PHYSICAL CHARACTERISATION AND QUANTIFICATION OF TOTAL ABOVE GROUND BIOMASS DERIVED FROM FIRST THINNINGS FOR WOOD FUEL CONSUMPTION IN IRELAND

By

Nicholas Mockler

A Thesis for the Degree of Masters in Science in Forestry

DECLARATION

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of MSc. in Forestry, is entirely my own work and has not been taken from the works of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: ____________________________

Date: _____________________________

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' What the current generation will sow, the next generation will reap '

ABSTRACT

Comprehensive knowledge of wood fuel properties assists in the optimisation of operations concerned with the harvesting, seasoning, processing and conversion of wood to energy. This study investigated the physical properties of wood fuel. These properties included moisture content and basic density. The field work also allowed for the quantification of above ground biomass partitions. The species investigated were alder (*Alnus glutinosa*), ash (*Fraxinus excelsior* L.), birch (*Betula* spp.), lodgepole pine (*Pinus contorta* Dougl.), Norway spruce (*Picea abies* (L.) Karst.), and Sitka spruce (*Picea sitchensis* (Bong.) Carr.). The primary variation sources investigated were spatiotemporal. This included sampling at different times of the year (dormancy, flushing and the growing season) in three different locations on the basis of latitudinal zones (South East, Midlands and North West of Ireland or 52^{o}N, 53^{o}N and 54^{o}N). The age of stands where sampling took place ranged from 12-17 years old.

The findings for moisture content, basic density and biomass have been accumulated from a large dataset (~ 4934 subsamples). Moisture content and basic density ranged between 38-65% and 344-498 $kg \cdot m^{-3}$ respectively in the stem wood sections between the six species. Ash was the only species that had a distinguishable temporal trend in stem wood moisture content. Ash stem wood moisture content was lower during dormancy and higher during flushing and the growing season. Moisture content in the branch wood sections ranged from 44-54% between the six species. In most cases, branch wood moisture content reduced significantly for all six species at flushing in comparison to dormancy. With all six species, basic density reduced with an increase in latitude. The quantification of above ground biomass found an increase of 43-53% in the biomass that can be potentially harvested from whole trees, in contrast to harvesting only merchantable stem sections. An evaluation of stand biomass estimation methods using biomass expansion factors (BEFs) to convert standing volume per hectare to biomass in oven dry tonnes and energy content per hectare was also made. BEFs ranged from 1.9-2.3 between the six species. However the utility of the BEFs from this study must be exercised with caution, due to the narrow ages and sizes of the trees sampled, in addition to including above ground biomass components only.

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INTRODUCTION

This dissertation documents a field investigation into physical wood fuel properties. The properties investigated were the moisture content and basic density of wood. Six species were investigated: alder (*Alnus glutinosa*), ash (*Fraxinus excelsior* L.), birch (*Betula* spp.), lodgepole pine (*Pinus contorta* Dougl.), Norway spruce (*Picea abies* (L.) Karst.), and Sitka spruce (*Picea sitchensis* (Bong.) Carr.).

Chapter one consists of a literature review that documents a background to the work undertaken, and its relevance to current industry research requirements. The literature review has been accepted for publication in a national peer reviewed journal: *Irish Forestry - Journal of the Society of Irish Foresters*. The title of the paper is: *The use of wood as a renewable source of energy in Ireland - Developments and knowledge gaps in the control of wood fuel quality*. The main author is Nicholas Mockler. The co-authors are Tom Kent and Eleanor Owens.

Wood fuel supply chain research covers many topics. More specifically, this work involved the characterisation of two physical wood fuel quality parameters. Moisture content and basic density were the two properties investigated. Chapters two and three document the effects of moisture content and basic density on wood fuel supply chain optimisation, in addition to the findings made in this study for both fuel properties. Sampling methods in the field for the determination of moisture content and basic density also allowed for the quantification of biomass. The background and findings made for biomass in this study are documented in Chapter four. Chapter five documents conclusions based on the main findings and shortcomings of Chapters two-four.

AIMS AND OBJECTIVES

The aims and objectives of this study are three-fold:

- First, to characterise moisture content and investigate spatiotemporal and partition variation.
- Second, to characterise basic density of stem sections and its spatial variation.
- Third, to quantify above ground biomass and energy content.

The purpose of this investigation is to ascertain the fuel properties of wood biomass under Irish conditions. Comprehensive knowledge of wood fuel properties assists in the optimisation of operations concerned with the harvesting, seasoning, processing and conversion of wood to energy. The study also aims to quantify total above ground biomass. The harvesting of all tree components (stem, tops < 7 cm, branches) has received increased interest in Ireland due to their potential as a source of fuel, and also to close gaps on demand shortfalls for wood energy into the future (COFORD Round Wood Demand Group (CRDG), 2011, Kent, 2012, Phillips, 2011). Quantifying biomass also provides a baseline determining the energy content of wood.

Six tree species from stands ranging from 12-17 years of age were chosen. Stands of this range of ages currently represent two thirds of the Irish forestry estate (NFI, 2007). Three conifers: lodgepole pine, Norway spruce and Sitka spruce were chosen. These species represent an extensive share of the proportion of total forest cover in Ireland (~ 67%), and contribute to the majority of round wood produced in Ireland (NFI, 2007, Phillips, 2011). The remaining three species chosen were broadleaves: alder, ash and birch. Due to an increase in private sector planting of broadleaves during the last 25-30 years, these three species have featured prominently (Short and Radford, 2008). Although alder, ash and birch are not featured in round wood forecasts for conventional end uses, they have potential as a considerable source of wood fuel (Kofman and Kent, 2009c). Broadleaf first thinning is also an essential operation for the future quality and production potential of privately owned forests (Short and Radford, 2008). In total, the six tree species represent 76% of the Irish forestry estate (NFI, 2007).

