D_w*(1-0.01M)		SVC* D_w*(1-0.01M)	D_w*SVC	1000*D_w^{-1}
	Bulk Density, dry (kg m^{-3})	BD_d*SVC	BD_d*SVF^{-1}*(1-0.01M)$^{-1}$		BD_d*(1-0.01M)$^{-1}$	SVC*(100-M)*BD_d^{-1}
	Bulk Density, as received (kg m^{-3})	BD*(100-M)*SVC^{-1}	BD*SVC^{-1}	BD*(1-0.01M)		1000*SVC*BD^{-1}
	Volume Weight Factor (m^3 t^{-1})	10*(100-M)*f^{-1}	1000* f^{-1}	SVC*10*(100-M)*f^{-1}	1000*SVC*f^{-1}	

Table 5.3. Volume-weight-energy conversions

		Output parameter					
		Solid Volume (m^3)	**Bulk Volume (m^3)**	**Total Mass (t)**	**Dry Matter (odt)**	**Energy (GJ)**	**Energy (MWh)**
Input parameter	**Solid Volume (m^3)**		V_s*SVC^{-1}	V_s*D_w*0.001	V_s*D_d*0.001	V_s*$q_{p,net,m}$*D_w*0.001	V_s*$q_{p,net,m}$*D_w*3600^{-1}
	Bulk Volume (m^3)	V_b*SVC		V_b *BD*0.001	V_b *BD_d*0.001	V_b *$q_{p,net,ar}$*BD*0.001	V_b*$q_{p,net,m}$*BD*3600^{-1}
	Total Mass (t)	m_w*f	m_w*1000*BD^{-1}		m_w *(10-0.001M)	m_w *$q_{p,net,m}$	m_w *$q_{p,net,m}$*3.6^{-1}
	Dry Matter (odt)	m_d *1000* D_d^{-1}	m_d *1000*BD_d^{-1}	m_d (1-0.01M)$^{-1}$		m_d *$q_{p,net,d}$	m_d *$q_{p,net,d}$*3.6^{-1}
	Energy (GJ)	$E_{(GJ)}$*$q_{p,net,m}^{-1}$*f	$E_{(GJ)}$*($q_{p,net,m}$*BD)$^{-1}$ *1000	$E_{(GJ)}$*$q_{p,net,m}^{-1}$	$E_{(GJ)}$*$q_{p,net,d}^{-1}$		$E_{(GJ)}$*3.6^{-1}
	Energy (MWh)	$E_{(MWh)}$*$q_{p,net,m}^{-1}$ *f*3.6	$E_{(MWh)}$*($q_{p,net,m}$*BD)$^{-1}$ *3600	$E_{(MWh)}$*$q_{p,net,m}$*3.6	$E_{(MWh)}$*$q_{p,net,d}^{-1}$ *3.6	$E_{(MWh)}$*3.6	

Table 5.4. Energy conversions

		Output parameter					
		Gross Calorific Value, dry (MJ Kg $^{-1}$)	**Gross Calorific Value, dry, Ash free (MJ Kg $^{-1}$)**	**Net Calorific Value, dry, vol (MJ Kg $^{-1}$)**	**Net Calorific Value, as received, vol (MJ Kg $^{-1}$)**	**Net Calorific Value, dry, press (MJ Kg $^{-1}$)**	**Net Calorific Value, as received, press (MJ Kg $^{-1}$)**
Input parameter	**Gross Calorific Value, dry (MJ Kg $^{-1}$)**		$q_{gr,d}(1-0.01A)^{-1}$	$q_{gr,d}-0.206H$	$(q_{gr,d}-0.206H)*(1-0.01M)-0.02305M$	$(q_{gr,d}-0.212H)-0.0008(O+N)$	$(q_{gr,d}-0.212H)-0.0008(O+N)*(1-0.01M)-0.02443M$
	Gross Calorific Value, dry, Ash free (MJ Kg $^{-1}$)	$q_{gr,daf}(1-0.01A)$		$q_{gr,daf}*(1-0.01A)-0.206H$	$(q_{gr,daf}*(1-0.01A)-0.206H*(1-0.01M)-0.02305M$	$(q_{gr,daf}(1-0.01A)-0.212H)-0.0008(O+N)$	$[(q_{gr,daf}(1-0.01A)-0.212H)-0.0008(O+N)]*(1-0.01M)-0.02443M$
	Net Calorific Value, dry, vol (MJ Kg $^{-1}$)	$q_{v,net,d}+0.206H$	$(q_{v,net,d}+0.206H)*(1-0.01A)^{-1}$		$q_{v,net,d}(1-0.01M)-0.02305M$	$q_{v,net,d}-0.006H-0.0008(O+N)$	$[q_{v,net,d}-0.006H-0.0008(O+N)]*(1-0.01M)-0.02443M$
	Net Calorific Value, as received, vol (MJ Kg $^{-1}$)	$[(q_{v,net,m}+0.02305M)*(1-0.01M)^{-1}]+0.206H$	$\{[(q_{v,net,m}+0.02305M)*(1-0.01M)^{-1}]+0.206H\}*(1-0.01A)^{-1}$	$(q_{v,net,m}+0.02305M)*(1-0.01M)^{-1}$		$[(q_{v,net,m}+0.02305M)*(1-0.01M)^{-1}]-0.006H-0.0008(O+N)$	$\{[(q_{v,net,m}+0.02305M)*(1-0.01M)^{-1}]-0.006H-0.0008(O+N)\}*(1-0.01M)-0.02443M$
	Net Calorific Value, dry, press (MJ Kg $^{-1}$)	$q_{p,net,d}+0.212H+0.0008(O+N)$	$[q_{p,net,d}+0.212H+0.0008(O+N)]*(1-0.01A)^{-1}$	$q_{p,net,d}+0.006H+0.0008(O+N)$	$[q_{p,net,d}+0.006H)+0.0008(O+N)]*(1-0.01M)-0.02305M$		$q_{p,net,d}*(1-0.01M)-0.02443M$
	Net Calorific Value, as received, press (MJ Kg $^{-1}$)	$(q_{p,net,m}+0.02443M)*(1-0.01M)^{-1}+0.212H+0.0008(O+N)$	$[(q_{p,net,m}+0.02443M)*(1-0.01M)^{-1}+0.212H+0.0008(O+N)]*(1-0.01A)^{-1}$	$(q_{p,net,m}+0.02443M)*(1-0.01M)^{-1}+0.006H+0.0008(O+N)$	$[(q_{p,net,m}+0.02443M)*(1-0.01M)^{-1}+0.006H+0.0008(O+N)*(1-0.01M)-0.02305M$	$(q_{p,net,m}+0.02443M)*(1-0.01M)^{-1}$	

5.2.2 Case study. Using VEWTOOL to quantify and value four Short Rotation Forestry stands for different markets

The tool was utilised in a case study, evaluating quantity and value of biomass harvesting four Short Rotation Forestry (SRF) stands for different markets, based on the current Irish wood market conditions. Particularly seven questions were answered:

- Question 1: What is the quantification of the stands depending on market segment?
- Question 2: Is valuation of biomass to different quantification units depending on market segment?
- Question 3: Is financial value per hectare the same whether priced in cubic metres or tonnes?
- Question 4: What is impact of moisture content on quantification?
- Question 5: How does Volume Weight Factor vary with varying moisture?
- Question 6: How does quantification vary between using pre-defined or localised data?

Four SRF stands were measured by a combination of field work and laboratory work (see Chapter 4). In summary, the merchantable volume per hectare was calculated, where merchantable volume is the stem solid volume until a minimum diameter of 7 cm. The remainder of each tree, made up of the stem top and branches and termed residues were weighed in the field after harvesting. Samples of merchantable stem and residues were oven dried so moisture content and dry matter were calculated. The ratio between dry mass and solid volume of the merchantable stem determined basic density. Finally, subsamples of merchantable stem and residues were used to determine energy parameters: calorific value and ash content.

A summary of the stands' datasets that were used as inputs in the tool is detailed in Table 5.5. and Figure 5.6.

Table 5.5. Summary of SRF stands site description and biomass quantification.

Site	Species	Location	Stocking (trees ha^{-1})	Merchantable volume (m^3 ha^{-1})	Residues dry mass (odt ha^{-1})
EUC-WEX	*Eucalyptus delegatensis*	Kilbora, Co. Wexford	436	413	9
POP-CAV	*Populus* spp.	Ballyhaise Co. Cavan	258	330	26
EUC-WAT	*Eucalyptus nitens*	Cappoquin, Co.Waterford	842	743	24
POP-KIL	*Populus* spp.	Kildalton Co. Kilkenny	291	428	26

Table 5.6. Summary of SRF stands parameters from field measurements and laboratory analyses. Standard deviation of sampled parameters estimates in parenthesis.

Site	Basic Density (kg m^{-3})	Moisture Content Stem (%)	Moisture Content Residues (%)	Gross Calorific Value, dry. Stem (MJ kg^{-1})	Gross Calorific Value, dry Residues (MJ kg^{-1})	Ash Content Stem (%)	Ash Content Residues (%)
EUC-WEX	435 (40)	54 (2.0)	45 (1.6)	19.6 (0.05)	20.0 (0.10)	0.4 (0.03)	1.7 (0.06)
POP-CAV	311 (31)	54 (3.1)	43 (2.0)	19.4 (0.12)	19.3 (0.61)	1.1 (0.08)	1.7 (0.11)
EUC-WAT	388 (40)	61 (2.0)	52 (3.4)	19.2 (0.09)	20.0 (0.12)	1.2 (0.11)	2.3 (0.16)
POP-KIL	282 (36)	54 (4.1)	47 (1.9)	19.5 (0.15)	19.5 (0.12)	0.9 (0.10)	2.5 (0.92)

Relevant measurements and parameters for quantification for different markets were collected. Data collected in a market survey (Chapter 2, de Miguel *et al.*, 2016) showed a price of €40 t^{-1} at mill gate for pulpwood, the main assortment for the target fuel and fibre uses. Pulpwood in Ireland is the small roundwood, cut in 3 m length logs with a minimum end diameter of 7 cm. Oversize logs and logs with defects are also classified as pulpwood. Pulpwood may be chipped at forest roadside or can be transported to panel board mills for use in board manufacture or wood fuel producers for processing into woodchip and firewood. In this case study it was assumed all merchantable volume was valued at €40 t^{-1}. Residues, including the top of the tree, from 7 cm diameter to stem tip, and branches, can also be used as wood fuel. The mill gate price for residues was €22 MWh^{-1} (question 2).

Although pulpwood is traded mainly by weight, industry often quotes prices in cubic metres and tonnes interchangeably (question 3). If the market was fair, the harvested biomass value should not change independently of the unit price used. Therefore, mass unit price and solid volume unit price should be the same when one tonne of wood is exactly one cubic metre. However, this only happens in very specific conditions of basic density and moisture content. In other conditions, the ratio between total mass and solid volume should be:

$$\frac{P_{m_v}}{P_v} = 10 * (100 - M) * \mathrm{D_d}^{-1}$$

(Eq 5.1)

Where

M, moisture content in % of total weight;

D_d , basic density in kg m^{-3};

P_{mv}, unit price per t;

P_v, unit price per m^3.

Moisture content of wood is a very variable parameter and it changes if the wood is left in storage for a period of time. This variation influences the quantity of raw material in total mass and energy units: the tool was used to assess this influence (question 4). The minimum moisture content of the air dried wood is around 20% in Ireland. The variation of the ratio between total mass and solid volume with changes in moisture content was also calculated for the four SRF stands (question 5).

Finally, the use of predefined values when the user does not have localised parameter values was tested (question 6). Quantification and valuation of the 4 stands by using default values of calorific value and ash content was carried out. Default values were sourced from the Solid Biofuel Standard (ISO 17225-1: 2014). Ash content, expressed in dry weight percentage, was 0.3% and 5% for roundwood and residues respectively and gross calorific value, dry expressed in megajoules per kilogram were 20.1 MJ kg^{-1} and 19.7 MJ kg^{-1}, for roundwood and residues respectively. The results were compared to those using direct lab measurements of calorific value and ash content as inputs (Table 5.6 and Chapter 4).

The user defined parameters to run the tool in this case study were:

- Raw material type: Roundwood or logging residues for assortment and woodchip for fuel type. This only determined the Solid Volume Factor predefined value.
- Moisture Content: defined in Table 5.6
- Conversion factor weight-volume: Basic density described in Table 5.6. was selected but gross density, bulk density or volume weight factor could be used instead.
- Solid Volume Factor: in this case a predefined value for woodchip material of 0.4 was used.
- Calorific value: e.g. gross calorific value, dry in Table 5.6 was used but any other form of calorific value can be used.
- Ash content: defined in Table 5.6
- Total merchantable volume per ha: described in Table 5.5
- Total above ground biomass per ha: defined in Table 5.5
- Price: €40 t^{-1} was used for roundwood and €22 MWh^{-1} was used for residues.

5.3 Results

5.3.1. VEWTOOL, a volume-energy-weight conversion tool

VEWTOOL is comprehensive volume-energy-weight conversion tool developed in Excel (Figure 5.3). It is divided into its various components: Fuel Basic Parameters, Volume-Weight-Energy, Converter Financial Converter Calorific, Value Converter and Carbon Converter. The division in different sections allows for independent use of the area of interest.

INPUT PARAMETERS

	Parameter	Unit	User values	Predefined values
FUEL BASIC PARAMETERS	**Essential parameters**			
	Moisture Content	w-% ar	54	
	Basic Density	kg m-3	435	
	Solid Volume Content or Factor			0.4
	Gross Calorific Value, dry	MJ kg^{-1}		20.10
	Ash content	w-% d		0.3
	Desciptive parameters. Raw material type			
	ID			Decidous wood
	Assortment			Roundwood/Whole tree
	Fuel Type			Woodchip/Hogfuel
CONVERTER: WEIGHT, VOLUME AND ENERGY UNITS	**Convert from:**			
	Solid Volume	m3	1.00	

OUTPUT PARAMETERS

CONVERSION FACTORS		Parameter	Quantity	Unit
	WEIGHT-VOLUME	Basic Density	435	kg m^{-3}
		Gross Density	946	kg m^{-3}
		Bulk Density, dry	174	kg m^{-3}
		Bulk Density, as received	378	kg m^{-3}
		Volume Weight Factor	1.06	m^{3} t^{-1}
	ENERGY CONTENT PER MEASUREMENT UNIT	**Measurement Unit**	**Energy Content**	**Unit**
		Solid Volume	6.94	GJ m^{-3}
		Bulk Volume	2.78	GJ m^{-3}
		Total Mass	7.34	GJ t^{-1}
		Dry Matter	18.82	GJ t^{-1}
		Solid Volume	1.93	MWh m^{-3}
		Bulk Volume	0.77	MWh m^{-3}
		Total Mass	2.04	MWh t^{-1}
		Dry Matter	5.23	MWh t^{-1}

To:		
Solid Volume	1.00	m^{3}
Bulk Volume	2.50	m^{3}
Total Mass	0.95	t
Dry Matter	0.44	odt
Energy GJ	6.94	GJ
Energy MWh	1.93	MWh

Figure 5.3. Unit conversion tool Excel interface. A clear separation divides the input and output sections. Yellow cells are dropdown menus that offer various parameters choice options to the user; dark green cells are essential input parameters and light green cell allow to choose between default values or prioritise the users own values.

CONVERTER: FINANCIAL	Specific currency	€		**Total price**	**40.00**	**€**
	Specify a price per:			**Measurement Unit**	**Unit price**	
	Solid Volume	€ m -3	40	Solid Volume	40.00	€ m -3
				Bulk Volume	16.00	€ m -3
				Total Mass	42.30	€ t -1
				Dry Matter	91.95	€ odt -1
				Energy GJ	5.76	€ GJ -1
				Energy MWh	20.75	€ MWh -1

CONVERTER: CALORIFIC VALUES	Gross Calorific Value, dry	MJ kg-1	0	20.10	Gross Calorific Value, dry	20.10	MJ kg^{-1}
	Ash content	w-% d	0	0.3	Gross Calorific Value, dry, Ash free	20.16	MJ kg^{-1}
	Hydrogen Content	w-% d		6.2	Net Calorific Value, dry, vol	18.82	MJ kg^{-1}
	Oxygen Content	w-% d		44	Net Calorific Value, as received, vol	7.41	MJ kg^{-1}
	Nitrogen Content	w-% d		0.1	Net Calorific Value, dry, press	18.82	MJ kg^{-1}
					Net Calorific Value, as received, press	7.34	MJ kg^{-1}

CONVERTER: CARBON	Carbon Content	w-% d		49	Total carbon	0.21	t
					Total CO_2	0.78	t

Figure 5.3. (Continued)

5.3.2 Case study results

5.3.2.1 Question 1: What is the quantification of the stands depending on market segment?

Quantification of biomass in different units of volume, mass and energy was carried out using VEWTOOL. Table 5.7 shows the amount of raw material where merchantable volume per hectare in cubic metres was input and quantification of raw material in the other units was output.

Table 5.7. Biomass quantification to different bases per hectare in the four SRF stands, where input parameter is underlined, MV is merchantable volume and R is residues.

SRF site		**EUC-WEX**		**POP-CAV**		**EUC-WAT**		**POP-KIL**	
Parameter	**Unit**	**MV**	**R**	**MV**	**R**	**MV**	**R**	**MV**	**R**
Solid Volume	m^3 ha^{-1}	<u>413</u>	21	<u>330</u>	84	<u>743</u>	62	<u>428</u>	92
Bulk Volume	m^3 ha^{-1}	1033	52	825	209	1858	155	1070	230
Total Mass	t ha^{-1}	387	16	223	46	739	51	262	49
Dry Matter	odt ha^{-1}	180	<u>9</u>	103	<u>26</u>	288	<u>24</u>	121	<u>26</u>
Energy GJ	GJ ha^{-1}	2803	168	1553	463	4059	449	1851	473
Energy MWh	MWh ha^{-1}	779	47	431	129	1127	125	514	131
Total carbon	t ha^{-1}	88	21	50	84	141	62	59	92
Total CO_2	t ha^{-1}	323	52	184	209	518	155	217	230

5.3.2.2 Question 2: Is valuation of biomass to different quantification units depending on market segment?

SRF biomass was valued in different units of volume, mass and energy. Using a base price of €40 m^3 & €40 t^{-1}, biomass price per quantity unit was presented for other parameters (Table 5.8). Residues have the potential to be harvested and used for energy. Using a base price of €22 MWh^{-1}, residues biomass per quantity unit was presented in other bases (Table 5.9).

Results show the influence of parameter variation on price and the incapacity of only one unit to represent a fair valuation, what suggests unit must be related to market segment.

Table 5.8. Unit prices in different bases for the merchantable volume of the four SRF stands, where input unit price is €/t.

Unit price		EUC-WEX	POP-CAV	EUC-WAT	POP-KIL
Solid Volume	€ m^{-3}	37.83	27.04	39.79	24.52
Bulk Volume	€ m^{-3}	15.13	10.82	15.92	9.81
Total Mass	€ t^{-1}	40.00	40.00	40.00	40.00
Dry Matter	€ odt^{-1}	86.96	86.96	102.56	86.96
Energy GJ	€ GJ^{-1}	5.60	5.75	7.28	5.67
Energy MWh	€ MWh^{-1}	20.15	20.69	26.23	20.42
Carbon t CO2	€ t CO_2	48.40	48.40	57.09	48.40

Table 5.9. Unit prices in different bases for the residues of the four SRF stands, where input unit price is underlined.

Unit price		EUC-WEX	POP-CAV	EUC-WAT	POP-KIL
Solid Volume	€ m^{-3}	49.78	33.84	54.66	31.37
Bulk Volume	€ m^{-3}	19.91	13.54	21.86	12.55
Total Mass	€ t^{-1}	62.94	62.03	54.94	58.96
Dry Matter	€ odt^{-1}	114.44	108.83	140.87	111.25
Energy GJ	€ GJ^{-1}	6.11	6.11	6.11	6.11
Energy MWh	€ MWh^{-1}	22.00	22.00	22.00	22.00
Carbon t CO_2	€ t CO_2	61.20	58.20	75.34	59.50

5.3.2.3 Question 3: Is financial value per hectare the same whether priced in cubic metres or tonnes?

Table 5.10 shows financial comparison between trading by weight or by volume using the same industry-quoted price of €40 m^{-3} and €40 t^{-1}. The variation in total value per hectare when trading roundwood in cubic metres compared to tonnes was €898 ha^{-1} for EUC-WEX site, €4,276 ha^{-1} for POP-CAV site, €152 ha^{-1} for EUC-WAT and €6625 ha^{-1} per ha in POP-KIL. This means an average of 3% higher value when trading for m^3 for the eucalyptus stands (EUC-WEX and EUC-WAT sites) while 36% for the poplar stands (POP-CAV and POP-KIL sites). The tool was also used to calculate the value per ha of residues for the stands so a total above ground biomass was calculated (Table 5.10). Results in Table 5.10 show that price per tonne and price per cubic metre are not the same and there is a disadvantage to the forest owner of end-users specifying payment per tonne.

Table 5.10. Financial value per hectare delivered of the merchantable volume for the four SRF stands (EUC-WEX, POP-CAV, EUC-WAT and POP-KIL).