1. CHAPTER 1 – LITERATURE REVIEW

1.1. Introduction

In Ireland, consumption of wood for energy has increased in recent years for a number of reasons. The heavy dependence on finite resources of imported fossil fuels, declining indigenous energy production, and the adverse effects of climate change have been the key factors driving this increase. In response to these issues, a series of policies have been ratified, initially out of concerns for global climate change. The Kyoto Protocol set out aims to reduce greenhouse gas emissions (GHG) by 5.2% globally. Ireland, as a signatory of the Kyoto Protocol, has agreed to limit the growth in GHGs to 13% above 1990 levels by a target period of 2008-2012 (North and Healion, 2003, Government of Ireland, 2007). The Kyoto protocol commitments instigated a number of initiatives by the Irish Government to formally develop strategies in the effort to mitigate climate change. Among these strategies included encouraging an increase in the use of renewable energy resources. The Energy Policy White Paper, in particular the Sustainable Energy Sub Programme, committed to an investment of €276 million for the development of a renewable energy sector in Ireland over the course of the National Development Plan (NDP) 2007-2013 (Department of Communications, Marine and Natural Resources, 2007a). The Irish Bioenergy Action Plan outlined where this Government investment should be implemented for the development of a renewable energy sector in Ireland, including recommendations for increasing wood energy consumption (Department of Communications, Marine and Natural Resources, 2007b). The EU Renewable Energy Directive (RED, 2009/28/EC) set out a commitment that 20% of total energy use is to be derived from renewable energy resources by 2020. In accordance with this directive, Ireland has committed to a 16% target for renewable energy resources by 2020 under the National Renewable Energy Action Plan (NREAP, 2010). Targets under this plan relevant to wood consisted of the following (NREAP, 2010).

- 12% renewable heat energy generation by 2020;
- 30% co-firing with biomass at the three peat-fuelled power plants by 2015;
- 800 MW of Combined Heat and Power by 2020.

The realisation of these targets poses significant challenges. Despite a favourable policy environment, the consumption of wood for energy in Ireland is underdeveloped. This literature review documents the incentives in place to assist in the development of a wood energy sector in Ireland, and the challenges in maintaining and increasing consumption to fulfil policy targets. Research to support the development of a wood energy sector is also documented. In particular, this literature review will focus on research into wood fuel trade standardisation and quality control, as these have an influence on instilling consumer confidence in the use wood for energy.

1.2. Emergence of wood energy consumption

In Ireland, there is an unsustainable reliance upon imported fossil fuels, as 95% of total primary energy requirement (TPER) is derived from fossil fuels and 88% of TPER is imported (Dennehy *et al.,* 2012). This leaves Ireland in a precarious position in attempting to maintain security of fuel supplies. As a result, the consumption of renewable energy resources should be increased (wind, solar, geothermal, biomass, tidal, wave and hydro), as they are underutilised, indigenous and do not pollute the atmosphere (O'Rourke *et al.,* 2009). In 2011, the contribution of renewable energy to TPER was 6.5% and fell under three sub-categories; electricity (RES-E), heat (RES-H) and transport (RES-T) (Dennehy *et al.,* 2011). Wood contributes mostly to RES-H consumption. Moreover, wood can also contribute to RES-E generation by means of co-firing and combined heat and power (CHP). Co-firing refers to electrical energy generation through the mixture of biomass and non-biomass sources, whereas CHP is a single process where thermal and electrical energy is generated together (REFIT III, 2012). RES-H accounted for 5% of all thermal energy produced in Ireland during 2011, with 77.5% derived from biomass fuels in general (Dennehy *et al.,* 2011). Since 2008 to the present, a series of documents have provided specific year-by-year estimates of wood energy consumption, in addition to incentives already in place to increase its use (Knaggs and O'Driscoll, 2008, Knaggs and O'Driscoll, 2012b). In 2012, 33% of the total round wood harvest in Ireland was used for energy purposes and has made an overall contribution of 0.81% to TPER (Knaggs and O'Driscoll, 2010, Knaggs and O'Driscoll, 2012b). Table 1.2.1. provides a breakdown of the consumption of wood for energy in Ireland.

Table 1.2.1. Consumption of domestic, commercial and industrial wood fuel products (000 m^3 overbark) during the period of 2008-10 (O'Driscoll, 2011).

Product	End user	2008	2009	2010
Firewood	Domestic heating	171	184	199
Roundwood chipped in forest	Commercial heating	63	53	39
Short rotation coppice	Commercial heating	1	4	1
Wood pellets & briquettes	Domestic heating/commercial heating	82	110	121
Charcoal	Domestic use	2	2	2
Energy and forest products industry consumption	Process drying/heating/combined heat and power	384	418	554
	Total	**703**	**791**	**916**

Table 1.2.1 indicated that the forest products industry is the majority consumer of wood energy at 55-60% of the total. Markets for densified fuels such as wood briquettes and pellets have also been increasing in recent years in Ireland, as they are a cost competitive heating alternative to oil and gas for domestic and commercial heating (Knaggs and O'Driscoll, 2008). Firewood for domestic use has also increased, primarily due to the increased availability of wood from private sector first thinnings (Knaggs and O'Driscoll, 2012b).

The emergence of the increased use of wood for energy also coincides with the development of incentives and policy mechanisms to promote an increase in its use. A carbon tax on fossil fuel sources was introduced by the Irish Government through the Budget and Finances Act 2010, with exemptions made for renewable energy resources and participants in Emission Trading Schemes (ETS) (Department of Finance, 2010). This tax included a charge of €15 $tonne^{-1}$ of CO_2 emitted, since increased to €20 $tonne^{-1}$ (Department of Finance, 2010, Department of Finance, 2012). Coinciding with the introduction of this tax, fossil fuel consumption has reduced mainly due to the economic downturn Ireland has experienced (Gargan, 2012). These carbon tax regimes initially covered fossil fuels such as mineral oil and gas, whereas solid fuels such as coal were not included. This was due to a need for the development of trade specifications for the sulphur content levels allowable for the residential consumption of coal in Ireland (Department of Finance, 2010, Gargan, 2012). However, solid fossil fuels such as coal and peat have now been ratified for inclusion under carbon tax regimes as of the 1st May 2013 (Revenue Commissioners, 2013).

Contractually binding fixed price tariff mechanisms for renewable energy producers over the course of fifteen years under the Renewable Energy Feed-In-Tariff scheme is another example of an incentive to stimulate wood energy consumption (REFIT III, 2012). A variety of grant schemes with funds totalling €89 million have been made available under the direction of the Sustainable Energy Authority of Ireland (SEAI) (Knaggs and O'Driscoll, 2010). Domestically and commercially, the Greener Home and ReHeat schemes provided grants for the installation of renewable energy technologies. Among the technologies approved for grant aid are wood chip and wood pellet stoves and boilers (Knaggs and O'Driscoll, 2010). Other grants available include the CHP scheme, which provides grants for the installation of biomass powered CHP facilities (Knaggs and O'Driscoll, 2010).

According to Phillips (2011) there are three wood pellet manufacturing facilities and three CHP plants operating in Ireland that are using wood fuel. As of 2009, products such as wood chip, sawdust and pellets contributed to 66,000 tonnes to co-firing of peat with biomass at Edenderry Power (Reilly, 2010). This biomass consumption for co-firing has since increased to 156,000 tonnes as of March 2012, with the majority of this biomass sourced from the sawmilling and forestry sectors (Bord na Móna, 2012). An increase to 500,000 tonnes of biomass fuel is anticipated to be required for co-firing by the year 2020 in accordance with the NREAP (2010) co-firing targets of biomass with peat. In order to meet such demand, not all fuels will be derived from wood biomass (Reilly, 2010, Knaggs and O'Driscoll, 2012a). The availability of incentives, demands for co-firing and the installation of wood pellet manufacturing and co-generation plants have created a supply and demand situation for wood fuel products. Ultimately, an appraisal of the different policies in place to incentivise wood energy consumption can only be evaluated over time to measure their effectiveness, as most of this increase in wood biomass consumption in Ireland has occurred over the course of the last five-six years. In addition to the incentives, there are issues to be addressed if further growth in the use of wood for energy in Ireland is to be encouraged. Forecasting the supply and demand of raw material harvested from forest resources is essential to facilitate further developments and investment to increase the use of wood for energy.

1.3. Forecasting round wood supply and demand

Phillips (2011) compiled an all-Ireland round wood supply forecast for the 2011-2028 period. In conjunction, the COFORD Round Wood Demand Group (CRDG, 2011) compiled demand scenarios for round wood over the 2011-2020 period. Both reports concerned the wood processing and energy sectors. A key output from Phillips' (2011) forecast was that a large contribution of round wood will be available from private sector thinnings, mostly from forests established in the last 20-30 years. The thinning area in Irish forests has been forecasted to double from 22,800 ha in 2011 to 49,400 ha in 2028 (Phillips, 2011). The availability of round wood volume from private and state forests in Ireland has been forecasted to increase from 3.79 million m^3 in 2011 to 6.95 million m^3 in 2028 (Phillips, 2011). The majority of this round wood contribution will come from coniferous species, which include spruce species (84%), lodgepole pine (*Pinus contorta* Dougl.) (9%) and other conifers (7%).

Phillips' (2011) forecast also included information about resource availability for energy production, and estimated an increase from 1.07 million m^3 in 2011 to 1.75 million m^3 in 2028. The CRDG (2011) forecasted round wood demand for conventional uses and energy generation. Wood energy demand forecasts were based on scenario models formulated by the SEAI for the period 2011-2020. The CRDG estimated that demand for wood energy will nearly double from 1.6 million m^3 to 3.1 million m^3 during the forecast period of 2011-2020. Wood for energy supply in 2020 is estimated at 1.5 million m^3 by Phillips (2011), indicating a considerable shortfall compared to the 3.1 million m^3 2020 demand scenario. In addition to this shortfall, there are other issues regarding the mobilisation of material from thinnings to meet such supply and demand.

1.3.1. Issues with the mobilisation of wood for energy supply and demand

In the private forest sector, despite the forecasted increase of round wood available from first thinnings, there are constraints to mobilising this resource. Insufficient economies of scale result from small average plantation sizes of 8 ha and individual plantations that can range from 1-2 ha in size (Fennessy, 2005, Byrne and Legge, 2008). Moreover, there are a number of factors that will further affect the mobilisation of thinnings from the private forest sector. These factors include a landowner's management objectives, site access difficulties, poor ground conditions, the risk of windthrow, excessive infrastructure requirements, lack of knowledge on how to conduct thinning operations, marketing issues, perceived unfavourable prices for round wood, and high harvesting costs (Maguire *et al.*, 2010, Casey and Ryan, 2012). Another facet to the mobilisation problem is that the competition for round wood between the sawmilling and wood energy sectors will further affect supply and demand forecast scenarios (Phillips, 2011). Nonetheless, a number of initiatives have been developed in recent years that may affect the allocation of first thinnings for energy use.

1.3.2. Initiatives for thinning mobilisation and supply chain development

To resolve mobilisation issues and initiate first thinning in privately owned plantations, farm forest owner group co-operatives supported by Teagasc have developed in recent years. The objectives of such groups are to collectively thin plantations and develop markets for wood processing and/or energy in the private forest sector. There are currently 26 farm forest owner groups in total around Ireland (Teagasc, 2012). The efficacy of these groups in delivering upon their objectives may possibly be reflected in the record number of felling license applications made to the Forest Service during 2012 from private forest owners (Magner, 2012), coupled with favourable round wood prices for first thinnings in recent years (Casey and Ryan, 2012). In 2011, 386,000 m^3 of thinnings were harvested from privately owned forests, representing 14% of the total round wood harvest, the remainder attributable to Coillte (84%) and imports (2%) respectively (Knaggs and O'Driscoll 2012b).This emergence of private forest sector first thinning coincides with an increase in domestic firewood consumption. The firewood market experienced a 35% increase from 2006 to 2011 (O'Driscoll, 2011). Total firewood consumption derived from indigenous sources in 2011 was 225,000 m^3, although this may be an underestimate as markets typically operate on a local basis, making it difficult to derive accurate estimates (Magner, 2012, Knaggs and O'Driscoll, 2012b). Despite this increase in thinning and fire wood consumption, the harvesting of thinnings for energy is only one part of a broader wood fuel supply chain from producer to consumer.

1.4. Wood fuel supply chains

Until recent times in Ireland, there was a lack of research into all the aspects of the use of wood for energy. The limited number of articles included guidelines for the construction of portable firewood mills (Donovan, 1946), and notes on firewood extraction (Deasy, 1947). A considerable body of research into the use of wood for energy was instigated in Ireland as a response to the oil crisis of the 1970s. This research included trials examining forests established at tighter spacings than normal to maximise dry matter production for energy consumption (McCarthy, 1979), seasoning trials of small sized round wood (Savill, 1979), biomass sampling from the point of view of nutrient removals as a result of total tree harvesting (Carey and O'Brien 1979, Carey, 1980), and an appraisal of wood biomass availability within State-owned forests for energy purposes (McCarthy and Keogh, 1983). There was little research into the use of wood for energy from the 1980s and onward. The only significant bodies of work over this intervening period were an evaluation of the processing of above-ground logging residues from clearfell areas for the production of wood briquettes (Coggins, 1996), an evaluation of above ground logging residue harvesting supply chains (Hoyne and Thomas, 1997), and a feasibility study into the development of a wood energy sector in Ireland (North and Healion, 2003). More recently, the Forest Energy Programmes of 2006-2008 were the first comprehensive published works concerning the development of cost-competitive wood fuel supply chains appropriate to Irish conditions (Kofman and Kent, 2007, Kent *et al.,* 2011). The programmes provided for support measures that stimulated owners to carry out first thinning operations in private plantations.