	Unit	**EUC-WEX**	**POP-CAV**	**EUC-WAT**	**POP-KIL**
Merchantable volume	m^3 ha^{-1}	413	330	743	428
Total price (from unit price €40 t^{-1})	€ ha^{-1}	15,622	8,924	29,568	10,495
Total price (from unit price €40 m^{-3})	€ ha^{-1}	16,520	13,200	29,720	17,120
% Difference		5%	32%	1%	39%
Residues odt ha^{-1}	odt ha^{-1}	9	26	24	26
Total price of residues (from unit price €22 MWh^{-1})	€ ha^{-1}	1,030	2,830	2,745	2,892
Total price for above ground biomass (from roundwood unit price €40 t^{-1})	€ ha^{-1}	16,652	11,754	32,313	13,387
Total price for above ground biomass (from roundwood unit price €40 m^{-3})	€ ha^{-1}	17,550	16,030	32,465	20,012
% Difference		5%	27%	0%	33%

5.3.2.4 Question 4: What is impact of moisture content on quantification?

VEWTOOL was used to evaluate the influence of moisture content and basic density on the quantity of raw material expressed on different units. Moisture content and basic density had an impact in the solid volume of raw material when expressing it in mass and in energy. One cubic metre solid volume for each of the four stands was expressed as bulk volume, total mass, dry matter and energy at different moisture contents (Figure 5.4). When moisture content increases the amount of raw material expressed in total mass increases and in energy decreases, while volume and dry matter remain constant as they do not depend on moisture content. Eucalyptus has a higher basic density than poplar. Therefore, one cubic metre of eucalyptus has higher mass, both dry and total, and also higher energy content than poplar.

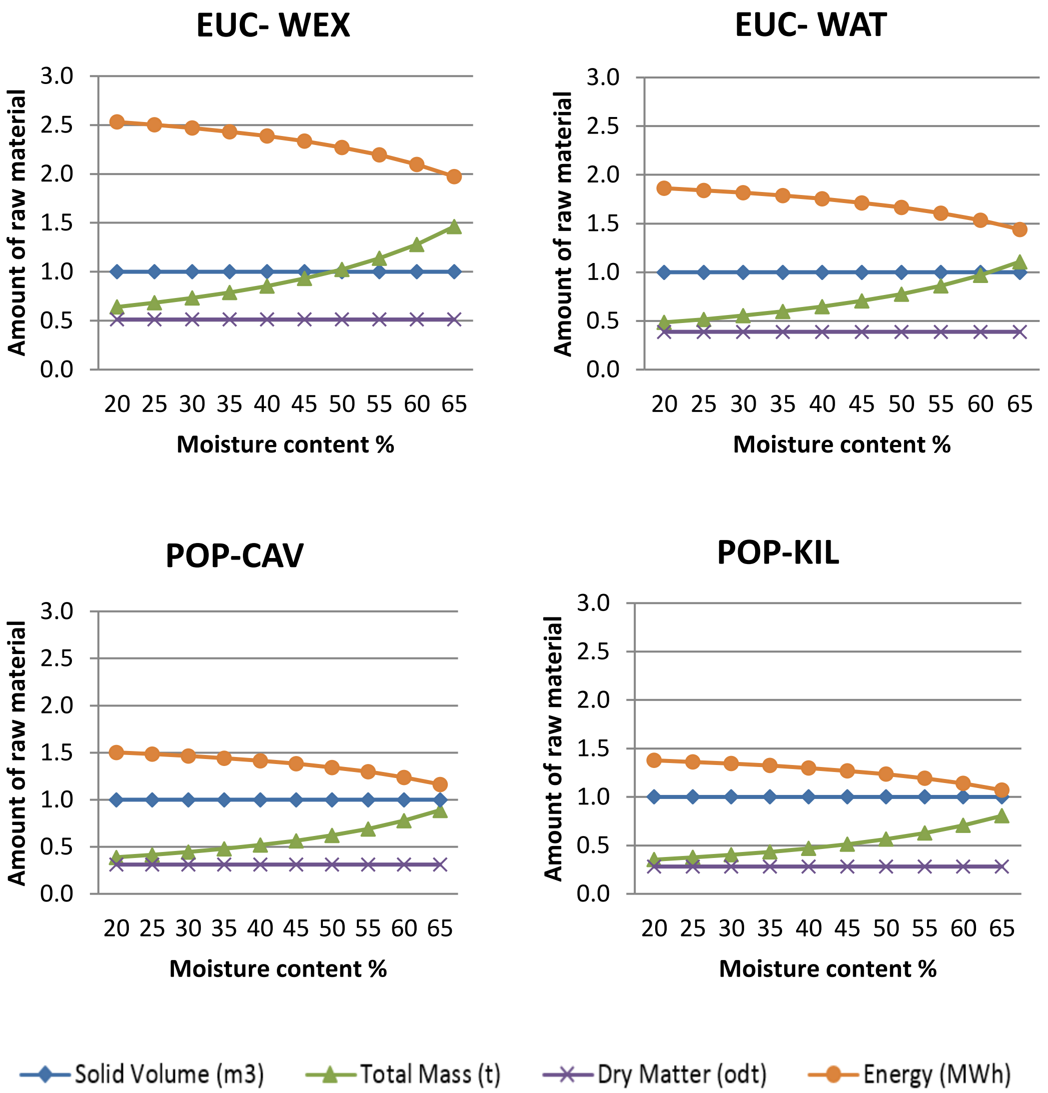


Figure 5.4. Effect of moisture content and basic density on amount of raw material on different bases for the four short rotation forestry stands (EUC-WEX, POP-CAV, EUC-WAT and POP-KIL).

The influence of moisture content on weight and energy content per ha for the 4 SRF stands was also studied (Figure 5.5). If wood was left to dry from the current moisture of the stands (detailed in Table 5.5) to 40%, there would be an average decrease of 116 t c in biomass weight and an increase of 79 MWh ha^{-1} in biomass energy content. If dried to 20%, the average decrease would be of 188 t ha^{-1} and the increase of 136 MWh ha^{-1}.

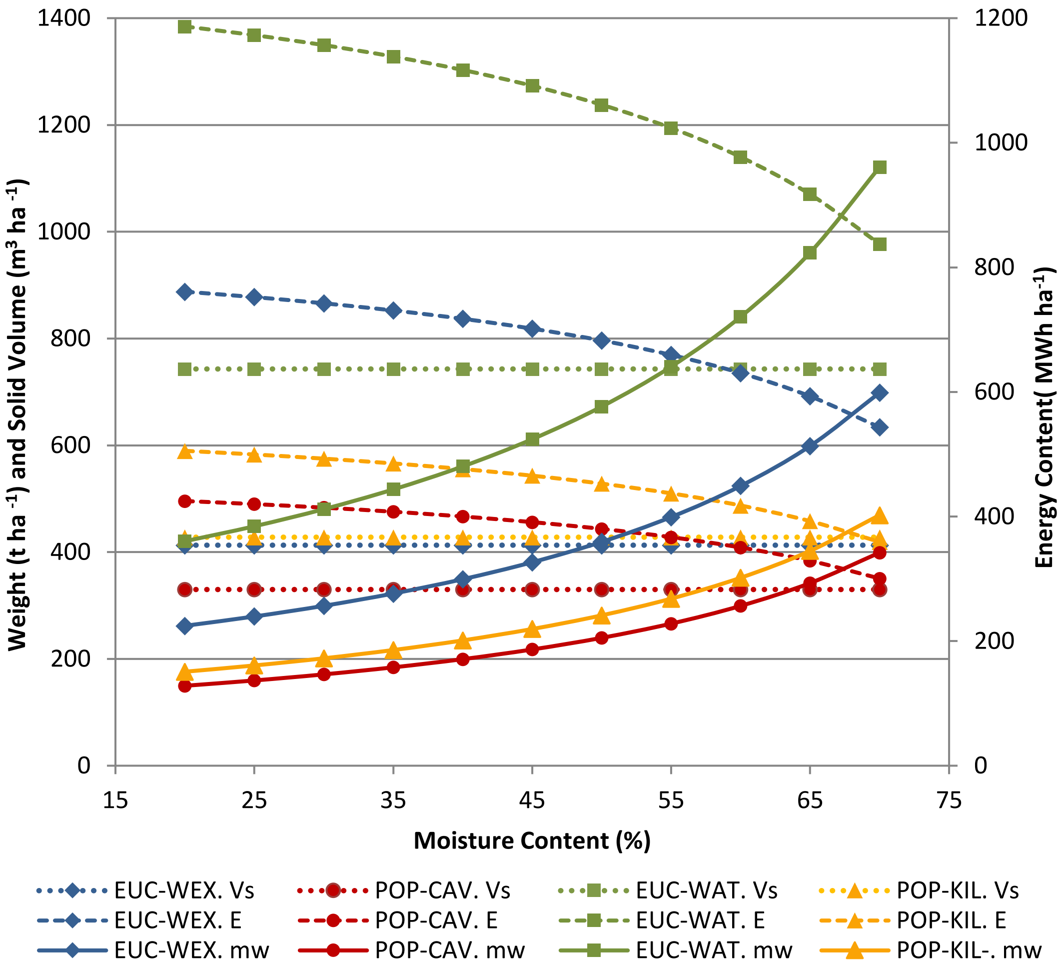


Figure 5.5. Comparison among the four SRF stands (EUC-WEX, POP-CAV, EUC-WAT and POP-KIL) of the influence of moisture content on solid volume, weight and energy content per hectare.

V_s, Solid volume m^3 ha^{-1}

E, Energy in MWh ha $^{-1}$

m_w, total mass or green weight t ha^{-1}

5.3.2.5 Question 5: How does Volume Weight Factor vary with varying moisture?

The data collected in the survey was based on the current Irish wood market dominated by Sitka spruce (*Picea sitchensis* (Bong.) Carr.), which has a mean density of 364 kg m^{-3} (WIT, 2017). In the case of Sitka spruce, one m^3 was equal to one tonne when moisture content was 63.6% (Eq 1) but for the SRF sites this occurs when moisture contents were 56.5%, 68.9%, 61.2% and 71.8% for sites EUC-WEX, POP-CAV, EUC-WAT and POP-KIL, respectively. In other conditions of moisture content, the ratio of price in weight and volume varied as in Eq 1 (Figure 5.6).

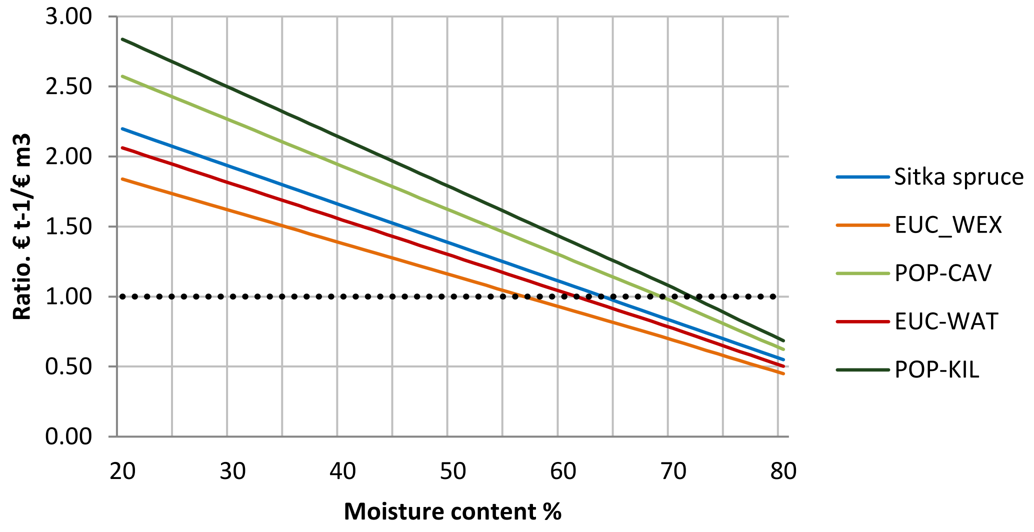


Figure 5.6. Relation between total mass and solid volume unit prices depending on moisture content for a same total price

In addition, wood for energy is also sold by energy units. Figure 5.7. shows the influence of moisture content on revenue per ha when the wood was sold by energy units, at €0.022 kWh$^{-1.}$ Values of total above ground biomass at current moisture of the stands ranged from €12,050 ha^{-1} in POP-CAV site to €27,490 ha^{-1} in EUC-WAT, while if the resource was left to dry until 20%, it ranged from €13,848 ha^{-1} in POP-CAV site to €33,739 ha^{-1} EUC-WAT site. This means an average of 15% increase on revenue per ha leaving to dry to 20%.

Figure 5.7 also shows the potential additional value of residue harvesting. Above ground biomass harvesting compared to only merchantable volume harvesting had an average €2359 ha^{-1} or 12% increase on revenue. However, costs were not discounted in this study for any merchantable volume and above ground biomass. If residue harvesting costs are high it could make only marginal additional revenue or even loss making. This suggest residue biomass availability could depend on price and residue harvesting costs.

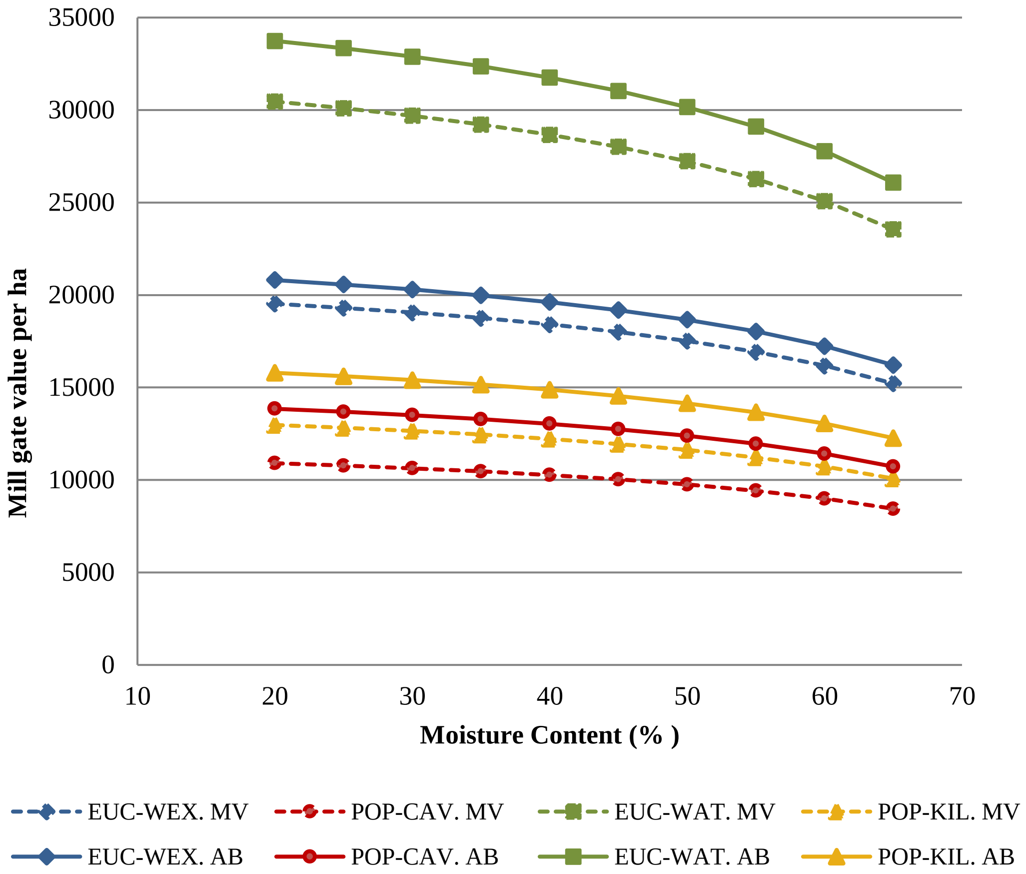


Figure 5.7. Comparison of value per ha for merchantable volume and total above biomass of the influence of moisture content on the 4 SRF sites when selling at €0.22 kWh-1. Costs were not discounted for any merchantable volume and above ground biomass.

MV Merchantable volume

AB Total above ground biomass

VEWTOOL was used to make a comparison between energy products prices per cubic metre when the wood is sold in other units. While woodchip producers buy pulpwood in tonnes or cubic metres, woodchips and brash bundles are valued by energy content. Table 5.10 shows the variation on mill gate prices per cubic metre for each of the energy products and sites. The same input parameters of each site (basic density, moisture content and energy content) was used as in previous example. While eucalyptus sites maintain similar unit price in cubic metres independent of the input unit price, poplar site unit prices in cubic metres decreases considerably when input prices are in tonnes and in kilowatt hours. This is due to the volume weight relationship described above.

Table 5.11. Mill gate unit prices for energy products of the four SRF stands (EUC-WEX, POP-CAV, EUC-WAT and POP-KIL) in € m^{-3} considering each stand characteristics of moisture content, basic density and energy content.

Input mill gate price	Assortment	Raw material sold as	Mill gate prices € m^{-3} EUC-WEX	POP-CAV	EUC-WAT	PO-KIL
€40 m^{-3}	Pulpwood	Pulp to woodchip producers	40.00	40.00	40.00	40.00
€40 t^{-1}	Pulpwood	Pulp to woodchip producers	37.02	25.92	38.80	24.52
€0.022 kW h^{-1}	Pulpwood	Woodchip from pulp chipped in the forest	41.42	28.65	34.37	26.30
€0.022 kW h^{-1}	Residues (tops and branches)	Woodchip from residues chipped in the forest	44.50	30.12	37.86	27.79

5.3.2.6 Question 6: How does quantification vary between using pre-defined or localised data?

The use of default values of ash content and calorific value, tested on the quantification and valuation of the 4 stands, showed similar results to using lab values and default values with variations of around 2% (Table 5.12).

Table 5.12. Comparison of quantification and valuation for the merchantable volume and residues of the four SRF stands by using direct measurements vs default values of calorific value and ash content. Input merchantable value and dry matter, underlined.

		EUC-WEX		POP-CAV		EUC-WAT		POP-KIL	
Parameter	**Unit**	**Lab**	**Default**	**Lab**	**Default**	**Lab**	**Default**	**Lab**	**Default**
Roundwood Volume	m^3 ha^{-1}	<u>413</u>	<u>413</u>	<u>330</u>	<u>330</u>	<u>743</u>	<u>743</u>	<u>428</u>	<u>428</u>
Roundwood Energy	MWh ha^{-1}	786	796	428	455	1,150	1,201	510	535
Residues Dry Matter	odt ha^{-1}	<u>9</u>	<u>9</u>	<u>26</u>	<u>26</u>	<u>24</u>	<u>24</u>	<u>26</u>	<u>26</u>
Residues Energy	MWh ha^{-1}	47	46	129	133	125	123	132	133
Residues price per ha	€ ha^{-1}	1,029	1,015	2,830	2,933	2,745	2,708	2,892	2,933
Aboveground biomass price per ha	€ ha^{-1}	16,651	16,637	11,754	11,857	32,313	32,276	13,387	13,428

5.4 Discussion and conclusions

By answering the seven case study questions described above, the results demonstrate the capacity of VEWTOOL to:

a) Quantify biomass to different bases. The tool allowed to express stands in different units of volume, mass and energy while provided the ability to the effect of moisture content and basic density on the amount of raw material on different bases.

b) Value biomass to different bases. VEWTOOL served to calculate financial value of the stands while made possible to compare unit prices given in different units, and particularly to demonstrate the relation between price per tonne and cubic metre. The ability of the tool to evaluate effect of moisture content and basic density on value was also shown in the case study.

VEWTOOL allows for appropriate valuation of different biomass types to different markets based on quantification units relevant to that market. Results showed no one unit can represent a fair quantification, it must be related to market segment. VEWTOOL can help forest landowners, woodfuel suppliers and foresters to quantify, price and compare wood products for different markets. This increase of information can encourage more transparency in the market. In addition, researchers can also benefit from using this tool while comparing results to other sources in different units.

The ability of the tool to convert prices to different units allows for a comparison of unit prices. Roundwood volume per hectare of the standing trees is usually measured pre-harvesting. However, if the material is sold for markets based on other units, such as weight, dry matter or energy content, then quantification in these units is required for a fair and transparent market. Although in a fair market the total value of the stand for a same product should be the same independently of the units, results of the SRF study case showed significant differences in the current Irish system. There are up to €6,625 ha^{-1} difference between trading by cubic metres and by tonnes. Only at very particular conditions of moisture content specific for each basic density (one tonne and one cubic metre), the prices are the same. This tool can also be useful for landowners to calculate the most profitable markets but accurate wood moisture and density is required to get appropriate results as these parameters are highly variable to site. Appropriate measurement systems of these two parameters are essential to obtain accurate results from the tool and should be introduced in the trade system.

Furthermore, moisture content of wood is a very changeable parameter and its variation causes significant changes in weight and energy content but not in volume. Therefore, stand value when the material is sold by weight or energy content varies at different moistures but not when is sold by volume. Oven dry weight is commonly used to quantify biomass because of the variability of weight with moisture content. However, it does not consider the condition of the biomass: in particular the energy content as received, an essential parameter for biomass sold for energy purposes. Therefore, quantifying biomass by oven dry weight means that the variation in energy content and weight on biomass valuation and supply chain costs is lost.

The tool also facilitates estimating a target moisture content to dry a product in order to get a specific return. The forest owner can add value to biomass by storing and reducing moisture content. However, although it would be useful to encourage reducing moisture to increase energy content, since often woodfuel is traded by weight, the landowners could lose money if selling a drier wood. It would only work if market pays based on energy content. Furthermore, storing biomass to dry would tie up capital for the drying time, so the forest owner should plan and consider this when taking the drying option. In addition, an achievable moisture content should be targeted. Climate and season affect highly wood drying so it could be difficult to reduce considerably moisture content of wood stored in the forest in Ireland even if it is stored for months (Coates *et al.*, 2016).

VEWTOOL is a comprehensive instrument that educates the user in the conversions, improving on some of the other existing tools that do not provide the equations used for the conversions and the definitions of the parameters (Austrian Energy Agency 2008; Nylinder, M. & Kockum, F., 2016; FPInnovations, 2020). VEWTOOL can be used anywhere on any species, improving on other tools limited to some local requirements, such as the EECA Business Calculator, designed for *Pinus radiata* only. Flexibility is another advantage of VEWTOOL as it allows the user to start with different parameters and convert from these. The user's own values may be input when available unlike other tools such as RenSMART Calculators (RendSMART,n.d.) that only have fixed values for the conversions. VEWTOOL indicates the source of information for the equations and predefined values, compared to other tools that do not provide this information such as the Wood FuelCalculator (Nejc Kebe, 2014) which gives certain species options but provides no source information about parameters used for the conversions.