The programmes involved an examination of the feasibility of using Scandinavian wood fuel harvesting and processing technologies that had not been previously trialled in Ireland. These included the production of wood chip material for industrial and domestic purposes, in addition to small-scale firewood supply chains from privately-owned forest plantations. Trials were mostly conducted on first thinning sites of both conifer and broadleaf tree species in different locations throughout Ireland. Other trials examined the storage and seasoning of wood fuel assortments in a forest environment and at dedicated terminals. Another feature of the research programme was the testing and evaluation of the physical and chemical properties of wood chip and firewood. The physical and chemical properties of wood have an obvious influence on the quality of wood energy products, and therefore affect supply chain optimisation and efficiency.

1.4.1. Quality control for emerging and established wood fuel products

In Ireland, the increased use of wood for energy generation in recent year's means there is a compelling need to analyse wood properties that influence energy conversion to ensure transparency in the indigenous and international trade of wood fuel. The reasons for this are twofold. First, to ensure that wood enters the energy market on a cost-competitive basis with well-established fossil fuels. Due to comparatively higher oxygen content, wood is of a lower fuel density in comparison to fossil fuels such as coal, gas and oil (Dembris, 2004, Swithenbank *et al.*, 2011). Second, international trade of wood fuel products is a likely scenario for countries that lack the indigenous resources to fulfil policy predictions for increasing wood fuel consumption (Hillring, 2006). This is especially the case in Ireland, given the constraints in the supply of thinnings from the private forest sector, competition with the sawmilling sector and overall predicted shortage of raw material to meet demands for wood energy into the future. There is also a need to establish wood quality parameters for the testing of emerging and established wood fuel products. A key highlight of previous trials on the Forest Energy Programme was the benefits of utilising all the partitions of a tree, rather than the production of wood fuel products derived from round wood only.

Irish studies into Sitka spruce (*Picea sitchensis* (Bong.) Carr.) have found that the majority of the total biomass accumulated in trees is in stem wood sections (Carey and O'Brien, 1979, Carey, 1980, Green *et al.*, 2007). The remaining biomass, known as logging residues, is material left behind on site after the harvesting of round wood from stems. This material includes branches, foliage, unmerchantable stem sections and stumps that could be harvested for energy from clearfell areas (Hakkila, 2004). The quantification and characterisation of logging residues for conversion into energy in Ireland has been identified as a knowledge gap (Kent *et al.*, 2011). In addition, the harvesting and processing of logging residues has the potential to reduce the predicted shortages in wood fuel supply from now until 2020 (Kent, 2012). Although logging residues are typically harvested from clearfell areas, trials in Ireland have found that harvesting whole trees from first thinning sites proved to be a lower cost operation. This is due to a two-fold increase in the biomass that can be harvested from whole trees in contrast to standard round wood harvesting for energy only (Kent *et al.*, 2011). Residue material was partially included in Phillips' (2011) energy supply forecast in the form of unmerchantable < 7 cm diameter stem sections, but neither the potential contribution of harvesting whole trees from first thinnings, nor logging residues from clearfell areas was estimated. Against the background of potential wood fuel products derived from logging residues, in tandem with wood fuel products that are already established, a number of initiatives concerning quality control in the regulation of trade between wood fuel producers and consumers have been developed in recent years in Ireland.

1.5. Standardisation and initiatives to regulate wood fuel trade

In wood energy terms, fuel quality is defined by the influence of fuel properties on optimal energy output, expressed as megajoules (MJ) or kilowatt hours (kWh) (Alakangas *et al.*, 2006, Kofman and Kent, 2007). Over the last decade the European Commission (EC) mandated the development of standards for the harmonisation of wood fuel trade within and outside the EU (Alakangas *et al.*, 2006). Standards are a set of rules to ensure quality which are described in unambiguous documents designed for repeatable and reproducible use (Loibneggar, 2011, Solid Standards, 2011). With this mandate for trade standardisation, the solid biofuels Technical Committee (TC) 335 was formed to develop standards in biomass trade (Kofman, 2010). Ireland is represented on TC 335 through the National Standards Authority of Ireland (NSAI) (Kofman, 2012). Other developments included the BioNorm project which evaluated the standardised lab testing procedures for both physical and chemical properties of wood, its suitability for energy conversion technologies, and the optimum utilisation of machinery operating in the field for the production of wood fuel (Alakangas *et al.*, 2006, Obernberger *et al.*, 2006).

Standards typically begin as Technical Specification (TS) drafts. After a period of use for five years, TS drafts are evaluated as to whether or not they should be upgraded to a European Standard (EN) (Kofman, 2010, Solid Standards, 2011). After 10 years of development, 28 EN standards have been adopted by participating countries and are now serving a role in the preliminary development of international trade standards for solid biofuels (Kofman, 2012). Standards specify suitable terminology common to participants (e.g. EN-14588, 2010); specify quality parameters for wood fuel products (e.g. EN-14961-1, 2010) and to define quality assurance specifications for use between wood fuel producers and consumers (e.g. EN-15234-1, 2011). Quality assurance standards are based upon internal agreements of fuel specifications between producers and consumers (Loibneggar, 2011). In Ireland, independent audits of internal trade agreements between wood fuel producers and consumers has been initiated in recent years through the wood fuel quality assurance scheme (WFQA), instigated by preliminary testing of European Standards on the Forest Energy Programme (Kent, 2009). The WFQA is an industry-led initiative to certify wood fuels produced in Ireland in accordance with the National Working Agreement 4: 2009: Woodfuel Quality Assurance: Requirements (NSAI, 2009). The resulting WFQA label is a quality mark awarded to wood fuel producers who meet the standards of external audits (Kofman, 2010). Standards also exist for the scientific lab testing of the physical and chemical properties of wood fuels. For practical purposes, the implementations of such standards are required for quality assurance audits of wood fuel producers, and in the settlement of product quality disputes between producers and consumers (Kofman, 2010).