One limitation of VEWTOOL is the lack of a feasible range and error range for the default values defined in the Solid Biofuel Standards. It would be recommended to produce this information in the future and include it in the tool. Also directly measured values would benefit from a range and error range, are they are generally only sample estimates. Another additional work would be to include a biomass expansion factor (BEF) parameter. This would allow calculating the whole tree quantity and value when only merchantable volume and BEF are known but not the total above ground biomass, as merchantable volume is easily estimated using forest mensuration procedures (Matthews and Mackie, 2006) but calculating the quantity of above ground biomass is much more resource intensive (Picard *et at.*, 2012).

Valuation carried out in this chapter was based on biomass value delivered to the enduser, so did not take into account the supply chain costs of harvesting, extraction, transportation and processing up to the point of entry to the enduser. This valuation is useful from the perspective of estimating the economic potential of the SRF system, but not from the perspective of the landowner. For instance, results from the case studied showed the additional biomass from residue harvesting could add value to the forest owner but it would depend on market prices and cost of this additional harvesting. If after costs are included, residue harvesting offers only marginal benefits or is loss making, forest owners will not see any advantage in residue harvesting. This problem was addressed later in this dissertation. Supply chain cost are described in Appendix B and valuation considering these costs was carried out in Chapter 6.

Different wood markets interested in a variety of wood characteristics (volume, weight, energy) have been developed and this includes an emerging carbon market. A correct quantification and value of all these wood characteristics is required for a more fair and transparent market. This tool represents an improvement in this direction, providing a comprehensive framework for quantification, value and comparison of wood for the different markets.

Chapter 6: Determining short rotation forestry *Eucalyptus* spp. and *Populus* spp. recovery value and log product yields using optimal bucking in Ireland

Chapter 6: Determining short rotation forestry *Eucalyptus* spp. and *Populus* spp. recovery value and log product yields using optimal bucking in Ireland

Abstract

Short Rotation Forestry (SRF) is a new forestry practice in Ireland that is expected to increase in response to the increasing demand for fuel to achieve renewable energy targets and fibre for board products. This paper analyses the effect of optimal stem-level bucking, the process of cutting tree stems into shorter logs, on the financial value to the short rotation forest owner. Two analyses were carried out: 1) Optimal log product yields and value recovery of four SRF sites (two eucalyptus and two hybrid poplar stands) at their current age; 2) Optimal financial rotation of one of the eucalyptus stands. Eleven supply chains and two payment unit methods of quantifying roundwood were evaluated. VALMAX was the log bucking optimisation programme used and had as inputs: 1) biomass measurements (reported in Chapters 4 and 6); and 2) market data on logs specifications and mill gate prices collected in a market survey (reported in Chapters 2 and 3). The main findings were: 1) Supply chains generating a product assortment mix had higher revenue than those producing a dedicated energy crop or fibre crop; 2) Eucalyptus sites had higher value, an average of €16,087 ha^{-1} while poplar sites had lower value averaging €8,134 ha^{-1}. Factors influencing this were higher yield of products from eucalyptus (mean of 584 m^3 ha^{-1}) compared to poplar (mean of 436 m^3 ha^{-1}) and higher basic density of eucalyptus (mean of 412 kg m^{-3}) compared to poplar (mean of 297 kg m^{-3}); 3) Assuming 1 tonne equals 1 m^3 of roundwood in quantification for payment purposes affects revenue, particularly the poplar stands due to their lower basic density; 4) Optimal financial rotation for the eucalyptus stand was 20-21 years for all the supply chains, considering a discount rate of 5%.

6.1 Introduction

6.1.1 Short Rotation Forestry in Ireland

Short Rotation Forestry (SRF) is defined by Christersson and Verma (2006) as "the silvicultural practice under which high-density, sustainable plantations of fast-growing tree species produce woody biomass on agricultural land or on fertile but degraded forest land". SRF rotation length is usually between 8 and 20 years.

Currently the SRF area in Ireland is very limited and has mainly focused on eucalyptus and to a lesser extent hybrid poplar (Teagasc, 2014a). Coillte, the Irish semi-state forestry company, established a series of field trials of eucalyptus in 1992/93 with the main objective of timber production (Neilan and Thompson, 2008). In 2008, Coillte started the establishment of eucalyptus plantations for fibre production for panel boards and biomass for energy (Thompson *et al.*, 2012). A survey of the newer Coillte plantations carried out in 2014 indicated that there were 333 ha of eucalyptus on 53 sites, particularly in the south and east of Ireland, established over the previous 6 years (Coates, 2017). Regarding poplar, a total of 80 ha were estimated in 2003 (Keary, 2003), with no evidence of subsequent expansion as poplar was not a species approved under the Afforestation scheme until 2014 (DAFM, 2014).

One of the aims of Ireland's forest policy is to encourage planting by private landowners in order to increase the forest national cover from the current 11% (Forest Service, 2017) to 18% by 2046. Ireland's 100% State aid funding for forestry for the period 2014 to 2020 is standardised in the Irish Forestry Programme 2014-2020. A new grant premium category was described there for Forestry for Fibre: this has the objective of meeting the supply-demand gap for fibre, energy and other wood product applications that is forecasted to arise over the next 2 decades (DAFM, 2014). SRF grants in Ireland allow for a rotation between 10 to 20 years (DAFM, 2014) with a target rotation of 12 to 15 years for eucalyptus. Although sawmills and fibreboard mills are the main wood industries in Ireland, the wood energy sector has also developed in recent years (IFFPA, 2016) and annual wood fuel demand is predicted to increase from 1.91 Mm^3 in 2014 to 3.26 Mm^3 in 2020 in the whole island of Ireland (COFORD, 2015). Fibreboard production is also expected to expand from 1.4 Mm^3 of wood fibre in 2014 to 1.6 Mm^3 by 2020 (COFORD, 2015), while roundwood harvested in the Ireland is predicted to increase from 3.0 Mm^3 in 2016 to 3.7 Mm^3 in 2020 (O'Driscoll, 2017). Furthermore, a considerable increase in roundwood demand to 4.7 Mm^3 in 2020 is also predicted. This will produce an expected shortage of 0.9 Mm^3 by that year in the Ireland (COFORD, 2015).

SRF could also help to meet Ireland's renewable energy targets, which are set to reach 32% of total energy supply on the European Union by 2030 (European Directive 2018/2001), while only 9.5% of the Gross Final Energy Consumption came from renewable sources in 2016 (NREAP, 2017). A total of 2,269 ktoe (kilo tonne of oil equivalent) of energy consumption should come from renewable sources by 2020 while only 1,605 ktoe were expected from renewable sources in 2015 (NREAP, 2010). Domestic forest biomass is expected to contribute 258 ktoe energy in 2020 (Ibid). The afforestation programme planting target for SRF is 3,300 ha by 2020. However, SRF establishment has been very limited until 2020 and since the industry has not yet demonstrated acceptance of SRF material, SRF markets in Ireland have not yet been developed. Data on market raw material requirements and prices as well as perceptions on the use of SRF was gathered by surveying 30 companies of the current Irish wood processing and biomass sectors (see Chapter 2). It was found that the wood energy sector was the most favourable toward SRF. The other sectors agreed that the main use of SRF would be energy. Some pallet and fibre users would also consider using SRF.

The harvesting method in Ireland is cut to length (CTL). The harvester processes different roundwood assortments and places them in bunches that are forwarded to the roadside. With the development of the forest energy sector, the integrated and the whole tree harvesting methods are also used in thinnings (Coates *et al.*, 2016) and in addition to pulp logs, both whole trees and residues in bale form are already used for wood fuel in Ireland (Coates *et al.*, 2014). In the integrated harvesting method, the harvester processes sawlog assorments only and the rest of the tree is separated as a biomass product. Both sawlog and biomass are forwarded to roadside and stacked separately. In the whole tree method the harvester processes the whole tree into lengths that are suitable for the forwarder to extract to roadside.

6.1.2 Bucking optimisation

Mathematical models have been used since the early 1960s to deal with wood procurement problems (Rönnqvist, 2003). Optimal allocation of wood products was described as the process of maximising the net value recovery, meaning the financial return the forest owner will gain from the sale of forest products once all the costs have been subtracted and operational and marketing constraints have been met (Murphy, 1998).

A part of the allocation process that takes place in the harvesting operation is bucking, thus the activity of cutting tree stems into shorter logs with specific diameter ranges and length. The harvesting operation depends on volume, value and cost (Twaddle and Goulding, 1989), since:

$$Profit = Volume * (Value - Cost)$$

Optimal profit will be reached when volume and value are maximised while cost is minimised. Optimised bucking translates to an increase of value and therefore improves the harvesting process profitability and the net value recovery of the forest.

Since the resulting logs are often suitable for different products, bucking aims to optimise the cutting pattern that maximises the value from their use (Uusitalo, 2007). In the cut to length method, bucking occurs during harvesting. In other harvesting methods, such as the pole length or the whole tree method, the bucking takes place at a later stage of the supply chain, for instance at forest landing area or at the mill.

Three different levels of bucking optimisation have been identified: stem, stand and forest levels (Laroze, 1999). At the stem level the objective is to maximise the value of each individual tree and this is possible when the market is supply-constrained; that means the market will take the amount of each log type produced irrespective of its volume (Murphy *et al.*, 2004). This is the best situation for the forest owner. However, demand-constrained markets are more common than supply-constrained markets and the optimal bucking for individual stems may not meet market and operational constraints at the stand or forest level (Marshall *et al.*, 2006); in these cases bucking to order is necessary. Bucking to order means optimisation from the point of view of the log customers instead of the forest owner and aims to optimise the value at the stand or forest level, which does not necessarily maximise the value of every stem, as options will be constrained by the quantity of each size category that the industry is willing to take.

In a supply-constrained market and at the stem level, dynamic programming (DP) has been the most popular optimisation algorithm. The first stem level bucking optimisation algorithm that used DP was developed by Pneumaticos and Mann (1972) and since then a variety of algorithms have been proposed (Briggs, 1980; Sessions, 1988; Wang *et al.*, 2004; Arce *et al.*, 2004). The DP approach to bucking divides the potential merchantable stem into potential positions where each crosscut could be made. The length between potential positions is constant and each log length is a multiple of this value (Briggs, 1989). Market requirements on log lengths and diameters are constraints of the model, which limit the number of cutting locations. Market price variations decide the optimal cut. Other market constraints on external wood quality and sweep or internal properties, such as basic density, may also be included in DP models (Acuna and Murphy, 2005). Murphy *et al.* (2011) found that not taking sweep into consideration results in about 3% overvaluation. as this defect would reduce suitable volume for some products.

Researchers and industry have used different optimisation algorithms to answer bucking questions and software packages have been developed and used for this aim, as outlined in Table 6.1.

Table 6.1. Bucking optimisation software

Software name	Objective	Authors	Accessibility	Used by (Available referenced use)
AVIS (Assessment of Value by Individual Stems)	Determine optimal value of each stem based on the bucking	Geerts and Twaddle, 1984	No longer available	Twaddle and Goulding, 1989; Lang et al., 2010; Conradie et al., 2004; Boston and Murphy, 2003
OSU Buck	Determine optimal value of the stem based on the bucking and considering cost	Sessions *et al.*,1993	Commercial	Olsen et al., 1997; Pilkerton and Kellogg, 2011
Treeval	Determine optimal value of stem or stand based on the bucking	Briggs, 1989	Public domain	N/A
IP Buck	Determine optimal value of each stem based on the bucking including basic density	Acuna and Murphy, 2005	No longer available	Acuna and Murphy, 2005
Valmax	Determine optimal allocation of products to markets at stem, stand or forest level	Murphy, 2008	Commercial	Murphy, 2008; Acuna et al., 2009; Murphy et al., 2011
Optware	Maximise profit of log-supply operations	Optware Solutions LLC	Commercial	Optware Solutions LLC, 2019
WOODSIM	Maximise profit of log-supply operations	Halco. Sotware Systems Ltd.	Commercial	Halco. Sotware Systems Ltd., 2020
Atlas	Maximise profit of log-supply operations with option of including internal properties	Atlas Technology. Integral.	Commercial	Atlas Technology Integral, 2014
YTGEN	Prediction of optimal yields by recoverable log grade	Interpine Group Ltd	Commercial	Interpine Group Ltd, 2018

Many studies compared the effect of traditional bucking and bucking optimisation on economic value, where traditional bucking was manual bucking with chainsaw or mechanised by harvester but with the cut decision made by the operator not by an optimisation algorithm. While some results showed improvement in the economic value by optimising bucking (Boston and Murphy, 2003; Serin *et al.*, 2010; Lang *et al.*, 2010; Pak and Gülci, 2017) others found no considerable difference (Akay *et al.*, 2010; Herrera *et al.*, 2015). Those who reported improvement in profitability by using optimal bucking, described loss in value in traditional bucking due to inability to control length measurements (Boston and Murphy, 2003). Lengths produced were longer or shorter than the optimal and, as a result, logs were sorted in lower value products than the optimal recommended (Serin *et al.*, 2010; Lang *et al.*, 2010). However, those who reported no improvement in profitability by using optimal bucking, suggested that no difference was due to the small number of products analysed and their considerable difference in dimensions and sizes (Herrera et al., 2015).

The effects of bucking in different harvesting and extraction systems were also studied. For instance, Akay (2009) compared the effect of optimal bucking on two types of skidding: manual skidding and mechanised skidding. They found that economic value increased in the mechanised system as it allowed for the increased log length that optimum bucking recommended.

The effect of defects on bucking optimisation was studied and results suggested that applying bucking optimisation had a higher positive impact on the economic value of trees with more defects (Wang *et al.*, 2009; Akay *et al.*, 2015), while there was no change in value when trees had less defects and the manual bucking was made by an experienced operator (Wang *et al.*, 2004).

6.1.3 Valmax

VALMAX is an optimal log-making simulation software (Murphy, 2008) that combines market prices and product specifications with stand data to optimally allocate wood products from the standing timber. VALMAX was the optimisation tool used in this dissertation because it allowed the analysis from the point of view of the landowner, at stem level, and it was accessible compared to other software out of the cost limitations of this research project. At stem level, Valmax uses a DP algorithm. This software has been used worldwide in several analyses. For instance, it was applied in Australia to assess tree value and log product yields of radiata pine (*Pinus radiata*) (Acuna *et al.*, 2009). It was also applied to a SRF poplar (*Populus* spp.) plantation in Oregon, U.S. (Murphy *et al.*, 2011; Barnett, 2012). In these studies, detailed data provided by a terrestrial laser scanning inventory system was combined with VALMAX to evaluate standing tree net value recovery. This software was also applied in Irish Sitka spruce plantations to optimise allocation of wood fibre at an operational planning level including the wood energy market (Murphy *et al.*, 2010). That study found that the optimal allocation tool could increase the net recovery value from Irish forestry in a constrained log market. However, this previous application of VALMAX was limited by:

1) the unavailability of tree models, stand volume and stocking information for SRF species for Irish conditions. This information was collected as part of this work: four sites were identified and data on stem volume, shape and whole tree biomass was collected and are summarised below and detailed in Chapter 4;

2) the unavailability of market data on wood fuel product specifications and prices of different tree partition assortments for Irish wood energy markets. Since the Sitka spruce study (Murphy *et al.*, 2010), a functioning wood energy market has developed in Ireland (COFORD, 2015). This wood energy market data, in addition to data on current Irish wood processing industry specifications and prices, was reported (de Miguel *et al.*, 2016) and is described in Chapter 2;

3) the inability to convert prices from different units (e.g. €/GJ or €/odt to €/m^3). Data on dry matter and wood energy properties of SRF were collected (Coates *et al.*, 2017) and a woody biomass unit conversion tool that includes all these parameters and financial conversions was developed, as described in Chapter 5;

4) the inclusion of only one wood energy product, brash bundles, considered in the Sitka spruce study. Firewood and woodchip from roundwood, woodchip from whole trees and tree tops were described and included in addition to brash bundles in this study.

6.1.4 Objectives of the study

This study aims to determine maximum realisable value recovery of SRF in the Republic of Ireland from the point of view of the forest owner. Therefore, stem-level optimal bucking was used for biomass allocation to the pallet, panel board, woodchip and firewood markets as well as including the option of using the residues as hogfuel in the form of brash bundles and loose residues. Supply-constrained markets are assumed as there is a forecasted shortage of wood for Ireland.

Specific objectives are:

- to assess optimal net value recovery of the current Irish SRF resource using current prices from the market survey and stand data from sampled SRF sites;
- to explore the optimal financial rotation based on allocation of products to markets through stand data simulation at different ages based on the analysis of annual increment of the sampled tree rings.
- to investigate the effect of markets interchangeably quoting roundwood prices in weight and volume units, where the underlying assumption is one tonne is equivalent to one cubic metre.

6.2 Methods

Several datasets were required as inputs for the optimisation analysis to investigate the financial value of Short Rotation Forestry. In addition to the SRF stands' biomass quantification described in Chapter 4 and their potential market specifications discussed in Chapter 2, other additional data were required to carry out the financial analysis including:

- Stem profiles at current age for all stands;
- Previous years' stem profiles and Biomass Expansion Factor for one stand: EUC-WAT;
- Supply chain costs from harvesting to end-user.

6.2.1 Stands data collection: field work and lab work

Four SRF sites in Ireland, two eucalyptus (one of *Eucalytus delegatensis* and the other *Eucalyptus nitens*) and two poplar clones mixture (*Populus* spp.) stands were studied

Table 6.2 and Figure 6.1). A representative sample of trees (between 10 and 14 trees per site) was felled. Once felled, diameters were measured with callipers every metre along the stem and total height was also recorded. Stem volumes were calculated using Huber's formula. Biomass expansion factors (BEF), basic density and calorific value were also determined. This is described in detail in Chapter 4. It was assumed that some residues from the branches and top would remain on-site so the residue biomass was multiplied by a recovery factor of 0.67 (Murphy et al., 2010). A summary of site data inputs to Valmax is presented in

Table 6.2 and 6.3. Detailed information about the field work procedure followed was described in Chapters 4 and 6.

Table 6.2. Summary of stands characteristics.

Site	**Species**	**Location**	**Age**	**Stocking (trees ha^{-1})**	**Merchantable Volume (m^3 ha^{-1})**	**QMDBH (cm)**	**Height (m)**	**Biomass Expansion Factor**
EUC-WEX	*Eucalyptus delegatensis*	Kilbora, Co. Wexford	22	436	413	35	28.2	1.06
POP-CAV	*Populus* spp.	Ballyhaise, Co. Cavan	17	258	330	36	25.0	1.27
EUC-WAT	*Eucalyptus nitens*	Cappoquin, Co.Waterford	23	842	743	27	30.7	1.11
POP-KIL	*Populus* spp.	Kildalton, Co. Kilkenny	19	291	428	30	27.7	1.20

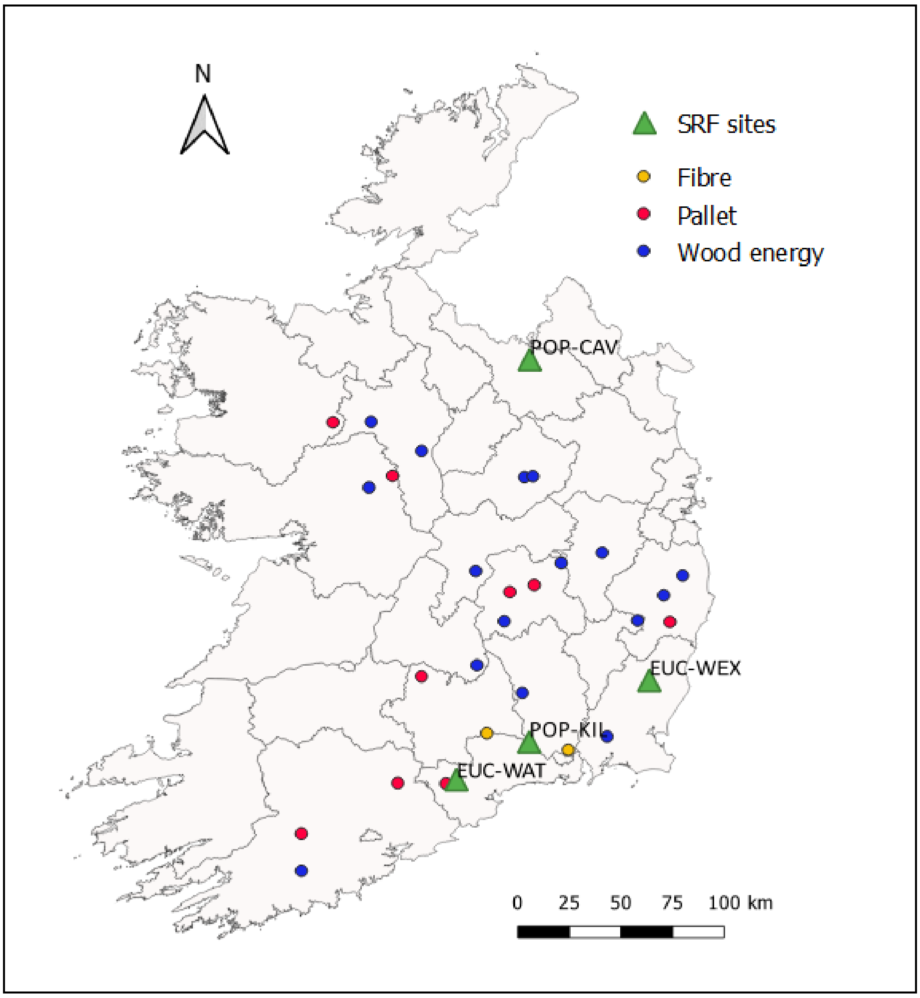


Figure 6.1. Map of field sites and wood processing companies surveyed

Table 6.3. Wood basic density, moisture content and calorific value for the four SRF stands. Roundwood refers to the stem from base to 7 cm diameter and residues refers to the top of the stem, from 7cm diameter to tip, plus the branches.