In relation to trading wood fuel, there are a number of parameters that have to be specified under standardised trade procedures. The origin of the raw material used to produce the wood fuel product; moisture content and ash content are among the most important parameters to specify when trading wood fuel (EN-14961-1, 2010, Nurmi, 1993). Other parameters that are necessary to specify depend upon the type of wood fuel being traded, for example the particle size of wood chip (EN-14961-1, 2010). Other properties are typically informative (voluntarily specified) when trading wood fuel such as heating values, presence of volatile matter and chemical properties as some examples. However, all wood fuel properties have a role to play in the optimisation of energy conversion processes.

1.6. Physical and chemical properties of wood

The primary energy conversion process of wood is by means of combustion (Obernberger *et al.*, 2006). A thermochemical process, combustion essentially converts the solid organic components of wood into water (H_2O) and carbon dioxide (CO_2), releasing heat energy (Obernberger *et al.*, 2006). Optimum combustion ensures that maximum energy output has been achieved; wood has fully volatilised, minimal emissions of GHGs and low amounts of wood ash have been produced, all depending upon the boiler capacity and fuel type (Savoleinen and Berggren, 2000, Obernberger *et al.*, 2006). To ensure optimum combustion, detailed analysis of physical and chemical wood properties are a necessary prerequisite (Ragland *et al.*,1990). There are a variety of properties that affect combustion efficiency. These properties include the calorific value of wood, moisture content, basic density, bulk density, particle size, the proportion of volatiles, chemical composition, ash forming elements and the quantity of impurities such as fungi, soil and stones (Savoleinen and Berggren, 2000, Loibneggar, 2011).

In its freshly felled state, wood typically contains 40-60% water and the remainder is dry matter biomass. The organic constituents of wood biomass consist of the long chain polymers cellulose (40-45% of total weight), hemicellulose (25-40%) and lignin (24-33% for conifers and 16-25% for broadleaves) (Alakangas, 2005, Bowyer *et al.*, 2007). The elemental composition of these organic constituents directly relates to the quantity of volatile gases released during combustion. Analysis of volatiles in wood is termed either as ultimate or proximate analysis. Proximate analysis of wood biomass consists of 80-90% volatiles, meaning it will give up this proportion of its weight to forming gases in the pyrolysis phase of combustion, the remainder being solid carbon (Savoleinen and Berggren, 2000, Alakangas, 2005). Ultimate analysis refers to the elemental composition of wood. The elemental composition of wood consists of 45-55% carbon (C), 4.5-6% hydrogen (H), 40-45% oxygen (O), 0.1% nitrogen (N), 0.1% sulphur (S) and 0.3-0.5% ash (Baker, 1983). This composition is relatively uniform between different tree species (Bowyer *et al.*, 2007). Wood also contains solid incombustible major and minor mineral trace elements that constitute wood ash (EN-14588, 2010, Obernberger *et al.*, 2006). Ash has a large diversity of major and minor constituent elements including aluminium (Al), antimony (Sb), arsenic (As), barium (Ba), cadmium (Cd), calcium (Ca), chlorine (Cl), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), phosphorus (P), potassium (K), silicon (Si), sodium (Na), sulphur (S), thallium (Tl), titanium (Ti), vanadium (V) and zinc (Zn) (Obernberger *et al.*, 2006). The concentration of these major and minor elements are relevant to and can affect the optimisation of energy conversion processes, including ash melting behaviour, fly-ash formation in chimney flues, aerosol emissions, particulate emissions, air purity and toxic elements. The elements specifically involved in the latter issues and the level of concentrations in different solid biofuels, including wood biomass, are reviewed extensively by Obernberger et al. (2006). The chemical elements of primary concern from a negative viewpoint are the quantities of Cl, N and S. Cl has the capability to react with K and Na to cause corrosion on heat transfer surfaces and chimney flues in boilers, whilst N and S possess the capability to convert into GHGs such as nitrous oxide (NO_x) and sulphur oxide (SO_x) (Hakkila, 2004, Alakangas, 2005, Obernberger *et al.*, 2006). However wood generally has low levels of Cl, N and S. Cl is an issue with wood fuels that contain a high proportion of foliage (Alakangas, 2005). In addition wood emits low levels of NO_x and SO_x if combustion is optimised (Obernberger *et al.*, 2006).

The physical and chemical properties of wood may vary for a variety of reasons. Physical properties such as moisture content can vary according to species, tree partitions, age, seasons, location, proportions of sapwood to heartwood and the time of year wood fuel products are in storage (Savoleinen and Beggren, 2000, Bowyer *et al.*, 2007). Basic density is another source of physical variation in wood fuel and can vary according to species, climatic effects on radial growth, presence of reaction wood, proportions of juvenile and adult wood, between tree partitions, within stems, silvicultural practices and genetic sources (Repola, 2006, Bowyer *et al.*, 2007, Jyske *et al.*, 2008).

Calorific values and ash-forming elements are typically classified by the inherent differences between tree parts such as stems, branches and foliage (Nurmi, 1993, Werkelin *et al.*, 2005). Investigations have shown that calorific values and chemical element concentrations are greater in the more physiologically active parts of trees such as foliage, followed by branch wood due to greater proportions of bark, descending in order to stem bark and concentrations being lowest in stem wood (Nurmi, 1993, Alakangas, 2005, Werkelin *et al.*, 2005). As branches and foliage are constituents of logging residue material that can be harvested for wood fuel products, the implications of its harvesting consequently have an effect on forest ecosystem nutrition dynamics. This is due to the removal of essential nutrients for tree growth as a result of intensified harvesting of wood for energy (Karltun *et al.*, 2008). To rectify excessive nutrient removal, one possible action that can be undertaken is the recycling of nutrients by means of fertilising forests with wood ash (Stupak *et al.*, 2008). Wood ash fertilisation has a two-fold benefit. These benefits include the capability of wood ash to neutralise soil pH on soils that tend to be acidic in nature, and a reduction in the costs of wood ash disposal in landfills resulting from increasing wood fuel consumption (Pitman, 2006, Stupak *et al.*, 2008). A synthesis of research into the utilisation of wood ash as a fertiliser in Nordic countries was reviewed by Rauland-Rasmussen et al. (2008). Nordic research has found that application of wood ash does not increase forest productivity on mineral soils, but has proven to be beneficial on less fertile peat type soils. Despite this observation, Rauland-Rasmussen et al. (2008) commented that there was a lack of research into the long term effects (> 10 years) of nutrient removals and wood ash application. However this has been remedied due to recent results accumulated from a 30 year wood ash fertilisation trial in Finland. Saarsalmi et al. (2012) found that tree productivity was greater in plots where wood ash supplemented with artificial N was applied in comparison to control plots where no fertiliser was applied. N, a key nutrient for healthy tree growth, must be added into wood ash fertilisers, as the naturally occurring N in wood is converted during combustion into NO_x (Obernberger *et al.*, 2006, Saarsalmi *et al.*, 2012). The higher productivity in the fertilised plots was observed by Saarsalmi et al. (2012) to be due to greater soil microbial processes in the circulation of N and C, in addition to higher concentrations of exchangeable Ca, K, Mg, and extractable P found within the chemical composition of the soil organic layers. Despite the apparent benefits of utilising wood ash as a fertiliser, there is a complexity of factors to consider. The point at which wood ash is collected during the combustion process, the wood burning temperature, the type of wood fuel product combusted, the presence of contaminants, the application method with regard to solubility, the amount applied in the field per hectare, the timing of application in a forest rotation, soil types, the types of soil organic layers, soil microbial sensitivities and soil water status all influence the suitability of ash as a fertiliser (Pitman, 2006, Karltun *et al.*, 2008, Rauland-Rasmussen *et al.*, 2008, Stupak *et al.*, 2008). In Ireland, research into all the different aspects of wood ash recycling is currently underway (O'Halloran, 2010).