Site	**Basic density Roundwood kg m^{-3}**	**Moisture Roundwood %**	**Moisture Residues %**	**NCV$_{ar}$* Roundwood GJ t^{-1}**	**NCV$_{ar}$ Residues GJ t^{-1}**
EUC-WEX	435	53.6	44.5	7.2	9.3
POP-CAV	311	54.2	42.6	6.9	9.1
EUC-WAT	388	61.4	53.0	5.6	7.5
POP-KIL	282	53.9	47.0	7.0	8.5

Where NCV$_{ar}$ is net caloric value as received in Gigajoules per tonne.

6.2.2 Market survey

Market data included log dimensions required by the Irish market and price paid. Specifications and prices of log types used in this study were collected through the market survey (Chapter 2 and Miguel et al., 2016) and are summarised in Table 6.4. Common small sawlog lengths in Ireland are 2.5, 3.1 and 3.7 m and 14 cm minimum diameter while the small roundwood, commonly named pulp in Ireland, is 3 m length and 7 cm minimum diameter. Figure 6.1 shows spatial distribution of the wood and energy processors that participated in the survey.

Table 6.4. Dimensions required by market sector and mill gate prices paid (from de Miguel et al., 2016). Specifications include a minimum and maximum allowed dimensions (and median). Prices include a minimum-maximum (and mean).

Market product	Length (m)	Top diameter (cm)	Bottom diameter (cm)	Price at mill gate (€ t^{-1}) [a]
Pallet A	3.0- 3.2 (3.1)	13.0- 18.0 (14.0)	30.0- 120.0 (40)	55-55 (55)
Pallet B	2.4-2.6 (2.5)	13.0- 18.0 (14.0)	30.0- 120.0 (40)	45-45 (45)
Firewood	1.8- 6.7 (3.0)	5.0- 25.0 (8.0)	20.0-100.0 (45.5)	34-42 (40)
Woodchip	3.0- 4.9 (3.0)	7.0- 14.0 (9.0)	40.0-100 (62.5)	34-42 (39)
Panel Board A	3.0- 3.0 (3.0)	7.0- 7.0 (7.0)	50.0-50.0 (50.0)	-
Panel Board B	3.0- 3.0 (3.0)	7.0- 7.0 (7.0)	35.0-35.0 (35.0)	-
Wood energy (Woodchip and hogfuel)	Any	Any	Any	65 € t^{-1} at 40% M% [b]

[a] *Assumed conversion between cubic metres and tonnes by the industry surveyed was 1 m^3 =1 t*

[b] *M % Moisture content in percentage*

As wood prices were used interchangeably in tonnes and cubic metres by wood and energy processors (de Miguel *et al.*, 2016), a comparison between both options was carried out. When mill gate prices were treated as € t^{-1}, basic density and moisture content from each stand and partition was used to convert to price per m^3 (Eq. 6.1).

No data on price of pulp for panel boards and wood energy was given in the survey due to confidentiality. As the roundwood specifications for panel board material are very similar as for firewood and woodchip, the same mill gate price of €40 t^{-1} or €40 m^{-3} was assumed.

Wood energy was valued as €65 t^{-1} at 40% moisture content (WDC, 2008). Each of the stands and partitions (main stem and branches) had different moisture contents so €65 per tonne was first converted to energy becoming 2.2 cents per kilowatt-hour (Eq 6.2). Then this value was converted to m^3 by using basic density, moisture content and calorific value of each stand (Eq 6.3, Chapter 5).

$$V_s = m_w * 10 * (100 - M) * D_d^{-1}$$

(Eq. 6.1)

$$E_{MWh} = m_w * q_{net,m} * 3.6^{-1}$$

(Eq. 6.2)

$$V_s = E_{MWh} * q_{net,m}{}^{-1} * 10 * (100 - M) * D_d^{-1} * 3.6$$

(Eq. 6.3)

Where

V_s, Solid volume;

m_w, Mass at green weight;

M, Moisture content, expressed as a percentage of total weight;

D_d, Basic density;

E_{MWh}, Energy in Megawatt hour;

$q_{net,m}$, Net calorific value, as received.

VALMAX requires prices per cubic metre and also includes the option of using price per tonne when basic density and moisture content are known. However, there is no option to input energy prices.

6.2.3 Stem profiles

Accurate stem shape is an essential parameter for the optimisation algorithm used to carry out the financial analysis. Therefore, detailed stem profiles were developed for the four SRF stands at their current age and at past ages (from 10 to 22 years) for the EUC-WAT site only in Appendix A. The expected rotation for SRF in Ireland is between 10 and 20 years. Currently there is no commercial experience of managing SRF forests for optimum rotation. Therefore, growth ring data from EUC-WAT site, were used to estimate stem volumes for previous years, as this stand was 23 years old and covered the full range of ages.

Previous annual growth was estimated from measurements of ring growth in sample discs every metre along the stem of 10 trees from EUC-WAT site (Appendix A). Discs were dried, sanded and prepared for stem analysis following Stokes (1968). Diameters down to 10 years old were recorded, as the minimum rotation of SRF is expected to be at least 10 years. Volumes were calculated using Huber's formula.

A single tree biomass expansion factor equation described by Coates *et al.* (2017) was used to estimate BEF. The equation was as follows:

$$BEF = 1.07625 + 12.6343 \times e^{(-0.262992x\,Total\ height\ (m))}$$

(Eq. 6.4)

Total height was estimated by using proportionality of diameters and height as described by Alemdag (1988), cited by Gilabert and Paci (2010).

Stocking was assumed to be constant at 842 trees per ha between year 10 and the current year 23 due to current lack of historical data for this stand and unavailability of yield models of eucalyptus in Ireland.

Net Present Value (NPV, Eq 6.5) was calculated to express revenues of different rotations at current value. Only clearfell value was considered as there are no thinnings planned in SRF. Establishment costs are independent of productivity and supply chain so they were not included in the NPV but should be similar for the 4 stands. Therefore, NPV in this study means discounted revenues or current value of revenues. Equivalent Annual Annuity EAA or Annual Equivalent Value allowed comparisons between NPV at different rotation lengths (Eq 6.6). An interest rate of 5% was used as it has been typically used in forestry in Ireland (Phillips, 1999).

$$NPV = -C + \frac{V}{(1+r)^n}$$

(Eq. 6.5)

$$EAA = \frac{r\ (NPV)}{1-(1+r)^{-n}}$$

(Eq. 6.6)

where

C, costs;

V, value of clearfell at n years;

r, interest rate expressed in decimal format;

n, rotation year.

6.2.4 Costs calculation

Wood, fibre and fuel users surveyed in Chapter 2 of this thesis described price delivered at the mill gate. This means that the raw material is delivered to the mill so harvesting and haulage costs were included in the interviewees' valuation information described in Chapter 2. However, the aim of this thesis is to investigate the financial value of SRF from the forest owners' point of view, so standing prices were also needed. Standing price means a price agreed before harvesting of the resource and represents the revenue from the tree crop on the lifetime investment of capital and time on the part of the landowner (Brazee and Mendelsohn, 1988; Malinen *et al.*, 2010).

Harvesting and haulage costs were calculated and subtracted from mill gate prices in order to compute residual standing prices. Eleven different supply chains, including cut to length (CTL), whole tree (WT) and integrated (INT) harvesting methods, were assessed and are described below.

6.2.4.1 Harvesting and extraction cost.

The eleven supply chains that were evaluated are described as follows (Coates pers. comm., 2017): Supply chain 1 describes the conventional CTL method that currently is the most commonly used harvesting method in Ireland. Supply chains 2 to 9 describe CTL methods but with an additional use of biomass for energy; supply chain 10 describes the integrated method and 11 the whole tree method. Supply chain 1 is based in on a harvester and forwarder system. All the other supply chains include specific wood energy equipment in their harvesting system (chipper, residue bundler, shredder). Table B.1 and Figure B.1. CTL harvesting method diagram, B.2 and B.3 in Appendix B summarise the supply chains. More specifically:

1. Roundwood production using a harvester and forwarder. A harvester fells and processes the tree stems by delimbing and cross-cutting into specific roundwood log assortments. The logs are extracted to the roadside by a forwarder, and then hauled to the end user in timber trucks. The branches and stem tops remain unused in the forest as logging residues.

2. Roundwood logs & hogfuel biomass production using a harvester, forwarder, residue bundler, and a shredder. A harvester fells and processes the tree stems into specific roundwood log assortments. The logs are extracted to the roadside by a forwarder, and then hauled to the end user in timber trucks. The logging residues are bundled using a residue bundler. The bundles are brought out to the forest roadside using a forwarder and are then hauled to the end user using timber trucks. The end user shreds the bundles into hogfuel for combustion.

3. Roundwood logs & biomass production using a harvester, forwarder, and a chipper. A harvester fells and processes the tree stems into specific roundwood log assortments. The logs are extracted to the roadside by a forwarder, and then hauled to the end user in timber trucks. The logging residues are extracted with a forwarder, and are chipped at the roadside, loaded into trailers and hauled as to the end user.

4. Sawlog and pulpwood woodchip production using a harvester, forwarder, and a chipper. A harvester fells and processes the tree stems into specific roundwood log assortments. The logs are extracted to the roadside by a forwarder. The sawlogs are hauled to the end user in timber trucks. The pulpwood logs are chipped at the roadside into trailers and hauled as woodchip to the biomass end user.

5. Sawlog, pulpwood woodchip, and hogfuel biomass production using a harvester, forwarder, chipper, residue bundler, and shredder. A harvester fells and processes the tree stems into specific roundwood log assortments. The logs are extracted to the roadside by a forwarder. The sawlogs are hauled to the end user in timber trucks. The pulpwood logs are chipped at the roadside into trailers and hauled as woodchip to the biomass end user. The logging residues are bundled using a residue bundler. The bundles are brought out to the forest roadside using a forwarder and are then hauled to the end user using timber trucks. At the end user, the bundles are shredded into hogfuel for combustion.

6. Sawlog, pulpwood woodchip, and biomass production using a harvester, forwarder and a chipper. A harvester fells and processes the tree stems into specific roundwood log assortments. The logs are extracted to the roadside by a forwarder. The sawlogs are hauled to the end user in timber trucks. The pulpwood logs are chipped at the roadside into trailers and hauled as woodchip to the biomass end user. The logging residues are extracted with a forwarder, and are chipped at the roadside, loaded into trailers and hauled as woodchip to the end user.

7. Roundwood woodchip production using a harvester, forwarder and a chipper. A harvester fells and processes the tree stems to specific roundwood log assortments. The logs are extracted to the roadside by a forwarder. All logs are chipped into trailers and hauled as woodchip to the end user.

8. Roundwood woodchip and hogfuel biomass production using a harvester, forwarder, chipper, residue bundler and shredder. A harvester fells and processes the tree stems to specific roundwood log assortments. The logs are extracted to the roadside by a forwarder. All logs are chipped into trailers and hauled as woodchip to the end user. The logging residues are bundled using a residue bundler. The bundles are brought out to the forest roadside using a forwarder and are then hauled to the end user using timber trucks. At the end user, the bundles are shredded into hogfuel for combustion.

9. Roundwood woodchip and hogfuel biomass production using a harvester, forwarder, chipper. A harvester fells and processes the tree stems to specific roundwood log assortments. The logs are extracted to the roadside by a forwarder. All logs are chipped into trailers and hauled as woodchip to the end user. The logging residues are extracted with a forwarder, and are chipped at the roadside, loaded into trailers and hauled as to the end user.

10. Sawlog and biomass production using a harvester, forwarder and chipper (integrated harvesting (INT))**.** A harvester fells and processes (delimbs and cross cuts) the sawlogs only from the trees. The remainder of the tree is stacked separately as a biomass product. The sawlogs are extracted to the roadside by a forwarder and are hauled to the end user in timber trucks. The remaining biomass product is forwarded to the roadside, chipped into trailers and hauled as woodchip to the biomass end user.

11. Wholetree biomass production using a harvester, forwarder and chipper (whole tree harvesting (WT))**.** The harvester fells and cross cuts the trees into sections that can be handled by a forwarder. The tree sections are extracted to the roadside by a forwarder, where they are chipped into trailers and hauled as woodchip to the end user.

A model to calculate cost for the eleven supply chains described above was developed (Coates, pers. comm. 2017) and used in this study. Cost data from previous studies in Ireland for the harvesting methods was used (Kent *et al.*, 2011; Coates *et al.*, 2014; Coates *et al.*, 2016). Input variables for the harvesting cost model were mean tree size for the CTL harvesting method and standing merchantable volume per hectare and Biomass Expansion Factor for the additional above ground biomass from branches and stem tops for integrated and wholetree harvesting. The forwarding cost model only depended on average forwarding distant, and this was assumed to be 250 m for all the supply chains. Labour costs for the harvesting and extraction operations were included in the model.

It was assumed harvesting cost for different assortments was the same. Harvesting times for different assortments were not known and there was no data about volume per assortment in SRF.

6.2.4.2 Transport cost

It was assumed the closest mill would take the material as there was no significant difference in unit prices between end-users for the same product. A fixed distance of 80 km to the mill was used for the calculations. The analysis focused on the supply chain, stand and age as variables. Further studies to analyse distance effect on optimal value would be beneficial. Transport costs were based on a six-axle articulated truck in 2015 (Coates E., 2017) from (Sosa A., Personal communication 2017), (Devlin and Talbot, 2014).

6.2.5 Optimisation tool: Valmax

The flow of inputs required for the optimisation tool is illustrated in Figure 6.2. Valmax needs three input files: a stem file, a biomass file and a market file (Blue boxes in Figure 6.2). Green boxes inputs are already described in Chapters 2 and 4. Red boxes inputs are detailed in Appendices A and B.

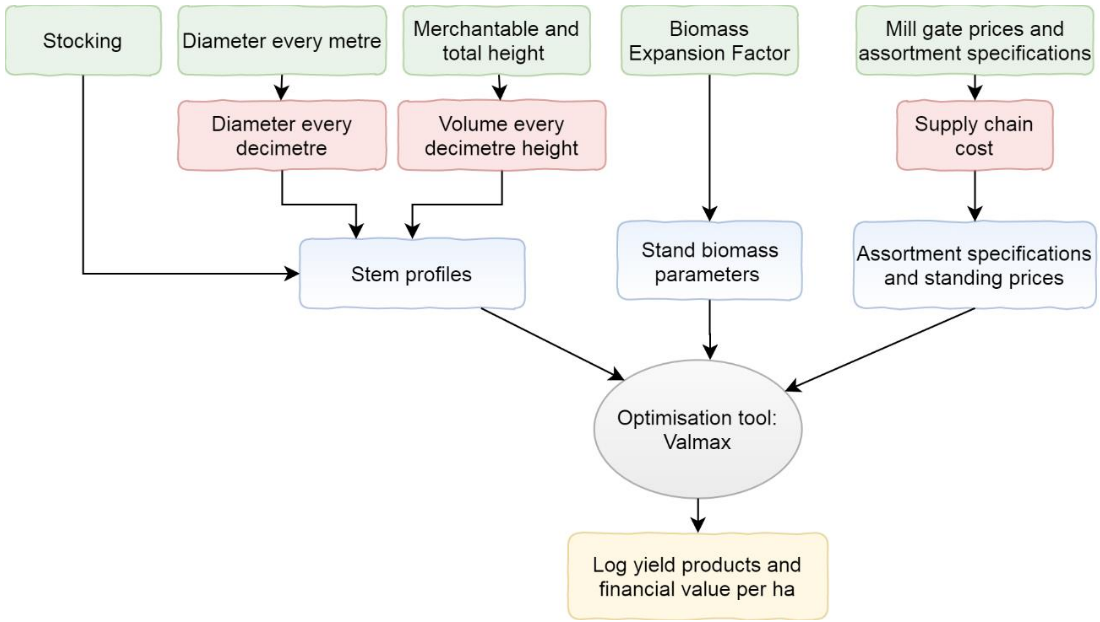


Figure 6.2 Flow of datasets required for the optimisation tool

Stand data with detailed stem profiles and total height measurements were used to build the stem files. BEFs and percentage of residues left on the forest were needed for the biomass parameters file, while log dimensions and standing prices (Table 6.4) were used for the market files (Figure 6.3). Two subcategories of the wood energy product (Table 6.4) when sourced from residues were described for the optimisation analysis: R_chip, when the residues were chipped roadside and R_hogfuel, when brash bundles were made from the residues at the forest to transport to end user where they were shredded. Furthermore, additionally to market products described in Table 6.4, waste, the stem's sections that did not meet the log dimension requirements of any product, was considered in the optimisation. In the supply chains with energy products a biowaste category was also included for the waste that could be used for wood energy, this means the sections of the merchantable stem that did not meet the log requirements of any market product but could be used for energy. The wood energy price (Table 6.4) was given to the biowaste category.

A total of 17 stem files (4 at current age and 13 at past ages), 17 parameter files (4 at current age and 13 at past ages) and 231 market files (88 at current age and 143 at past ages) were created and used as inputs to run the optimisation tool.

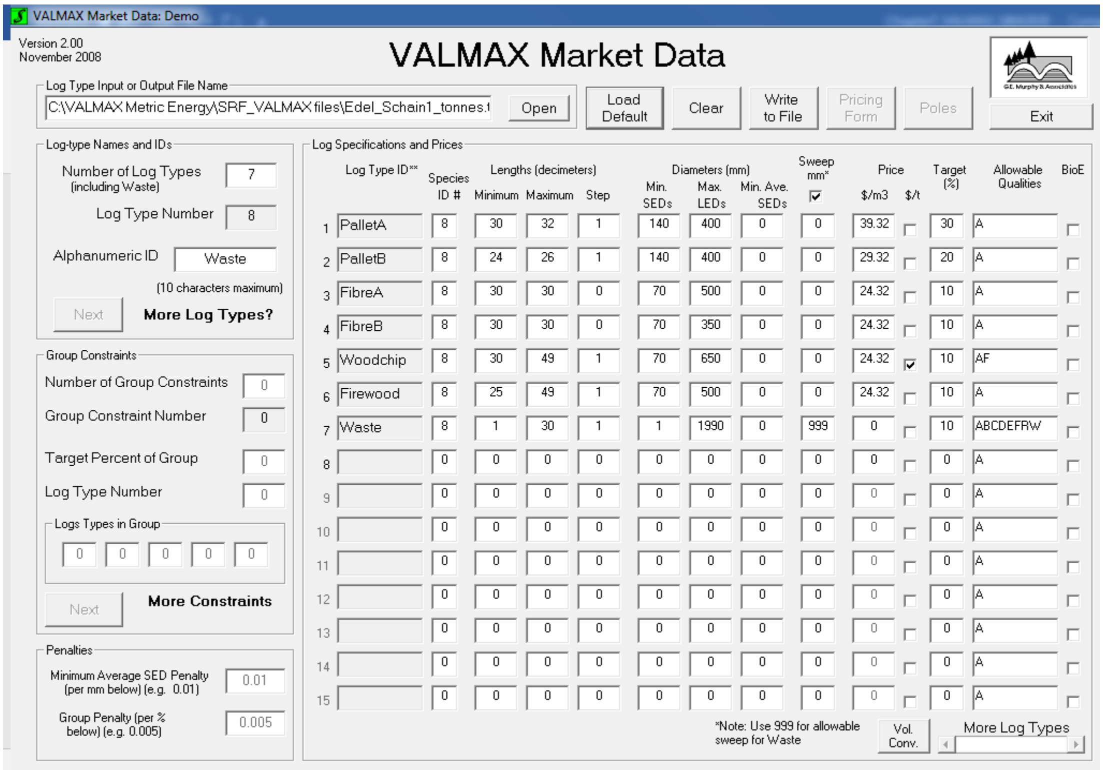


Figure 6.3.VALMAX screenshot. Example of log specifications file with log dimensions and price specifications from data collected in the market survey.

Three analyses were carried out:

1. Optimal net value recovery and log yield products of four SRF stands at current age.

2. Optimal financial rotation of stand from EUC-WAT site.

3. Variation in value recovery related to market pricing unit.

6.3 Results

<u>*6.3.1 Optimal net value recovery and log product yield of the four SRF stands at current age.*</u>

Mill gate prices in tonnes were used for this analysis, so the stand characteristics for each stand were used to convert prices to cubic metres.

6.3.1.1 Comparison of net recovery value for the 11 supply chains

The supply chain 3, cut to length method producing roundwood and woodfuel using a harvester, forwarder, and a chipper, had the highest modelled net revenues for the 4 sites among the analysed 11 supply chains (Figure 6.4, Table 6.5). Supply chains 1 to 6 and 10 (all including sawlog production) showed higher values than the supply chains with only energy products (supply chains 7, 8, 9 and 11). There was an average of €6,931 ha^{-1} difference between the lowest value supply chain and the highest value supply chain meaning a 60% change in value.

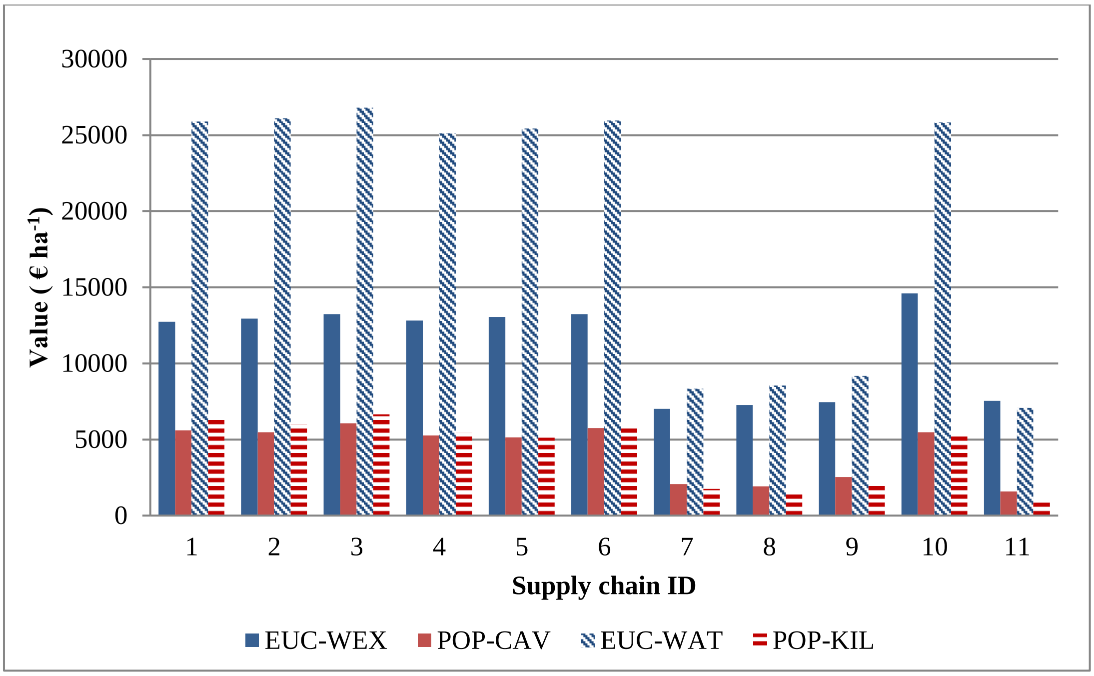


Figure 6.4 Net recovery value for the 4 SRF stands and the 11 supply chains studied

Table 6.5. Comparison of recovery value per cubic metre among the supply chains for the four sites

Site	EUC-WEX	POP-CAV	EUC-WAT	POP-KIL
Supply chain	€ m^{-3}	€ m^{-3}	€ m^{-3}	€ m^{-3}
1	30.82	17.00	34.85	14.76
2	31.33	16.60	35.13	14.03
3	32.07	18.41	36.07	15.55
4	31.02	16.60	33.82	12.69
5	31.61	15.56	34.23	11.96
6	32.07	17.41	34.95	13.47
7	16.99	6.24	11.23	4.08
8	17.59	5.80	11.50	3.34
9	18.06	7.69	12.36	4.86
10	35.36	16.60	34.76	12.45
11	18.23	4.80	9.52	1.98

*6.3.1.2 Comparison of net recovery value for the two genera (*Eucalyptus *and* Populus*)*

Eucalyptus sites (EUC-WEX and EUC-WAT) had higher value on average of €16,693 ha^{-1} while poplar sites (POP-CAV and POP-KIL) had lower value, averaging €7,201 ha^{-1} but volume per ha varied a lot between sites. However, despite EUC-WEX site and POP-KIL site have similar volume per ha (Table 6.2), the model predicted an average of 36% higher value for EUC- WEX site than for POP-KIL site (Figure 6.4). This seemed to be due to higher standing prices in cubic metres for EUC-WEX site when considering internal properties of wood (basic density and calorific value) to price the wood (Table 6.3). Stocking density in EUC-WAT was particularly high (

Table 6.2), so as expected, it had the highest volume per ha and also had the highest value (Figure 6.4).

6.3.1.3 Log product yield of the four SRF stands at current age

The modelled total product yield ranged from 366 to 789 m^3 ha^{-1} (Figure 6.5). The highest volumes were in EUC-WAT site and this was mainly due to the highest stocking of this stand. Volume of pallet material was maximised by VALMAX in the supply chains with this product while woodchip was preferred over fibre.

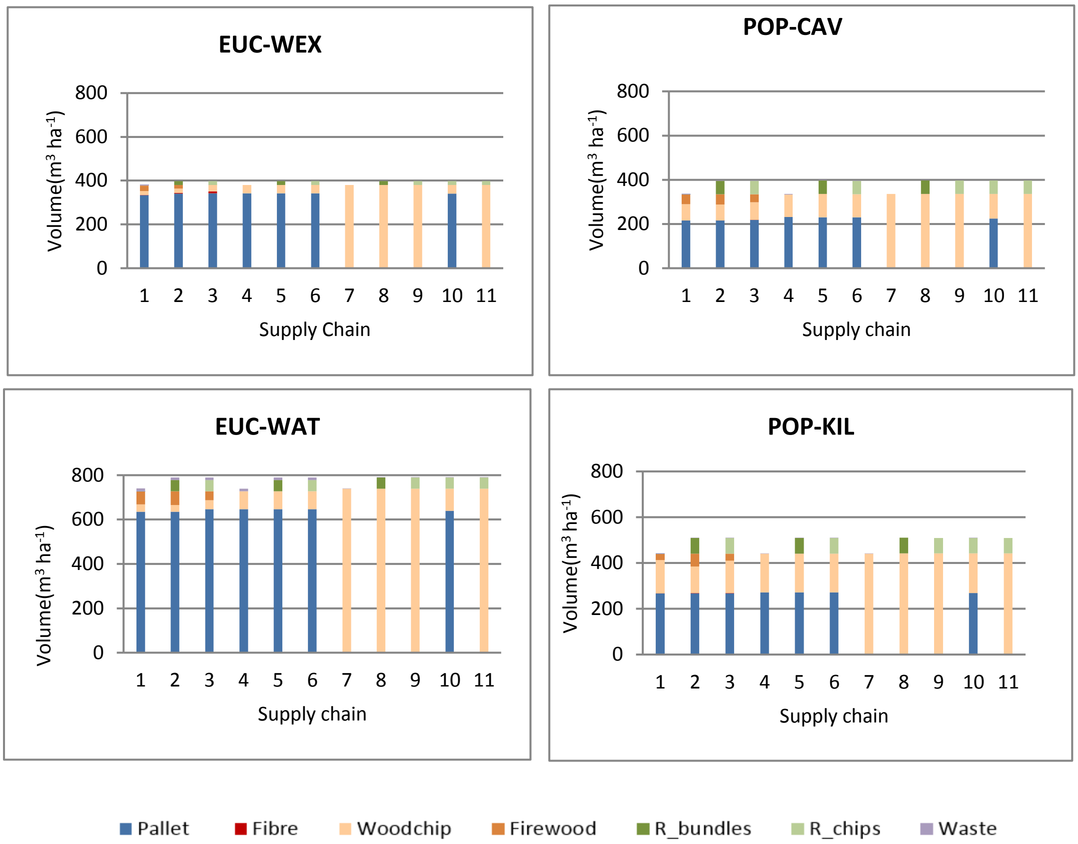


Figure 6.5. Optimal log yield products for the 4 SRF stands and 11 supply chains

Volume of pallet material was greater in eucalyptus sites (Table 6.6), thus 85% out of the total volume (EUC-WEX and EUC-WAT), compared to an average of 67% in poplar (POP-CAV and POP-KIL).

Table 6.6. Comparison of pallet allocation.

Site	Pallet Volume Average (%)
EUC-WEX	82
POP-CAV	67
EUC-WAT	87
POP-KIL	66

6.3.2 Optimal financial rotation analysis of EUC-WAT stand and effect on log product yields

6.3.2.1 Optimal financial rotation of the EUC-WAT stand

Figure 6.7 and Figure 6.8 show respectively discounted revenues and annual equivalent (Eq 6.5) of the total recovery value from ages 10 to 22 for EUC-WAT site. In keeping with the earlier analysis, the integrated harvesting (supply chain 10) had highest values in all the years and supply chains. Again, supply chains consisting of only energy products had the lowest values. For all the supply chains the annual equivalent increased each year from year 10 to year 21.

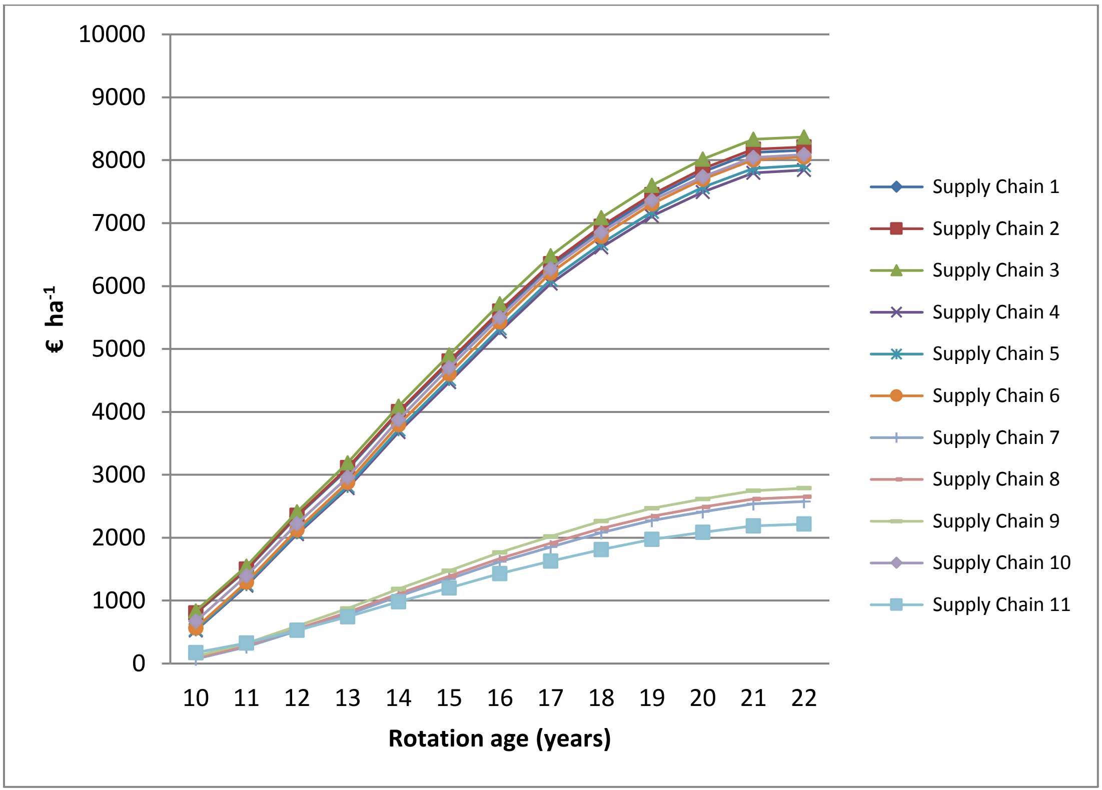


Figure 6.6. Discounted revenues of the 11 supply chains studied at rotations from 10 to 22 years.

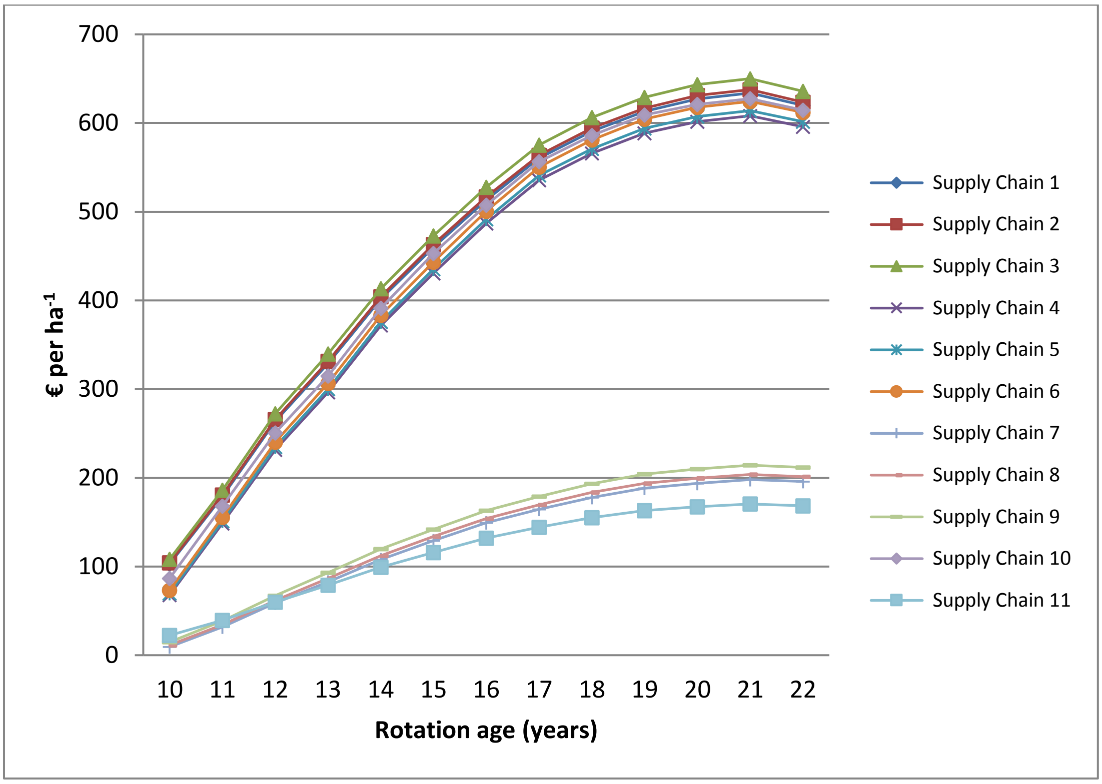
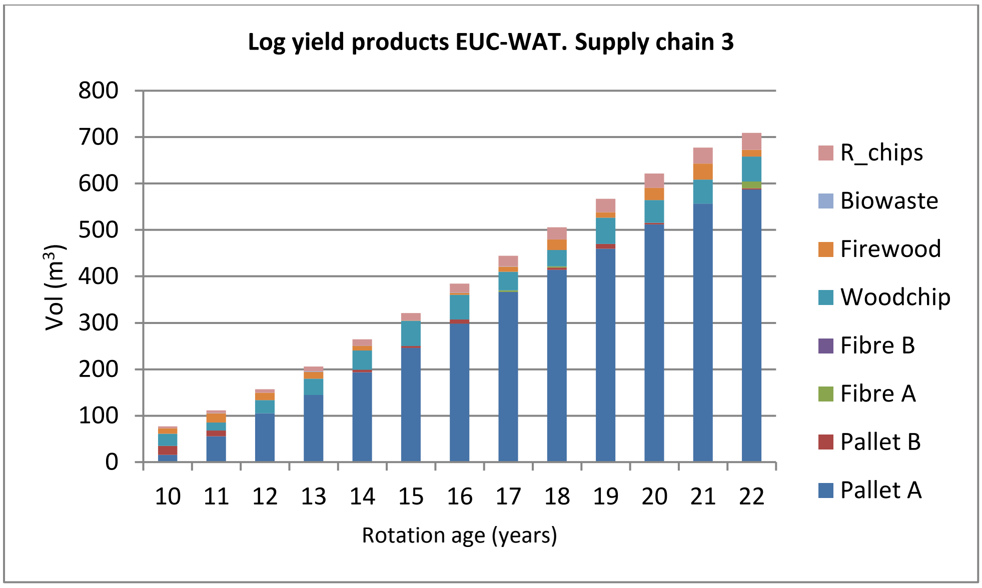


Figure 6.7. Annual Equivalent Value of the Discounted Revenues of the 11 supply chains studied from 10 to 22 years rotations.

6.3.2.2 Effect of age on log product yield of EUC-WAT stand.

Variation on log yield products with rotation was also analysed. There was a higher proportion of energy wood at shorter rotations, but absolute volume was very small compared to optimum rotation.

a)


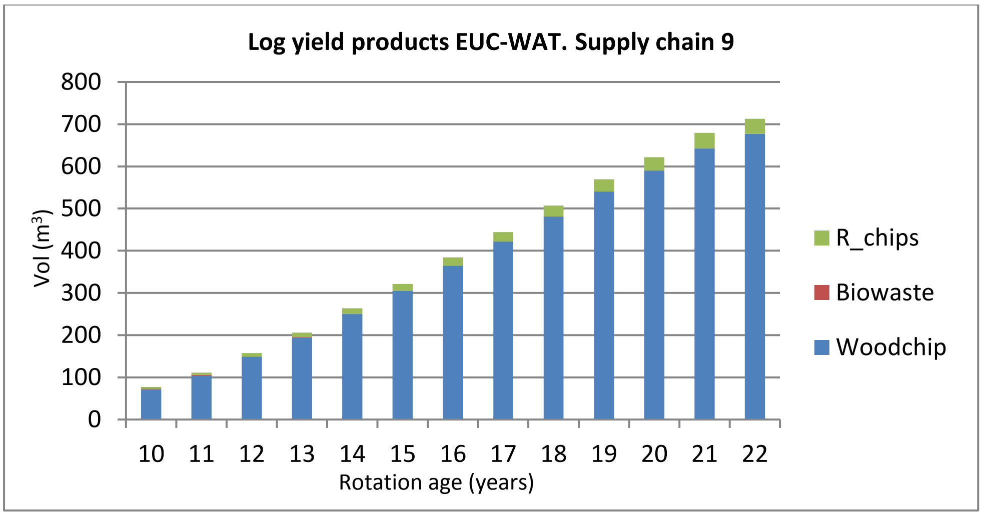
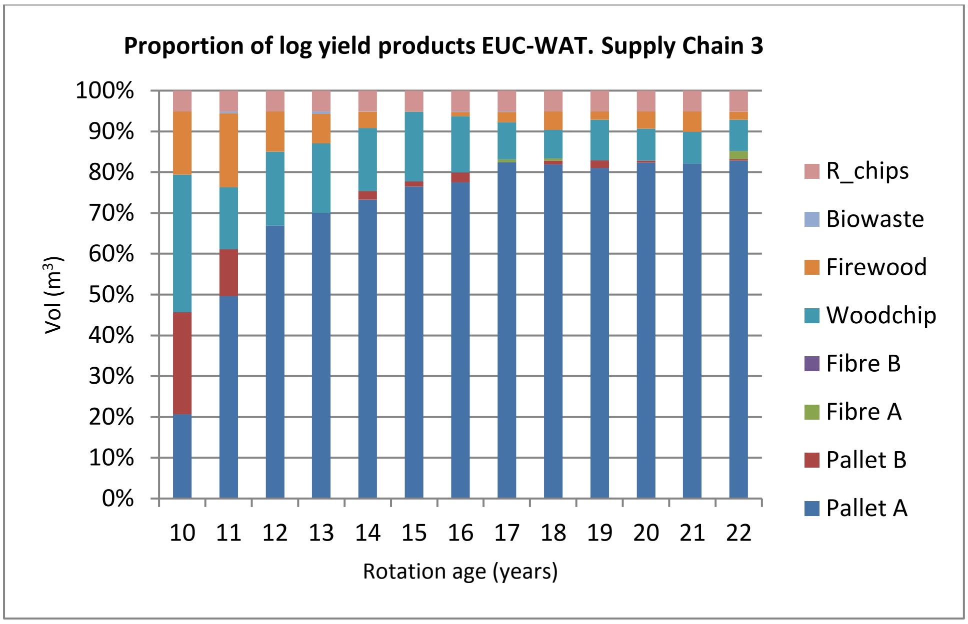
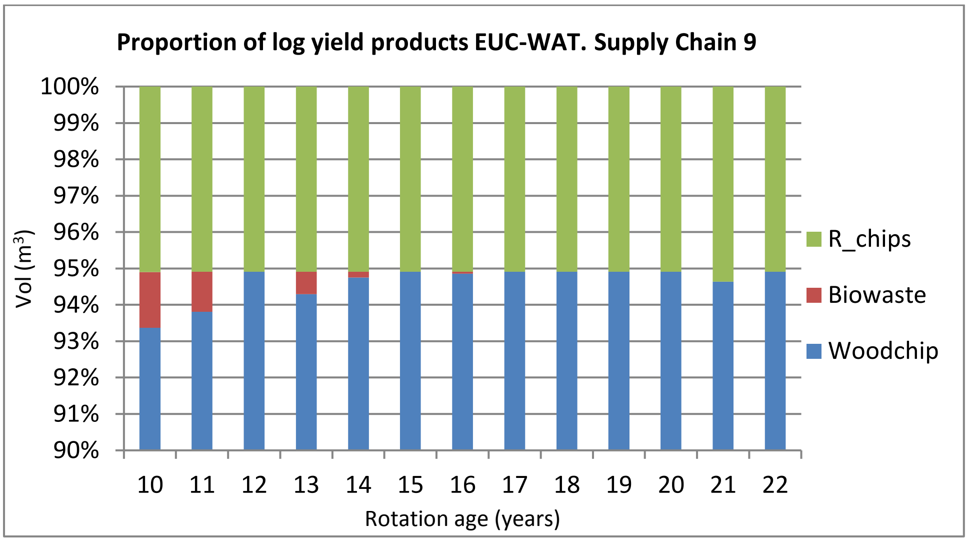
b)


Figure 6.8. Log yield products for rotations between 10 and 22 years for a Eucalyptus nitens *stand in Co. Waterford, EUC-WAT site. Example of a supply chain with a mix of products (supply chain 3, graph a) and a supply chain with only energy products (supply chain 9, graph b).*



a)



b)

Figure 6.9. Proportion of log yield products for rotations between 10 and 22 years for a Eucalyptus nitens *stand in Co. Waterford, EUC-WAT site. Example of a supply chain with a mix of products (supply chain 3, graph a) and a supply chain with only energy products (supply chain 9, graph b).*

6.3.3 Comparison of net recovery value on two pricing systems (volume and weight)

Results for the comparison of net value recovery considering mill gate prices in cubic metres and in tonnes showed differences particularly in poplar stands (Figure 6.4 and Table 6.6). Differences ranged from €1,046 ha^{-1} for supply chain 5 in EUC-WAT site to €8,629 ha^{-1} for supply chain 2 in POP-KIL site, with average differences for the eucalyptus sites of €1,258 ha^{-1} (about 6%) and for the poplar sites of €6093 ha^{-1} (49% of the stand value). There were no differences in prices in supply chains 7, 8, 9 and 11 as their only product was wood energy so their prices were in both cases converted from kWh^{-1}.