1.7. Research to address knowledge gaps on wood fuel properties in Ireland

In Ireland, wood fuel property databases of forest biomass fuel sources that have an impact upon fuel quality are absent. One aim of the research being carried out currently as part of the Forest Energy Programme in Waterford Institute of Technology is the development of a wood fuel property database covering the main commercial forest tree species in Ireland. The age-class for the characterisation of wood fuel properties is focussed upon stands ready for first thinning. The six species being investigated include alder (*Alnus glutinosa*), ash (*Fraxinus excelsior* L.), birch (*Betula* spp.), lodgepole pine, Norway spruce (*Picea abies* (L.) Karst.) and Sitka spruce. The main fuel properties to be investigated are moisture content and basic density. These are physical properties of wood that have an impact upon energy conversion efficiency. Moisture content is one of the most important wood fuel quality parameters. High moisture content can have an adverse impact on the energy generated from wood, can compromise the storage capabilities of wood fuel, and can increase the fuel consumption of trucks transporting wood intended for energy consumption (Hakkila, 2004, Serup and Kofman, 2005). These factors highlight the importance of developing strategies for harvesting and seasoning wood fuels with a view to reducing moisture content to a point suitable for end-user needs. Current research seeks to investigate the spatiotemporal variation in the moisture content of stem and branch wood partitions. This will aim to identify the most suitable times of year for harvesting and seasoning wood for energy production. The sampling methodology implemented for the measurement of moisture content in stem sections will also allow for an opportunity to investigate the basic density of the same six tree species. Basic density is an important wood fuel quality parameter that describes the potential energy content that may be yielded per unit volume (m^3) from wood fuel products. However, only basic density data for Sitka spruce have been reported for Irish conditions, at least within the public domain (Ward and Gardiner, 1976, Gardiner and O'Sullivan, 1979, Javadi *et al.*, 1983, Treacy *et al.*, 2000, Ní Dhubháin *et al.*, 2006, Green *et al.*, 2007, Tobin and Nieuwenhuis, 2007).

Samples used for the analysis of physical wood fuel properties will be used to create a repository for the analysis of chemical wood fuel properties. This will provide an opportunity to measure calorific values and quantify the major and minor chemical elements associated with wood ash formation. This work will also attempt to collate wood fuel property data generated from the previous Forest Energy Programme, data from private firms, and accredited wood fuel testing centres across Ireland.

1.8. Conclusion

In Ireland, increased consumption and a favourable policy environment means the use of wood for energy is increasing. However, there are issues to address in order to instil confidence into the use of wood for energy. Demands for wood fuel have been predicted to exceed supply in the future, especially if the harvesting and processing of round wood only for wood fuel is relied upon. This in turn will inevitably lead to interest in harvesting logging residues that have not been utilised in the past to meet the shortfall in wood fuel supply in Ireland. As a result, research will be required to assess the feasibility of harvesting operations and the characterisation of the physical and chemical fuel properties of whole trees from first thinnings and logging residues from clearfell areas. Furthermore, mobilisation of key forest biomass fuel sources, especially from private forest sector first thinning, is often dictated by individual circumstances. Nonetheless, although private forest sector first thinning is increasing, in addition to firewood consumption, there is a need to address the ramifications of the influence of fuel properties on achieving optimum energy output and the long-term sustainability of ecosystem productivity.

In spite of the policies and incentives in place to promote an increase in the use of wood for energy, without knowledge of the variety of properties that dictate wood fuel quality, consumers will not be able to optimise output from wood fuel. This may affect public and industry confidence in the use of wood fuel products, especially in an energy market where wood fuels have to compete with well-established fossil fuels. Indeed, adoption of European trade standards and initiatives such as the WFQA scheme will help to address the issues associated with wood fuel quality. However, the fuel quality specifications required by individual end users may not necessarily conform to the WFQA requirements and European trade standard specifications. Nevertheless, flexibility is allowed in terms of trade audits between wood fuel producers and consumers (EN-15234-1, 2011), and the very purpose of European standards is that they are evaluated every five years by the countries participating in their testing (Alakangas *et al.*, 2006). A good aid in the evaluation of wood fuel product quality and trade standards is a comprehensive knowledge of the fuel properties of forest biomass fuel sources before processing (e.g. round wood, above and below-ground logging residues).

The development of a database on the fuel properties of wood will serve as a template for the characterisation of wood fuel products derived from different forest biomass fuel sources in Ireland. In addition, this database will also provide a template to evaluate the suitability of European standards for testing different wood fuels under Irish conditions. The resultant data from this project will be made available to wood fuel producers and consumers through dissemination outputs. These outputs will be in the form of project reports, peer reviewed papers and an online database with a user query interface. Ultimately, it is envisioned that the dissemination of such information will confer an increased degree of confidence to the use of wood for energy in Ireland.

2. CHAPTER 2 - AN INVESTIGATION INTO PARTITIONAL AND SPATIOTEMPORAL VARIATION OF ABOVE GROUND BIOMASS MOISTURE CONTENT DERIVED FROM FIRST THINNINGS

2.1. Definition of moisture content

Moisture content is the expression of water as a percentage of total weight in wood, at the time of measurement (Bowyer *et al.*, 2007). Water is typically found within wood in a free form in cell lumens and in a bound form in cell walls (Bowyer *et al.*, 2007, Punches, 2004, Reeb, 2009). Two interchangeable expressions exist for the quantification of the moisture content in wood (Briggs, 1994).