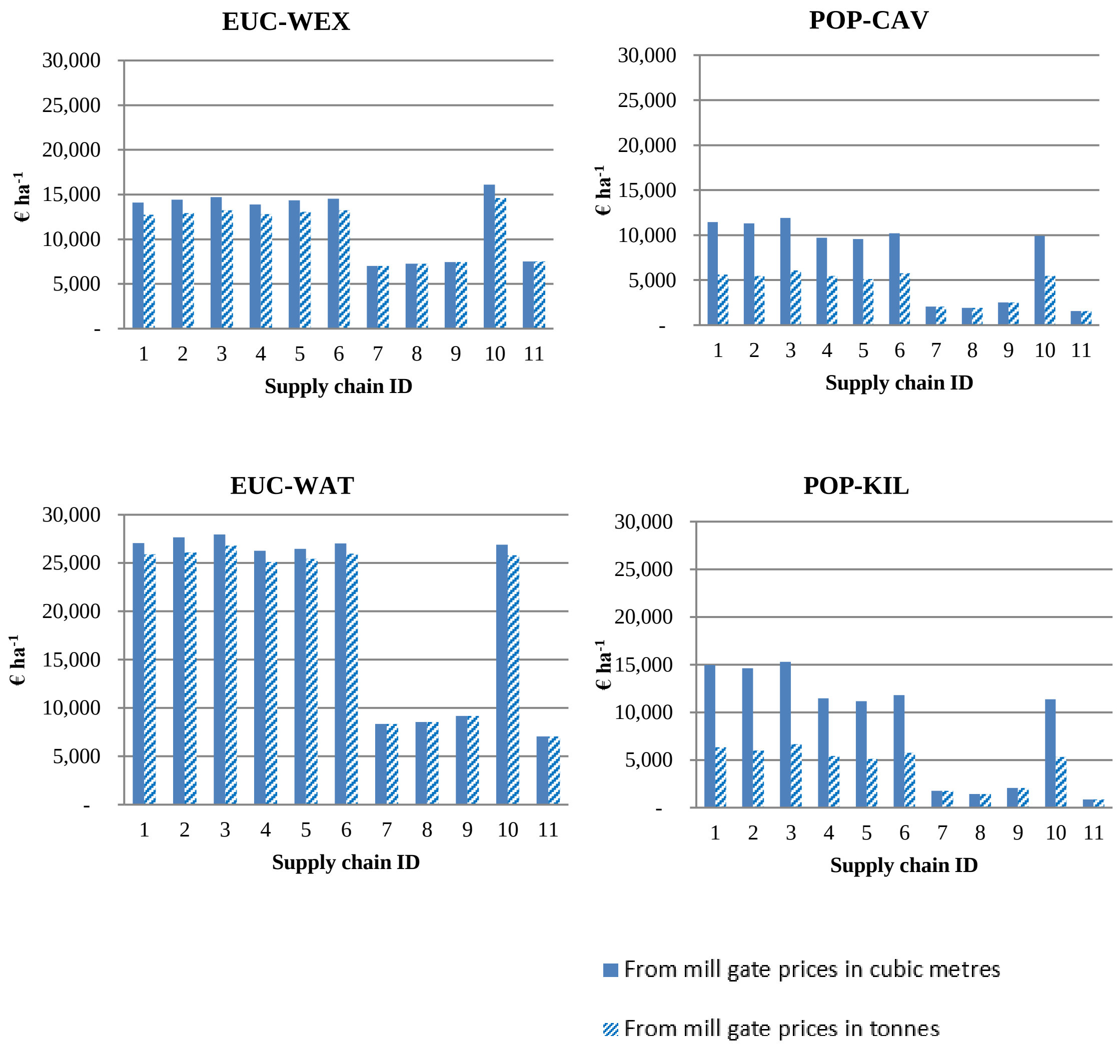


Figure 6.10. Comparison of optimal value per ha for the four SRF stands using mill gate prices in cubic metres and in tonnes.

Table 6.7. Comparison of stand value per unit of volume and weight per ha, considering mill gate prices in cubic metres vs. in tonnes. Supply chains 7, 8, 9 and 11, whose only product was wood energy, are excluded from the comparison.

Site	EUC-WEX		POP-CAV		EUC-WAT		POP-KIL	
Supply chain ID	A	B	A	B	A	B	A	B
1	34.19	30.82	34.68	17.00	36.41	34.85	34.91	14.76
2	34.91	31.33	34.28	16.60	37.23	35.13	34.20	14.03
3	35.63	32.07	36.13	18.41	37.65	36.07	35.71	15.55
4	33.63	31.02	29.46	16.60	35.35	33.82	26.80	12.69
5	34.76	31.61	29.03	15.56	35.64	34.23	26.07	11.96
6	35.22	32.07	30.90	17.41	36.39	34.95	27.58	13.47
10	39.00	35.36	30.07	16.60	36.19	34.76	26.56	12.45

Where,

A, stand value in € m^{-3} ha^{-1} (using mill gate prices in m^3)

B, stand value in € m^{-3} ha^{-1} (using mill gate prices in t)

6.4 Discussion

Supply chains with pallet material as a product had higher financial returns than supply chains producing energy only, with an average of 50% higher returns. If pallet develops as an alternative marketing option for SRF, landowners could double their returns compared to the target markets of fibre and energy. Either a change in market prices to make fibre and energy competitive to pallet, or an incentive for fibre and energy, would be needed to promote the use of SRF for the target markets.

To be approved for a SRF grant in Ireland, the crop rotation must be between 10 to 20 years (DAFM, 2014) and for eucalyptus the target rotation is 12 to 15 years. However, rotation analysis on the EUC-WAT site showed a higher return in a longer rotation for all the supply chains. Comparing a 12 year rotation to a 21 year rotation, annual equivalent revenue increased by more than 50%, with an average of 62%. Therefore, irrespective of the supply chain, longer rotations will give a higher return for the forest landowner. The higher return was achieved in the supply chains that produce pallet material: in this case the model also predicts that rotations of around

20-25 years are better, as previous research has suggested (Touza, cited by Riesco Muñoz, 2004; Sánchez Acosta *et al.*, 2008). A subsidy to increase profitability of energy wood production could result in shorter rotation (10-12 years) but the consequence would be poor efficiency of biomass production compared with a 20 year rotation.

Optimisation results showed higher financial returns when products were priced by volume than when they were priced by weight, with more pronounced value differences in the case of the poplar sites (POP-CAV and POP-KIL). This confirms the current practice of pricing by weight and volume interchangeably is not accurate and not fair on all market stakeholders as the ratio between volume and weight varies with wood properties.

Demand constraint was not considered, so it was assumed the market would take any quantity of product available and the forest owner would maximise the value of each individual stem. Therefore, higher unit price would be the first metric considered in the log product option and at equality of price, log size specifications. So, when possible, bucking optimisation resulted in large volumes of pallet, the highest value product considered in the study, averaging 76% of total volume in the supply chains with this option. However, this value could be overestimated as sweep was not measured, and this defect would reduce suitable pallet volume. In consequence, stand value would be overestimated in about 3% (Murphy *et al.*, 2011). If pallet production develops as a market for SRF, more research considering sweep would be needed. Other quality parameters would also be important but only if new markets have an effect on prices. A quality premium, or defect penalty, would require the adoption of a system to measure quality and to adjust value accordingly for SRF. Higher percentage of volume allocated to pallet in the eucalyptus compared to the poplar sites was due to the higher DBH in the poplar stands (Table 7.2) that made the bottom of the stem too big for the pallet specifications, so it was allocated to pulp. Considering the same price for all the pulp products (€40 t^{-1} or m^3 at mill gate), volumes of fibre and firewood were small compared to woodchip due to more flexibility in log dimensions for woodchip at the same price. This flexibility in dimensions allowed for more crosscutting options with less volume wasted. A premium price should be paid if the fibre market demands roundwood material in an unconstrained market, while keeping their current size specification. Otherwise a forest owner's best option would be woodchip for energy.

This work included the energy products from tops and branches (hogfuel and woodchip) as well as from main stem pulpwood (woodchip and firewood). Brash bundles had a negative value for poplar sites (POP-CAV and PO-KIL), which was also found in Sitka spruce stands by Murphy *et al.* (2010). However, the other energy products contributed positively to the total value recovery in all the sites.

VALMAX allows for accurate stem profiles and timber quality properties, such as sweep, to be accounted for in the log optimisation. However, when optimising for fibre and energy markets these properties are not relevant while other properties, such as basic density, calorific value or biomass expansion factor are important but not embedded in VALMAX. These properties were considered in this study, but it would be beneficial to have the ability to include variability of BEF per stem, and include basic density and calorific value per assortment. These properties are relevant for the main objectives of developing SRF in Ireland: as a fibre and energy resource. These parameters are essential as price paying potential depend on them, in addition to the ability to quantify biomass more precisely. Acuna and Murphy (2007) found that 'optimally bucking stems based on basic density may reduce the total value recovered by the forest owner, unless appropriate premiums are paid for additional properties.'

Harvesting cost for the poplar sites were lower than for the eucalyptus sites due to the higher mean tree size of the poplar stands. Similarly, for the EUC-WAT site, cost per unit of cubic metre decreases as age increases because of the increment of mean tree size with age. Tree size is found to be the key parameter influencing harvesting cost and making small tree diameter trees more expensive to fell (Holtzscher and Lanford, 1997).

As the only variable for the forwarding cost model was average forwarding extraction distant and this was fixed at 250 m for all the scenarios, there was no variation on forwarding cost between the sites or the potential rotation ages on the EUC-WAT site. There is a high influence of extraction distant on productivity and therefore on cost (Jiroušek *et al.*, 2007) but there are additional factors such as mean tree size, volume per hectare, and the number of timber assortments that influence extraction productivity (Sirén and Aaltio, 2003).

The machine systems employed in each supply chain were determined by the range of tree sections used and product assortment made available to the different markets. There were 3 supply chains: 1, 4 and 7, that only used merchantable stem while the rest of the supply chains used the whole tree. Among those supply chains using the whole tree, there were 3 supply chains: 8, 9 and 11 with only energy production but the production methods and machine systems differed between each.

There were some practical limitations that could have affected the results of this study: only 4 stands were analysed, with different species, stocking and ages and only one stand with annual growth measurement. Other existing limitations were on availability of information on the market size, diversity of assortments, knowledge of SRF and of species properties in Ireland. This data was collected as part of this dissertation (chapter 2). In addition, the following assumptions were made: the roundwood price paid by panel board mills was equal to the price paid by wood fuel producers. Also, harvesting costs were allocated equally to all products and the haulage distance was fixed at 80 km.

6.5 Conclusions

SRF is promoted to increase supply of biomass for fibre and energy in Ireland. However, growing SRF for fibre or energy will lower landowners returns substantially compared to the optimal solution of having a main assortment of pallet wood and small amounts of other products. Similarly occurred in the case study in Oregon (Chapter 3) were higher value products than chips were required for the development of SRF markets. The Only a substantial change in price, so that the roundwood price for energy or fibre was in line with pallet price, would change that. Otherwise, forcing landowners to grow SRF for energy wood would therefore require some sort of subsidy to compensate for the lower return.

Optimal economic rotation age was 21 years for all supply chains, even for only-energy supply chains, in the Eucalyptus stand that was studied. Further research on diverse stands and SRF species is needed.

Increasingly, forests may be valued for many products and services, but the value for each will depend on precise measurement of quantitative and qualitative parameters. This study identified differences between financial returns when products were priced by volume or weight, and when they were priced considering the internal properties determined in Chapter 4, particularly basic density. This is particularly important for fibre and energy markets, the main target markets of SRF in Ireland. The use of tonnes and cubic metres interchangeably by the current Irish industry was identified in the market survey in Chapter 2. There is a necessity of a system to value wood more accurately for different markets. Only when this system is established will the landowner be able to get a fair return when selling to fibre and energy markets. Furthermore, optimisation tools, like VALMAX, should be flexible in input parameters to allow for market requirements on wood pricing. We can only measure, model and predict forest value with a tool that takes all these parameters into account.

Also, more detailed information in the supply chain costs, such as allocating harvesting cost for different products or evaluating different haulage distances and optimal routes, could be included in future studies.

Although this study contains some limitations, the results give a first indication of the optimal markets, net value recovery and optimal rotation for SRF in Ireland that can support a forest landowner's decision-making until more data is available.

Chapter 7: Conclusions

Chapter 7: General discussion and conclusions

This dissertation has investigated the potential financial value of Short Rotation Forestry (SRF) in Ireland from the forest owner's perspective. Specifically: 1) potential markets for SRF were investigated; 2) the above-ground biomass productivity of four SRF stands (two eucalyptus and two hybrid poplar) for different market sectors was evaluated; 3) optimal financial value and allocation of products from eleven supply chains were analysed for the four stands; 4) key parameters for the valuation of wood for different market sectors were identified and 5) the optimum financial rotation was assessed in one eucalyptus stand.

The market survey of the Irish wood industry described in Chapter 2 identified the SRF potential markets and revealed the wood specifications and price paying potential required by industry. This data was used to carry out the financial analysis in Chapter 6 that revealed supply chains with pallet material were more profitable than energy only supply chains. This was confirmed in the study case in Oregon (Chapter 3) where products of higher value than pulp material for chips were created in order to make SRF development successful. Therefore, although renewable energy targets still need to be met and SRF has the potential to contribute to them it would not be the best choice for landowners whose main motivation is the economics.

The Irish market survey in Chapter 2 found cubic metres and tonnes were used interchangeably to trade wood biomass. Furthermore, energy units were also used. To be able to compare prices in different bases (weight, volume, energy) a unit tool, VEWTOOL was developed in Chapter 5. VEWTOOL was used to convert all the unit prices to cubic metres so the financial analysis carried out in Chapter 6 compared the returns from the two different pricing systems (tonnes and cubic metres) resulting in significant variation in returns particularly in the poplar stands.

In addition, gaps of knowledge and information needs such as the wood and fuel properties were identified in the market survey of Chapter 2. The survey in Oregon described in Chapter 3 indeed confirmed the SRF wood properties were useful in the initial development of markets. SRF wood and fuel properties such as basic density, calorific value, ash content were measured and described Chapter 4 and used for the conversions in Chapter 5 so they could be inputs in the financial analysis in Chapter 6. The higher returns of eucalyptus compared to poplar were due to the differences in wood properties such as the higher basic density of eucalyptus. This demonstrates the importance of making information on wood properties available to landowners and end users to better select the right species for the right market.

The results of this dissertation give recommendations for policy makers on the economic sustainability of SRF. Furthermore, the results provide new information and knowledge on the economics of SRF for landowners, their advisors and forest managers. This new information can aid decision making on establishing SRF and marketing the products from SRF harvesting. Finally, knowledge gaps were identified and recommendations to develop further research on the economics of SRF were made.

Findings

The overall finding of this investigation is that SRF is financially feasible in Ireland with a mean Equivalent Annual Annuity (EAA) of €325 ha^{-1} yr^{-1} standing value. Although fibre and energy were the policy target uses for SRF, it was found that other more profitable markets can develop for using SRF and will compete with fibre and energy end-users. While the supply chains with energy only products had a mean EAA of €142 ha^{-1} yr^{-1}, the ones that included pallet had a mean of €429 ha^{-1} yr^{-1}. Furthermore, units for the quantification and valuation of wood biomass should be related to market segment. The current Irish timber trade system uses volume in cubic metres and weight in tonnes interchangeably, but this is only valid at very specific conditions of basic density and moisture content. SRF stands studied in this dissertation showed a higher return for the landowner when sold by volume and particularly in the case of the poplar stands this increase was more pronounced, entailing 49 % higher return compared to selling by weight.

The main specific findings are:

- Maximum financial value was achieved by the eucalyptus stands and supply chains producing pallet material: an average EAA of €505 ha^{-1} yr^{-1}. The supply chains producing energy only products were considerably lower than those supply chains with diverse markets, with on average 50% lower returns. SRF will not contribute to meeting renewable energy targets if the pallet market develops, or another more financially attractive market compared to energy develops. In this situation, an incentive for energy use would be necessary if SRF has to contribute to meet renewable energy targets. Therefore, it is recommended that policy supporting SRF development, and the Forestry for Fibre Grant Premium category be reviewed in light of these findings.

- Markets can evolve between plantation establishment and the time of harvesting. Landowners and especially their advisors need to be aware of the market's unpredictability and the potential financial changes for competitive land uses, which can make other crops more attractive than SRF. On the other hand, a minimum production scale is required for industry to consider the use of SRF suggesting that establishment at scale is required. This creates a circular problem in that establishment can only be promoted if markets are assured and markets can only be developed if a minimum supply is guaranteed. This issue is crucial for SRF as the main motivation of establishment is financial.
- Availability of information and marketing strategies are key to the development of markets for new crops. Research and education materials are needed to satisfy landowners that markets are there. Flexibility on target markets reduces the risk for SRF growers. If SRF is specifically grown for fibre or energy, the risk associated with market changes will be higher than conventional forestry as the latter has a wider range of established markets. The market survey carried out in this dissertation revealed energy as the most favourable sector to use SRF but also confirmed other higher value, potential uses: particularly small sawlog for pallet material.
- In Ireland, with an average forest plantation size of 8.7 ha in the private forest sector, grower co-ops or the ability to market harvested material at scale is required. In addition to ensuring production scale, an association of small growers will also satisfy the preference of industry for not engaging with individual private forest owners.
- Understanding of the wood parameters relevant for each market sector and the conversions between parameters is needed by the supply chain stakeholders for fair trade. VEWTOOL, the unit tool developed in this

dissertation can be a useful instrument to fulfil knowledge gaps and carry out conversions.

- Biomass parameters for eucalyptus and poplar SRF were measured for the first time in Irish conditions, including basic density, calorific value, moisture content and BEFs.
- The eucalyptus stands showed higher basic density than poplar, an average of 412 kg m^{-3} compared to 297 kg m^{-3}, and also higher than Sitka spruce conventional forestry, which has a density of 364 kg m^{-3}. Fibre and energy markets prefer higher density wood, due to the impact of basic density on the volume weight relationship and on the energy content. Therefore, eucalyptus is preferred by fibre and energy markets.
- Basic density increased with height along the stem of both poplar and eucalyptus. Due to the markets' preference of higher density wood, the impact of basic density variation in the stem on price should be considered when performing log optimisation analysis for value recovery.
- SRF has the ability to produce a large amount of biomass in a reduced amount of time. The studied SRF eucalyptus and poplar stands produced between 19 and 32 m^3 per ha per year or 7.5 and 13.7 odt per ha per year, on average after between 17 and 23 years.
- The financial rotation for the studied eucalyptus stand was slightly longer, at 21 years, than the 10 to 20 year rotation aimed for SRF by policy, when estimated at a 5% discount rate. It is recommended that the target rotation for SRF should be extended beyond 20 years.

Recommendations

This research found policy implications are needed for the development of SRF and its economic sustainability. More specifically:

- Policy promoting SRF must be long term, and target not only landowners but also supply chain participants and end users. Current SRF policy is focused only on afforestation by landowners with the Forestry for Fibre Grant Scheme. However, supply chain participants and end-users were not aware of SRF and they are essential to secure the economic sustainability of SRF. Therefore, a more comprehensive and long-term policy targeting all the parties involved from the establishment to end-use are needed.

- Policy must support research and education to gain landowners and end-users acceptance. For instance, gaps on SRF wood properties and yield models were identified.

In addition, this research identified the following commercial implications needed for the development of SRF:

- Minimum resource scale to secure supply consistency. SRF markets can only be developed if a minimum supply is guaranteed but establishment of SRF can only be promoted if markets are assured. It is recommended a long-term agreement between landowners and end-users is made at establishment time so both sides can reduce risk. It is also recommended small landowners co-operate to more efficiently manage their crops and their products.
- Marketing strategies. Investment and resources allocated for the promotion of SRF are needed and were identified as a key factor for new markets development.
- Quantification and valuation of wood biomass related to market segment. To assure a fair trade of wood biomass it is recommended the standardisation of procedures for its measurement and pricing depending on the end use are developed.

Limitations

Although interviewees on the market survey gave perceptions of eucalyptus and poplar, 76% acknowledged that they were not familiar with these species. Only the responses of those who had prior experience or had some knowledge on SRF were considered for the results on the perceptions of using SRF. Structural wood properties of SRF for use as sawlog and chemical composition for use as fuel were identified in the survey as information required by end-users in order to accept SRF material but were outside the scope of this study.

Detailed data of four SRF stands was collected. However, the stands were very different: two stands were *Eucalyptus* genera, but different species; while, the other two *Populus*. Stands were different ages, at 17 and 23 years old. Stocking density ranged from 258 to 842 stems per hectare. These parameters influence productivity and therefore value per hectare. Where possible, unit values were used to compare stands.

The financial rotation study was limited to one eucalyptus stand only due to the lack of SRF stands within the target rotation years in Ireland and prior years' volumes were estimated by measuring rings increments. When more SRF stands grow to target rotation ages further data should be collected to develop yield models, which may be used to identify optimal financial rotation more accurately.

VALMAX, the value optimisation tool, was useful to evaluate maximum financial value, through value recovery and allocation of products using the actual stand parameters. However, VALMAX required certain input datasets in a specific way. For example, stem profile input files were required to present the stems diameters at every 10 cm length so assumptions on tree shape had to be taken to interpolate field measured diameters taken every 3 m length. The use of harvester head stem diameter datasets or terrestrial lidar scanner could be more efficient and accurate for stem profiles production. In addition, parameters that had a price impact for some of the SRF potential markets were not accounted for in VALMAX. For example, some markets prefer higher density so basic density variation along the stem should be accounted for in log optimisation. Similarly, energy content in different assortments should be considered.

This work focused on the economic sustainability of SRF. However, this is only one of the three pillars of sustainable forest management and the other two: environmental and social should also be evaluated and considered when taking on SRF.

Future research

It is recommended to carry out a comparative financial analysis of SRF with other land uses including non-forestry uses and Irish conventional forestry. This will provide clearer economic prospects to landowners and advisors when considering SRF alternatively to conventional forestry.

The optimal financial rotation of SRF stands and the impact of subsidies and different discount rates on this should be further researched. Furthermore, the impact of current subsidies on the market and the interaction of agricultural, forestry and energy subsidies should be investigated in Ireland.

Future studies could develop yield models and biomass equations for eucalyptus and poplar in Ireland, that would facilitate quantification of biomass over time, and is a basic tool for forest planning and resource optimisation. Furthermore, accurate and effective methods for measuring parameters relevant to each market sector could be developed. For instance, biomass equations for SRF could be developed to quantify total above ground biomass.

There is a need for applied research with industry to best match wood properties and end use. In the case of SRF as fuel material, further research on chemical composition of biomass is needed as this is very important for energy conversion systems. In the potential use of SRF as solid wood products, mechanical wood properties such as strength and stiffness, should be investigated.

In addition, there are potential products such as cross laminated timber (CLT) and biorefinery products that could be also investigated to develop with Irish SRF material as potentially these can improve landowner returns.

VEWTOOL could be further developed on a more intuitive easily usable interface that would allow users to benefit from it. For example, it can be fully integrated to the Irish Wood Fuel Database as this has already been done with some parts of the tool: the calorific value converter and the weight-volume conversion factors.

Higher values of basic density of eucalyptus compared to Sitka spruce conventional forestry means carbon sequestration density per hectare would also be higher in eucalyptus. Research on CO_2 absorption by eucalyptus should be carried out to clarify if eucalyptus could be a good alternative to reduce carbon emissions.

The use of optimisation tools for maximising the financial return including the parameters relevant to biomass markets, ie. basic density or calorific value of different partitions could be further developed.

Furthermore, comparison of the optimisation tool results with real SRF harvesting allocation of products could be investigated. This will describe the accuracy of the standing valuation from the owner’s point of view using a log optimisation tool, VALMAX, compared to the actual harvested allocation of products and its financial value.

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Appendices

Appendix A: Detailed stem profiles

A.1 Stem profiles at current age of the stands

A.1.1 Stem profiles of the main stems

Overbark diameters of the sample trees were measured at one metre intervals along the stem (see Chapter 2). However, the optimisation algorithm requires diameters at every decimetre interval. In this case, only manual measurements were available, so diameters were interpolated at 10 cm intervals on the stem between the one metre interval measurements (Figure A.1), following the equations (Eq. A.1 and Eq. A.2):

$$\frac{D_a - D_b}{1} = \frac{d}{L}$$

(Eq. A.1)

$$D_n = 2 * d + D_b$$

(Eq. A.2)

where

D_a and D_b are known real measurement diameters at a and b metres height of the stem;

D_n is the interpolated diameter at height b minus L;

d is D_a minus D_b.

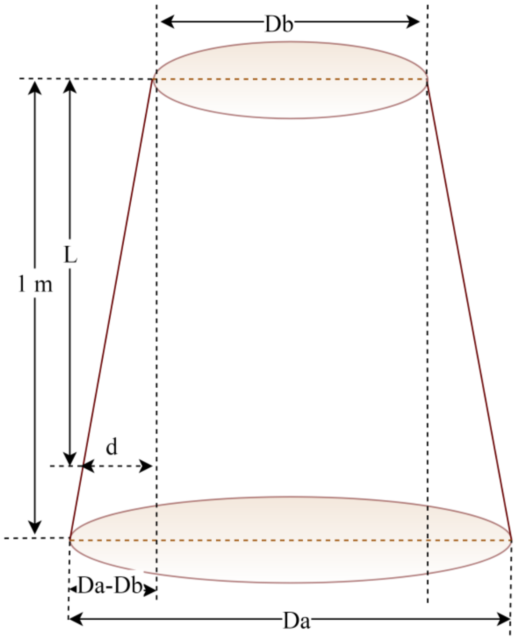

Figure A.1. Diagram of stem section between two real diameters measurements.

A.1.2 Stem profiles of the forks

Some of the sample trees in the poplar stands (POP-CAV and POP-KIL) presented forks of diameters greater than 7 cm and 3 m length, which also contributed to the total merchantable volume. These forks were treated as secondary main stems, so diameters were also measured at one metre intervals and interpolated to gain the correspondent diameters every decimetre. The part where the fork joined the main stem was assigned to energy products only in the financial analysis as it was assumed the logs from this section would not be suitable for roundwood assortments (Figure A.2).

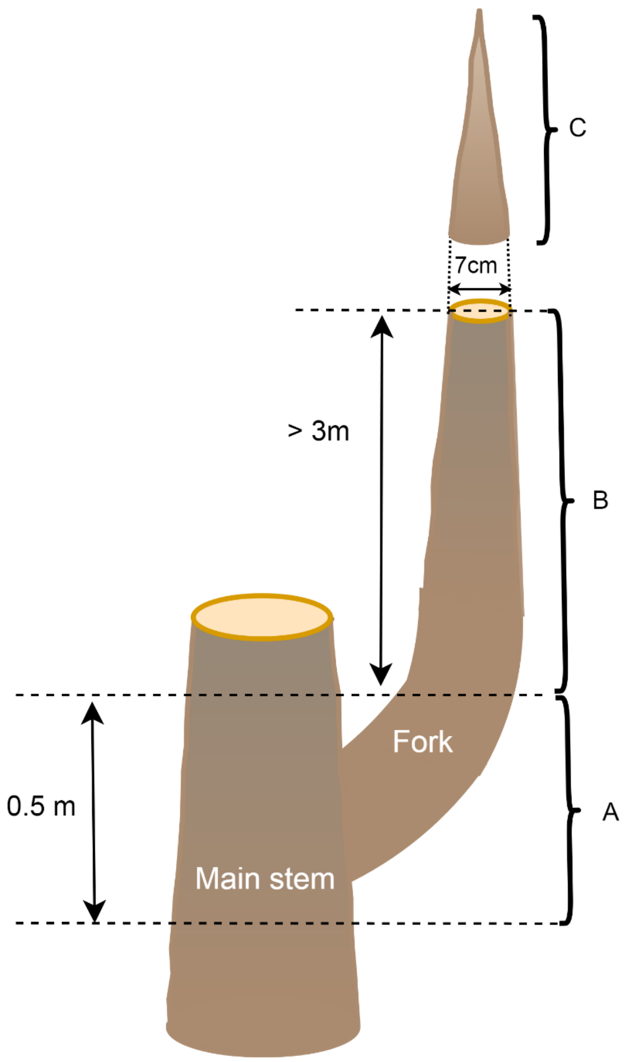

Figure A.2. Assortments of trees with forks greater than 7cm diameter and 3 m length. Section A was allocated to energy products only; section B allocated to roundwood and energy products and section C is the fork's top allocated to energy.

A.2. Stem profiles at past potential rotation ages

Stem profiles and overbark stem volumes for each year from 10 to 22 were required to carry out the financial optimisation analysis for the potential range of rotation ages. Stem profiles, volumes and discs from the current year 22 were used to estimate this dataset at past ages.

Discs were cut at three metre intervals along the stem of each destructively sampled tree, as represented in Figure A.3 (a). Annual growth rings were identified on these discs and were used to measure the annual diameter increment at the potential rotation ages. Total height at past ages was estimated by calculating proportionality of diameters and height at the current age and projecting it to past ages as detailed in

Equation A.3 and Figure A.3 (b) and described by Alemdag, cited by Gilabert and Paci (2010).

$$\frac{H_1}{Dn} = \frac{H_2}{D_{n-1}} = \frac{H_3}{D_{n-2}}$$

(Eq. A.3)

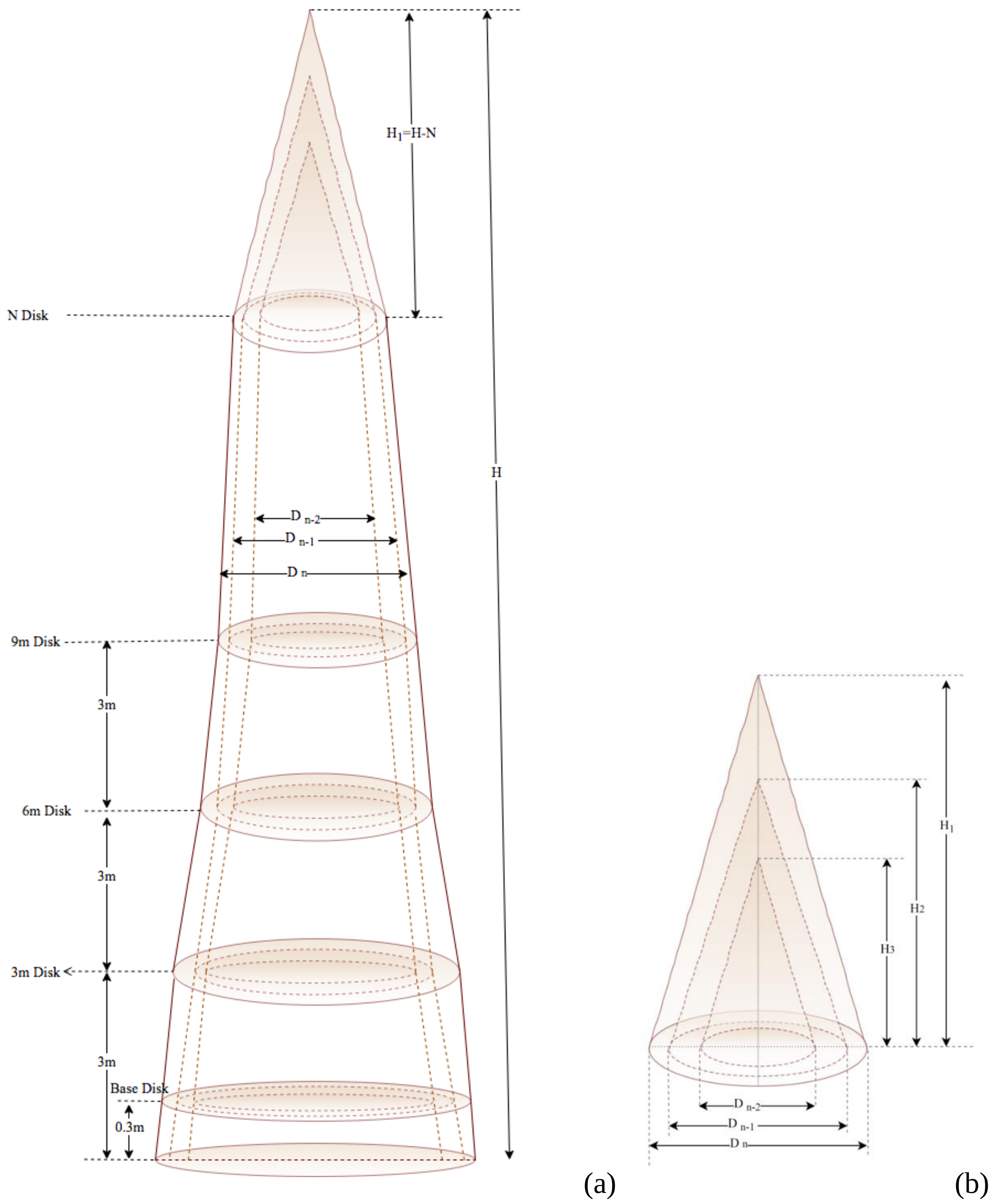

Figure A.3. (a): Diagram representing a stem and disc samples taken every 3 m. (b): detail of the top and proportionality used to estimate height.

Where,

H, total height at current age;

H_1, length from last disc to top at current age (n);

H_2, length from last disc to top at n-1 years of age;

H_3, length from last disc to top at n-2 years of age;

D_n, diameter at current age;

D_{n-1}, diameter at n-1 years of age;

D_{n-2}, diameter at n-1 years of age.

Stem diameters under-bark from ages 10 to 22 years were recorded for each disc. Bark thickness was measured on each disc and a percentage of bark volume per disc was calculated. This facilitated estimation of diameters over-bark at past ages as per Equation A.4 by using specific % bark volume per each disc. Table A.1. shows the bark percentages used to calculate diameters over-bark. The average bark percentage was 6.0%, and it varied from 2.8% to 14.0%.

$$D_{ob} = D_{ub} + D_{ub} * \%\ bark$$

(Eq. A.4)

Where,

D_{ob}, diameter over bark

D_{ub}, diameter under bark

Table A.1. Mean diameter over-bark at current age (23 years) and percentage of bark at 3 m height intervals on the stem of 10 Eucalyptus nitens *of the site in Cappoquin, Co. Waterford. Standard deviation in parenthesis.*

Disc	Diameter overbark (mm)	Bark (%)
Base	314 (97)	10.2 (3.1)
3m	266 (92)	5.7 (1.5)
6m	248 (88)	5.0 (1.6)
9m	223 (80)	4.5 (0.7)
12m	207 (82)	4.3 (1.0)
15m	186 (80)	4.9 (1.0)
18m	177 (74)	5.0 (1.2)
21m	166 (45)	5.4 (1.1)
24m	136 (29)	5.9 (2.0)
27m	104 (18)	9.3 (4.9)
30m	74 (14)	10.0 (3.0)

Diameters over-bark of each sample disc were grouped by tree and age to build stem profiles at different ages. An example of the profiles for one sample tree is graphed in Figure A.4. As explained above for profiles at the current age, interpolation was used to get diameters at every decimetre interval on the stem.

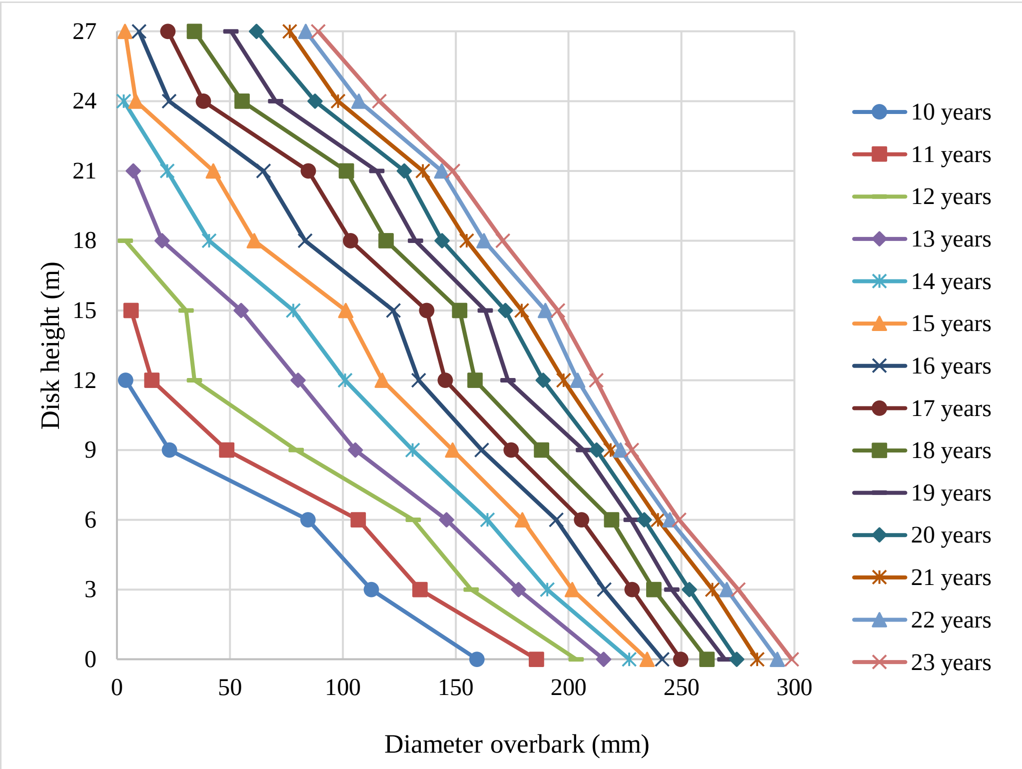

Figure A.4. Example of rings annual increment measurement. EUC-WAT site, tree sample 1.

Growth ring increment measurements showed a rapid increase, with ring width increasing an average of 6 mm per year, so diameters increasing an average of 12 mm per year, what means substantial addition in volume between the years measured (10-23 years old). There was on average just over 6m length of merchantable stem at 10 years old. This increased to 30 m length of merchantable stem at 23 years old.

Table A.2. Mean diameter overbark in mm at 3 m height intervals for ages between 10 and 23 years. Standard deviation in parenthesis.

Age (years)	Disc height										
	Base	3m	6m	9m	12m	15m	18m	21m	24m	27m	30m
10	165 (37)	123 (4)	85 (16)	55 (4)	48 (4)	43 (19)	25 (20)	-	-	-	-
11	183 (49)	143 (18)	105 (25)	70 (5)	61 (6)	55 (3)	32 (5)	-	-	-	-
12	202 (69)	161 (32)	128 (43)	92 (13)	66 (8)	64 (3)	34 (4)	13 (4)	-	-	-
13	219 (94)	177 (61)	145 (55)	113 (16)	80 (3)	79 (6)	55 (11)	22 (6)	-	-	-
14	233 (116)	192 (89)	162 (66)	131 (26)	99 (8)	83 (3)	71 (3)	34 (5)	9 (3)	-	-
15	247 (122)	204 (98)	176 (72)	146 (34)	119 (27)	103 (11)	83 (5)	46 (4)	16 (4)	11 (4)	-
16	257 (130)	216 (106)	190 (83)	161 (59)	137 (41)	120 (18)	104 (12)	69 (14)	32 (11)	19 (4)	7 (4)
17	267 (135)	225 (113)	201 (92)	174 (68)	151 (51)	134 (27)	121 (21)	93 (27)	50 (23)	31 (15)	15 (13)
18	277 (141)	235 (120)	211 (99)	185 (77)	165 (62)	146 (35)	136 (30)	113 (45)	72 (35)	45 (28)	25 (20)
19	286 (147)	244 (125)	221 (104)	196 (87)	177 (69)	157 (46)	148 (39)	129 (64)	90 (51)	62 (46)	35 (30)
20	294 (152)	251 (129)	229 (111)	204 (94)	188 (77)	167 (55)	158 (49)	143 (81)	105 (69)	75 (58)	47 (43)
21	302 (159)	257 (133)	237 (114)	213 (103)	196 (85)	175 (64)	165 (61)	154 (97)	118 (82)	81 (51)	74 (58)
22	309 (163)	262 (135)	243 (119)	218 (109)	202 (92)	181 (75)	171 (70)	162 (105)	129 (98)	98 (80)	65 (57)
23	314 (166)	266 (137)	248 (125)	223 (113)	207 (95)	186 (77)	177 (76)	166 (107)	136 (106)	104 (85)	74 65)

Appendix B: Supply chain costs

Variation in supply chain costs between sites and potential rotation ages were estimated in this Appendix. These factors were used as inputs for the optimisation tool in Chapter 6.

B.1 Supply chain descriptions

The eleven supply chains described Chapter 6 are summarised in Table B.1 and Figure B.1, B.2 and B.3.

Table B.1. Supply chains description summary

ID	Name & code	Harvest method	Harvest system	Tree section	Log type	Product assortment	Market segment
1	Roundwood production using a harvester and forwarder.	CTL	Harvester + Forwarder	Merchantable stem (D > 7cm)	Sawlog and pulp	Roundwood	Pallet and fibre or energy
2	Roundwood logs & hogfuel biomass production using a harvester, forwarder, residue bundler, and a shredder.	CTL	Harvester + Forwarder	Merchantable stem (D > 7cm)	Sawlog and pulp	Roundwood	Pallet and fibre or energy
			Residue bundler + Bundle forwarder + Shredder	Top + branches	-	Hogfuel	Energy
3	Roundwood logs & biomass production using a harvester, forwarder, and a chipper.	CTL	Harvester + Forwarder	Merchantable stem (D > 7cm)	Sawlog and pulp	Roundwood	Pallet and fibre or energy
			Biomass Forwarder + Chipper	Top + branches	-	Woodchip	Energy
4	Sawlog and pulpwood woodchip production using a harvester, forwarder, and a chipper.	CTL	Harvester + Forwarder	Merchantable stem (D > 14cm)	Sawlog	Roundwood	Pallet
			Harvester + Forwarder + Chipper	Merchantable stem (D: 7 to 14cm)	Pulp	Woodchip	Energy
5	Sawlog, pulpwood woodchip, and hogfuel biomass production using a harvester, forwarder, chipper, residue bundler, and shredder.	CTL	Harvester + Forwarder	Merchantable stem (D > 14cm)	Sawlog	Roundwood	Pallet
			Harvester + Forwarder + Chipper	Merchantable stem (D: 7 to 14cm)	Pulp	Woodchip	Energy
			Residue bundler + Bundle forwarder + Shredder	Top + branches	-	Hogfuel	Energy
6	Sawlog, pulpwood woodchip, and biomass production using a harvester, forwarder and a chipper.	CTL	Harvester + Forwarder	Merchantable stem (D > 14cm)	Sawlog	Roundwood	Pallet
			Harvester + Forwarder+ Chipper	Merchantable stem (D: 7- 14cm)	Pulp	Woodchip	Energy
			Biomass Forwarder + Chipper	Top + branches	-	Woodchip	Energy

Table B.1. (Continued).