The pulpwood and energy sector utilises the formula for moisture content on a wet weight basis, calculated by expressing the weight of water as a percentage of the total weight of the wood, as demonstrated in Equation 2.1. (Bowyer *et al.*, 2007, Briggs, 1994, EN-14774-2, 2010).

$$\mathrm{MC\%_{wb}} = \frac{\mathrm{Ww - Dw}}{\mathrm{Ww}} \text{ x } 100 \qquad (2.1.)$$

$\mathrm{MC\%_{wb}}$ = Moisture content on a wet weight basis expressed as a percentage

Ww = Wet weight of sample (kg)

Dw = Oven dry weight of sample (kg)

The wood processing sector utilises the formula for moisture content on a dry weight basis, calculated by expressing the weight of water as a percentage of the total weight of oven dry wood, as demonstrated in Equation 2.2. (Bowyer *et al.*, 2007).

$$MC\%_{db} = \frac{Ww - Dw}{Dw} \text{ x } 100 \qquad (2.2.)$$

$MC\%_{db}$ = Moisture content on an oven dry basis expressed as a percentage

Ww = Wet weight (kg)

Dw = Oven dry weight (kg)

Moreover, the two formulas are interchangeable depending on the expression of interest, as demonstrated in Equations 2.3. and 2.4. (Briggs, 1994).

To convert to $MC\%_{db}$ utilising the $MC\%_{wb}$ calculated: $MC\%_{db} = 100 \text{ x } \frac{MC\%_{wb}}{100 - MC\%_{wb}}$ (2.3.)

To convert to $MC\%_{wb}$ utilising the $MC\%_{db}$ calculated: $MC\%_{wb} = 100 \text{ x } \frac{MC\%_{db}}{100 + MC\%_{db}}$ (2.4.)

The simplified method to measure moisture content on a wet weight basis is a standardised procedure for wood fuel testing (EN-14774-2, 2010). This method is most useful, due to its accuracy and requiring only an oven and no other sophisticated equipment (Samuelsson *et al.*, 2006). In this method, a wood sample of 300 g minimum is first weighed and oven dried at 105^{o}C for 24-48 hours (EN-14774-2, 2010). This ensures that all free and bound moisture has been removed. The drying time is dictated by the size of the material. Large samples require 48-72 hours (EN-14774-2, 2010, Williamson and Wiemann, 2010). After oven drying, samples are immediately weighed, as wood is hygroscopic and will quickly reabsorb moisture (Josza and Middleton, 1994, Reeb, 2009). Investigations previously conducted in Ireland included the testing of wood chip and firewood in accordance with the simplified method. Discs of 25-30 mm cut from stem sections can also be used to determine moisture content (Clark and Daniels, 2000, Gibson *et al.*, 1985, Jensen and Davis, 1953, M^{c}Minn, 1986, Manwiller, 1975, Mochan, 2006, Shotaffer and Brackley, 1982). The oven drying method has also been tested as a reference against alternatives. These alternative methods have included freeze drying, xylene distillation, assessing instruments that can rapidly determine the moisture in wood and near infrared spectroscopy technology (AE BIOM, 2008, Dunnett, 2012, Mora *et al.*, 2011, Samuelsson *et al.*, 2006). In terms of using wood for fuel, the purpose of alternative methods are to find ways to determine moisture content more quickly than the oven dry method, especially where regular transactions are made for wood fuel that is sold on the basis of energy content, which is influenced by moisture content.

2.2. Effects of moisture content on wood fuel supply chains

Moisture content is the most important wood fuel quality parameter, as it has a negative relationship with the energy generated from wood (Nord-Larsen *et al.*, 2011). The energy content of wood is expressed as the calorific value, either on a gross (GCV) or a net basis (NCV) dependent on the treatment of water in the combustion process. GCV is the expression of heat units obtained from the complete combustion of a defined amount of wood fuel (in $MJ \cdot kg^{-1}$), with the condensation of water vapour formed during combustion (M^c^Kendry, 2002b, Savoleinen and Berggren, 2000, Serup and Kofman, 2005). Net calorific value is classified similarly, the difference being that the water vapour released in not condensed and remains in a vaporous state. There are two sources of water vapour. These sources include the moisture content and the hydrogen content of wood. Hydrogen is thermochemically converted to H_2O during combustion (Obernberger *et al.*, 2006). NCV is homogenous between species at the same moisture content. On an oven dry basis, NCV is higher in coniferous species in comparison to broadleaf species, due to a higher proportion of resinous compounds and lignin (Alakangas, 2005, Rolls, 2010, Roser *et al.*, 2008). Typical NCVs are 19.1 $MJ \cdot kg^{-1}$ for conifer wood and 18.9 $MJ \cdot kg^{-1}$ for broadleaf wood on an oven dry basis (EN-14961-1, 2010).

The initial stage of combustion involves the vaporisation of water. If there is excess moisture within wood, energy will be wasted on vaporising water as opposed to generating useful heat energy (Loibneggar, 2011). Fuels of high moisture content can also exacerbate GHG and hydrocarbon emissions, as the optimum temperatures required in combustion chambers will not be reached to fully volatilise elements such as nitrogen and sulphur (Hakkila, 2004). To derive the NCV as a function of moisture content, Equation 2.5. is used (Alakangas, 2005, EN-14961-1, 2010).

$$q_{p,net,ar} = q_{p,net,d} \times \left(\frac{100 - MC\%_{wb}}{100}\right) - 0.02443 \times MC\%wb \qquad (2.5.)$$

Where $q_{p,net,ar}$ = Net calorific value at constant pressure (p) as received (ar) in $MJ \cdot kg^{-1}$

$q_{p,net,d}$ = Net calorific value at constant pressure (p) on an oven dry basis (d) in $MJ \cdot kg^{-1}$

$MC\%_{wb}$ = Moisture content on a wet weight basis (%)

0.02443 = Correction factor for the enthalpy of vaporisation for water at 25°C

Equation 2.5 can then be used to illustrate the effects of moisture content on NCV as demonstrated in Figure 2.2.1.