ID	Name & code	Harvest method	Harvest system	Tree section	Log type	Product assortment	Market segment
7	Roundwood woodchip production using a harvester, forwarder and a chipper.	CTL	Harvester + Forwarder + Chipper	Merchantable stem (D > 7cm)	Sawlog and pulp	Woodchip	Energy
8	Roundwood woodchip and hogfuel biomass production using a harvester, forwarder, chipper, residue bundler and shredder.	CTL	Harvester + Forwarder + Chipper	Merchantable stem (D > 7cm)	Sawlog and pulp	Roundwood	Pallet and fibre or energy
			Residue bundler + Forwarder bundles + Shredder	Top + branches	-	Hogfuel	Energy
9	Roundwood woodchip and hogfuel biomass production using a harvester, forwarder, chipper.	CTL	Harvester + Forwarder + Chipper	Merchantable stem (D > 7cm)	Sawlog and pulp	Woodchip	Energy
			Biomass Forwarder + Chipper	Top + branches	-	Woodchip	Energy
10	Sawlog and biomass production using a harvester, forwarder and chipper.	INT	Harvester + Forwarder	Merchantable stem (D > 14cm)	Sawlog	Roundwood	Pallet
			Harvester + Biomass Forwarder + Chipper	Merchantable stem (D: 7- 14cm) + Residues	-	Woodchip	Energy
11	Wholetree biomass production using a harvester, forwarder and chipper.	WT	Harvester + Forwarder + Chipper	Whole tree	-	Woodchip	Energy

Where: CTL, Cut to length harvesting; IN, Integrated harvesting and WT, Whole tree harvesting.

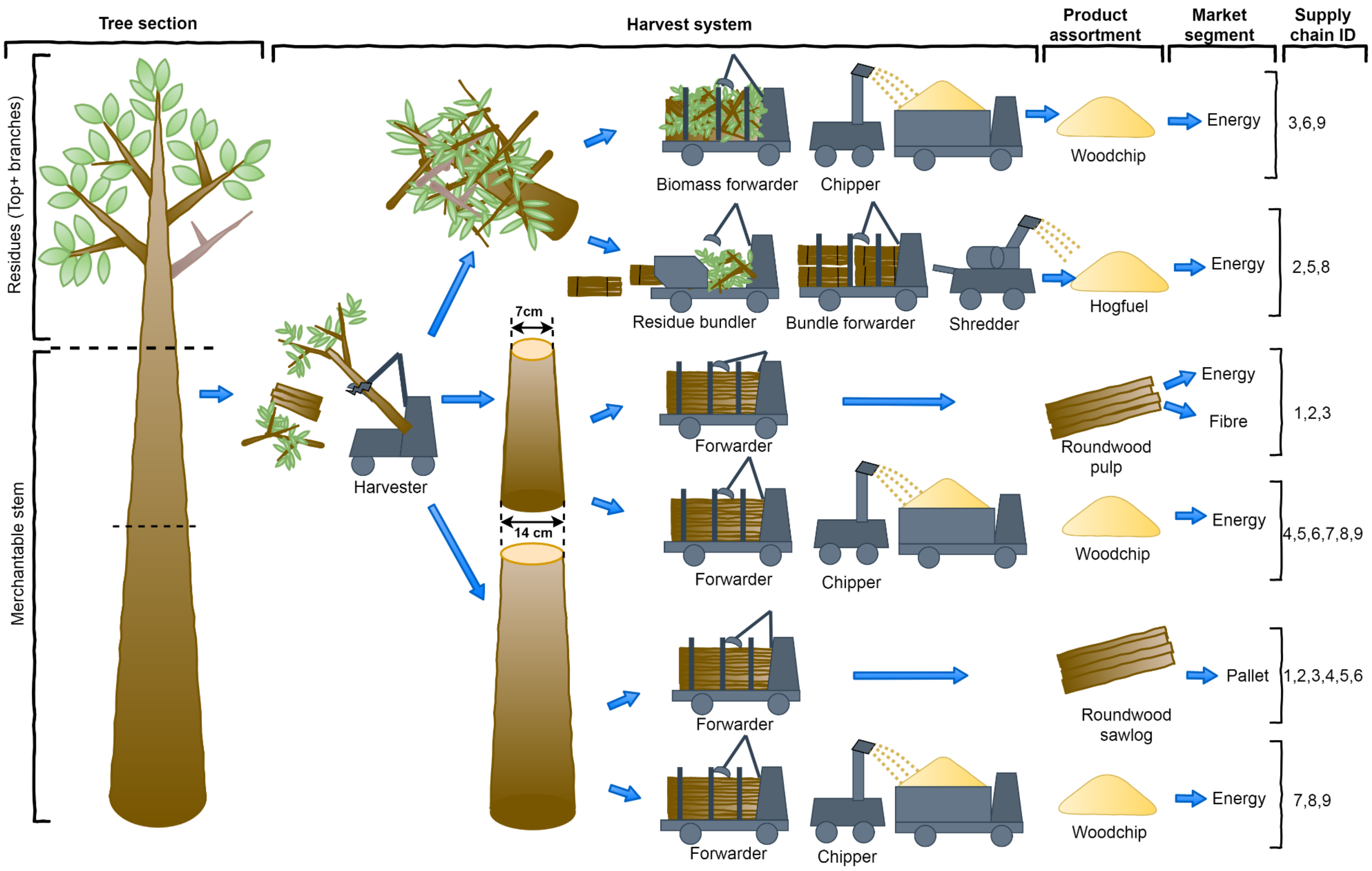

Figure B.1. CTL harvesting method diagram

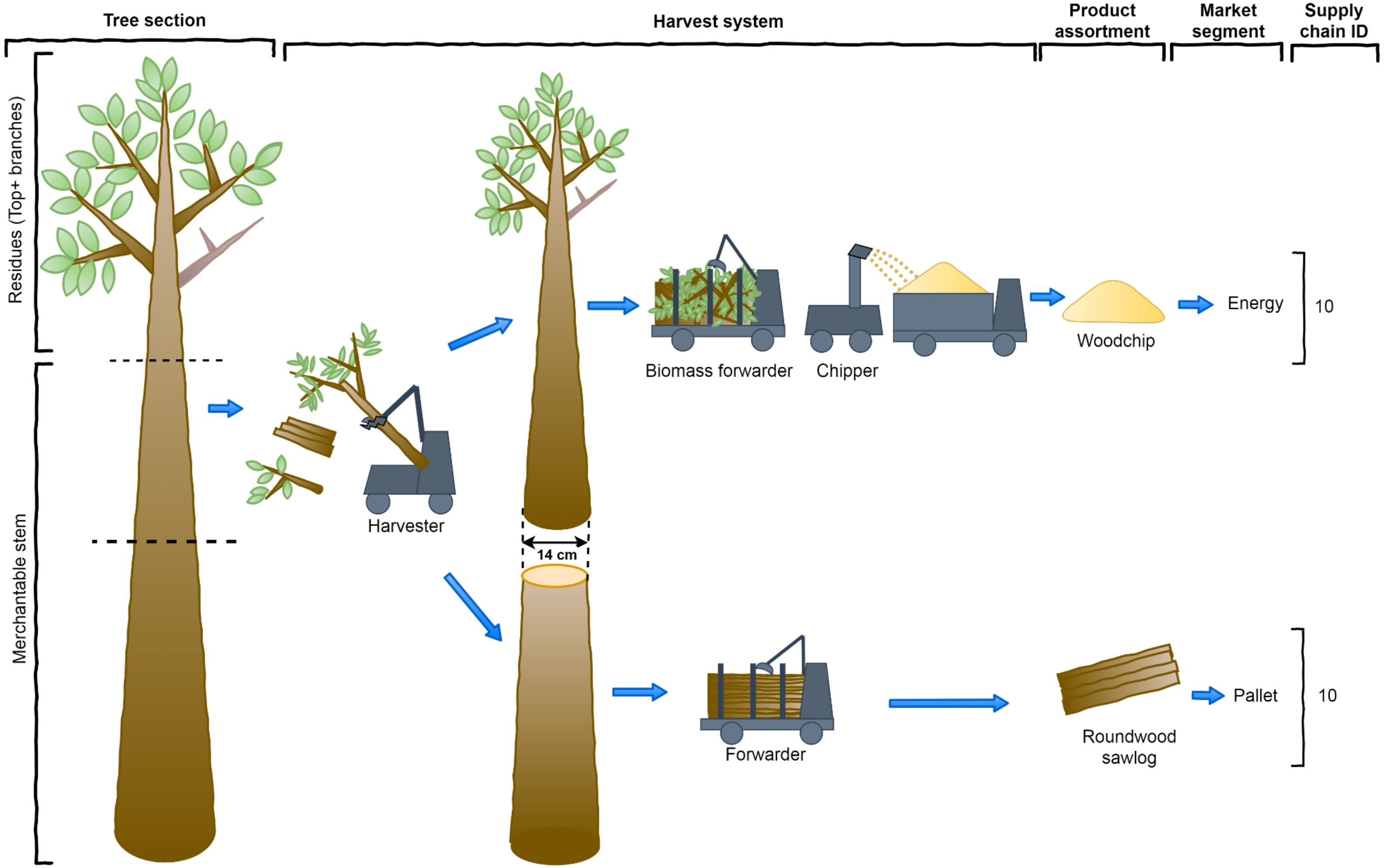

Figure B.2. Integrated harvesting method diagram

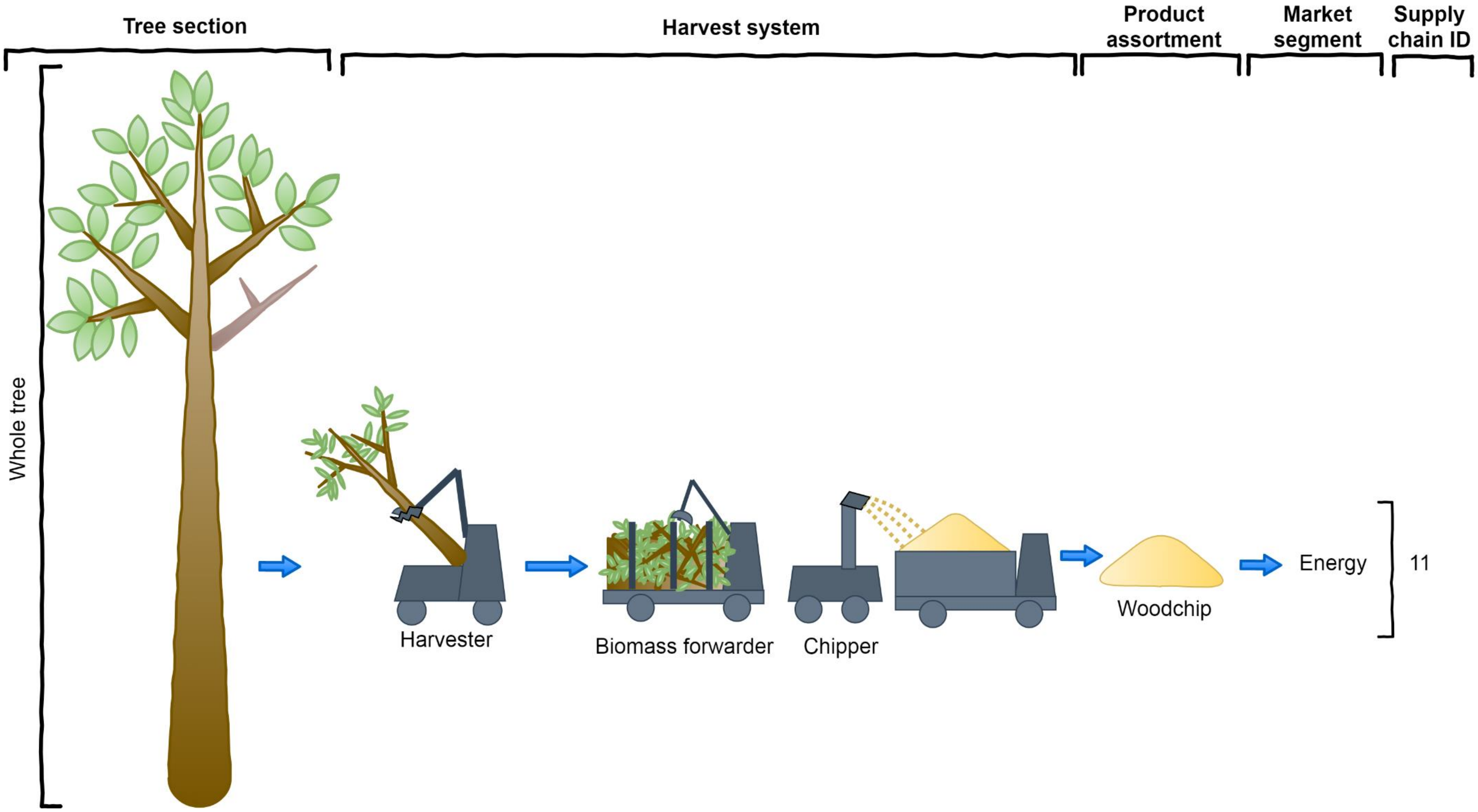

Figure B.3. Whole tree harvesting method diagram

B.2 Supply chain costs at current age

Table 2.1 shows mean tree volume and standing merchantable volume per hectare which were the inputs for the supply chain cost model. Results from the cost model for each of the SRF stands are presented in Table B.3.

Table B.2. Tree mean volume and standing merchantable volume for the four SRF stands.

Parameter	**EUC-WEX**	**POP-CAV**	**EUC-WAT**	**POP-KIL**
Tree mean volume (m^3)	0.95	1.28	0.88	1.47
Standing merchantable volume (m^3 ha^{-1})	413	330	743	428

Table B.3. Harvesting, extraction and chipping costs in € m^{-3}.

Machinery	**EUC-WEX**	**POP-CAV**	**EUC-WAT**	**POP-KIL**
Harvester CTL*	2.44	2.01	2.56	1.83
Harvester INT **	2.23	1.54	2.24	1.46
Harvester WT ***	2.10	1.45	2.12	1.38
Forwarder CTL	4.64	4.64	4.64	4.64
Residue Bundler	14.41	14.41	14.41	14.41
Bundle Forwarder	5.80	5.80	5.80	5.80
WT and Biomass Forwarder	7.73	7.73	7.73	7.73
Roadside Chipper	6.67	6.67	6.67	6.67
Roadside Shredder	4.08	4.08	4.08	4.08

*CTL. Cut to Length harvesting

**INT Integrated harvesting

***WT whole tree harvesting

Each assortment of the eleven supply chains was assigned its corresponding harvesting system as in Table B.1 and the operation costs described in Table B.4 were associated to each harvesting system.

Table B.4. Supply chain costs by assortments, expressed in € m^{-3}.

Supply chain ID	Product assortment	EUC-WEX	POP-CAV	EUC-WAT	POP-KIL
1	Roundwood (sawlog & pulp)	7.08	6.65	7.20	6.47
2	Roundwood (sawlog & pulp)	7.08	6.65	7.20	6.47
	Hogfuel from residues	24.30	24.30	24.30	24.30
3	Roundwood (sawlog & pulp)	7.08	6.65	7.20	6.47
	Woodchip from residues	14.40	14.40	14.40	14.40
4	Roundwood (sawlog)	7.08	6.65	7.20	6.47
	Woodchip from roundwood (pulp)	13.74	13.31	13.86	13.14
5	Roundwood (sawlog)	7.08	6.65	7.20	6.47
	Woodchip from roundwood (pulp)	13.74	13.31	13.86	13.14
	Hogfuel from residues	24.30	24.30	24.30	24.30
6	Roundwood (sawlog)	7.08	6.65	7.20	6.47
	Woodchip from roundwood (pulp)	13.74	13.31	13.86	13.14
	Woodchip from residues	14.40	14.40	14.40	14.40
7	Woodchip from sawlog & pulp	13.74	13.31	13.86	13.14
8	Woodchip from roundwood (sawlog & pulp)	13.74	13.31	13.86	13.14
	Hogfuel from residues	24.30	24.30	24.30	24.30
9	Woodchip from roundwood (sawlog & pulp)	13.74	13.31	13.86	13.14
	Woodchip from residues	14.40	14.40	14.40	14.40
10	Roundwood (sawlog)	6.87	6.18	6.88	6.10
	Woodchip from roundwood (pulp) & residues	16.62	15.93	16.64	15.86
11	Woodchip from whole tree	16.50	15.85	16.52	15.78

B.3 Supply chain costs at past potential rotation ages

The same process was used to calculate these datasets for the EUC-WAT site for each previous year from age 10 years to 22 years, in order to investigate potential rotation ages. Volume for previous years was calculated using the same approach as at current age. Volume per tree was calculated using Huber's formula. Volume per hectare was estimated assuming the same diametric distribution as at current age. It was also assumed that the current stocking was the same for previous years because information about stocking of this stand in the past was not available. Results of stand volume for previous years are presented in Table B.5.

Table B.5. Tree mean size and standing merchantable volume for the EUC-WAT site at ages between 10 and 22 years old.

Parameter	**EUC-WAT**												
Age (years)	10	11	12	13	14	15	16	17	18	19	20	21	22
Tree mean size (m^3)	0.08	0.12	0.17	0.22	0.29	0.35	0.42	0.49	0.56	0.63	0.70	0.75	0.81
Standing merchantable volume (m^3 ha^{-1})	69	101	143	189	242	297	356	413	475	529	586	632	684

Table B.6 presents harvesting, extraction and chipping costs for previous years. Mean tree volume and standing merchantable volume per hectare in Table B.5 were the inputs to the cost model.

Each assortment of the same eleven supply chains was associated to the respective costs at each previous year and the results are presented in Table B.7.

The haulage cost for 80 km distance was €8.60 per m^3 for roundwood material, €8.47 per m^3 for bundles and €9.16 per m^3 for woodchips (Coates pers. comm., 2017).

Table B.6. Harvesting, extraction and chipping costs in € m^{-3} of the EUC-WAT stand for ages between 10 and 22 years old

EUC-WAT harvesting, extraction and chipping cost (€ m^{-3})													
Age(years)	10	11	12	13	14	15	16	17	18	19	20	21	22
Harvester CTL*	12.08	9.45	7.51	6.27	5.34	4.67	4.14	3.76	3.43	3.20	2.99	2.85	2.71
Harvester INT**	7.65	6.26	5.16	4.42	3.84	3.41	3.06	2.80	2.57	2.41	2.27	2.17	2.07
Harvester WT***	7.23	5.92	4.88	4.18	3.63	3.22	2.89	2.64	2.43	2.28	2.15	2.05	1.96
Forwarder CTL	4.64	4.64	4.64	4.64	4.64	4.64	4.64	4.64	4.64	4.64	4.64	4.64	4.64
Residue Bundler	14.41	14.41	14.41	14.41	14.41	14.41	14.41	14.41	14.41	14.41	14.41	14.41	14.41
Bundle Forwarder	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80
WT and Biomass Forwarding	7.73	7.73	7.73	7.73	7.73	7.73	7.73	7.73	7.73	7.73	7.73	7.73	7.73
Roadside Chipping	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67
Roadside Shredding	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08

*CTL. Cut to Length harvesting

**INT Integrated harvesting

***WT whole tree harvesting

Table B.7. Supply chain costs for each assortment expressed in € m^{-3}.

Supply Chain ID	**Product assortment**	**Age (years)**												
		10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
1	Roundwood (sawlog & pulp)	16.72	14.09	12.15	10.90	9.98	9.31	8.78	8.40	8.07	7.84	7.63	7.48	7.35
2	Roundwood (sawlog & pulp)	16.72	14.09	12.15	10.90	9.98	9.31	8.78	8.40	8.07	7.84	7.63	7.48	7.35
	Hogfuel from residues	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30
3	Roundwood (sawlog & pulp)	16.72	14.09	12.15	10.90	9.98	9.31	8.78	8.40	8.07	7.84	7.63	7.48	7.35
	Woodchip from residues	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40
4	Roundwood (sawlog)	16.72	14.09	12.15	10.90	9.98	9.31	8.78	8.40	8.07	7.84	7.63	7.48	7.35
	Woodchip from roundwood (pulp)	23.38	20.75	18.81	17.57	16.64	15.97	15.45	15.06	14.73	14.50	14.29	14.15	14.01
5	Roundwood (sawlog)	16.72	14.09	12.15	10.90	9.98	9.31	8.78	8.40	8.07	7.84	7.63	7.48	7.35
	Woodchip from roundwood (pulp)	23.38	20.75	18.81	17.57	16.64	15.97	15.45	15.06	14.73	14.50	14.29	14.15	14.01
	Hogfuel from residues	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30
6	Roundwood (sawlog)	16.72	14.09	12.15	10.90	9.98	9.31	8.78	8.40	8.07	7.84	7.63	7.48	7.35
	Woodchip from roundwood (pulp)	23.38	20.75	18.81	17.57	16.64	15.97	15.45	15.06	14.73	14.50	14.29	14.15	14.01
	Woodchip from residues	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40

Table B.7. Supply chain costs for each assortment expressed in € m^{-3}(Continued).

Supply Chain ID	Product assortment	Age (years) 10	11	12	13	14	15	16	17	18	19	20	21	22
7	Woodchip from roundwood (sawlog & pulp)	23.38	20.75	18.81	17.57	16.64	15.97	15.45	15.06	14.73	14.50	14.29	14.15	14.01
8	Woodchip from roundwood (sawlog & pulp)	23.38	20.75	18.81	17.57	16.64	15.97	15.45	15.06	14.73	14.50	14.29	14.15	14.01
	Hogfuel from residues	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30	24.30
9	Woodchip from roundwood (sawlog & pulp)	23.38	20.75	18.81	17.57	16.64	15.97	15.45	15.06	14.73	14.50	14.29	14.15	14.01
	Woodchip from residues	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40	14.40
10	Roundwood (sawlog)	12.29	10.90	9.80	9.06	8.48	8.05	7.70	7.44	7.21	7.05	6.91	6.81	6.71
	Woodchip from roundwood (pulp) and residues	22.05	20.66	19.56	18.82	18.24	17.81	17.45	17.19	16.97	16.81	16.67	16.57	16.47
11	Woodchip from whole tree	21.63	20.31	19.27	18.57	18.03	17.62	17.29	17.04	16.83	16.68	16.55	16.45	16.36