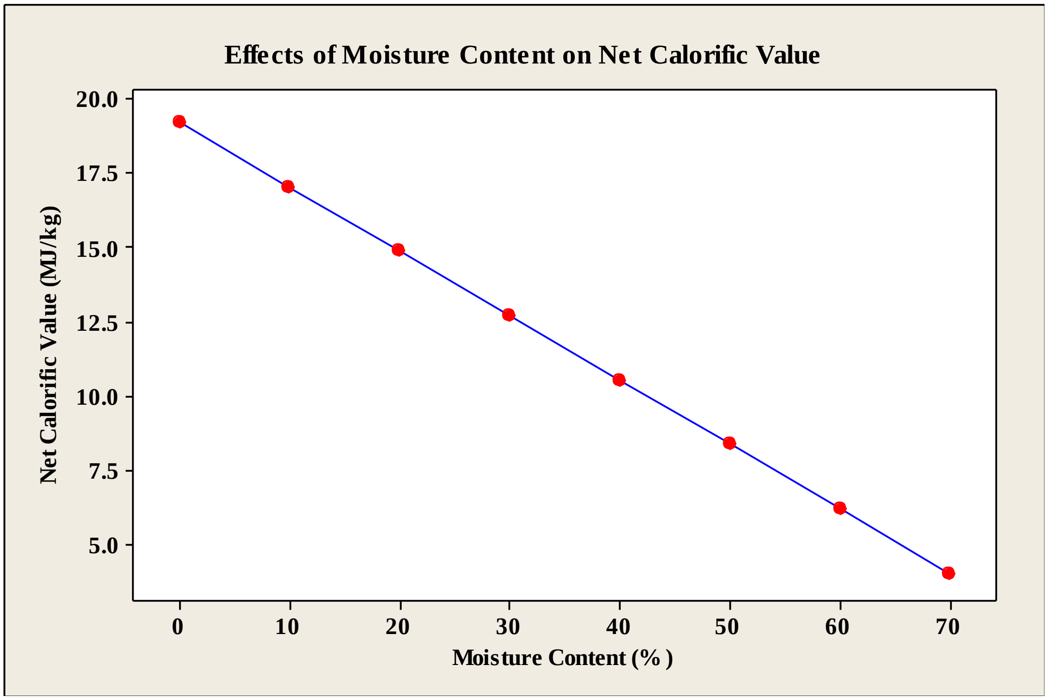

Figure 2.2.1. The effect of moisture content on NCV.

Although moisture content affects the combustion efficiency of wood, different types of combustion appliances can tolerate different moisture contents. Domestic stoves, small scale domestic and commercial boilers of nominal capacities < 100 kW_{th}, operate efficiently with wood fuels of 20-30% moisture content, whereas larger scale appliances such as CHP facilities can tolerate moisture contents of 45-55% due to the capability of boilers to condense water vapour and utilise it for heat energy (Hakkila, 2004, Kofman and Kent 2007, Obernberger *et al.,* 2006, Serup and Kofman, 2005).

Moisture content can adversely affect wood fuel storage and transportation costs. Above moisture contents of 20%, fuels such as wood chips are not suitable for storage. A wet environment in wood chip piles encourages the growth of fungi and bacteria that cause dry matter losses (Hakkila, 2004). Among the most common fungi and bacteria found in wood chip piles are *Aspergillus fumitagus* and *Actinomycetes* (Hernandez, 2012). These fungi and bacteria release airborne particle that are harmful to respiratory health (Serup and Kofman, 2005), and have also been reported to be carcinogenic (Hernandez, 2012). Fermenting bacteria in wet wood chip piles can also cause spontaneous self-ignition (Li *et al.*, 2006). Moisture content also has an adverse effect on transportation of wood fuel. Studies have shown that a reduction of moisture content to 30% from 50-60% leads to reductions in truck fuel consumption and CO_2 emissions (Sikanen, 2010). The issues highlighted show that controlling moisture content is a necessity in wood fuel supply chains. However, characterising moisture content is not straightforward, as it has many sources of variation.

2.3. Moisture content variation

In his review, Gates (1991) summarises the variation in moisture content: '*There is so much variability of the water content of forest trees it is extremely difficult to establish simple rules'*. The sources of moisture content variation include species, tree components, seasons, location, proportion of sapwood to heartwood, and the time of year wood fuels are being kept in storage (Bowyer *et al.,* 2007, Briggs, 1994, Gates, 1991, Savoleinen and Beggren, 2000, West, 2004). These sources of variation interact with each other, and makes characterising moisture content difficult (Matthews and Mackie, 2006).

2.3.1. Spatiotemporal variation of moisture content

In temperate forest biomes, annual tree growth begins during spring, slows down during summer time, ceases in autumn, and remains dormant during winter (Bowyer *et al.,* 2007, Josza and Middleton, 1994). Seasonal changes in Ireland follow this pattern, driven by fluctuations in temperature: winter (December-February), spring (March-May), summer (June-August) and autumn (September-November) (Keane and Sheridan, 2004). Early in the growing season during spring, increased transpiration coinciding with bud break in branch sections may lead to a decrease in moisture content in trees, due to the withdrawal of water by branches and foliage exceeding the uptake of water by roots through soil (Gates, 1991, Gorenson, 2002, Schulze *et al.*, 1985). The movement of water out of foliage during transpiration is attributed to increased radiation loads, lower relative humidity of air, and increased vapour pressure deficits (Gates, 1991, Keane and Sheridan, 2004). Atmospheric influences have shown to have a greater influence on the water movement in trees, whereas edaphic factors have not shown a strong correlation (Traver *et al.,* 2010). A number of studies into the spatiotemporal variation of moisture content have been conducted. Jensen and Davis (1953) found temporal fluctuations in the moisture content of aspen stems (*Populus tremula* L.). Initially sampling from one site, the authors found that stem wood moisture content was consistently lower from June to September (42-47%), and consistently higher during November to April (52-53%). The months of May and October signified the transition in these trends. The authors also studied spatial variation, and found that the same temporal changes in moisture content occurred in five different locations for aspen. Shotaffer and Brackley (1982) investigated spatiotemporal variations in the stem wood moisture content of balsam fir (*Abies balsamea* var. *balsamea*) and eastern spruce (*Picea rubens* Sarg.) in Maine. The authors took stem disc samples during periods collectively referred to as winter (January-April), summer (May-August) and autumn (September-December). The authors found no distinguishable temporal trends in moisture content change of the two species. Peck (1959), in a study into the moisture content of 32 species in the USA, found no distinguishable temporal differences in the moisture content of stems. Samples from Peck's study were taken monthly, over the course of a year.

Anatomically, temporal trends in moisture content may be explained by the distribution of water conducting xylem tissue. Xylem tissue is produced in the vascular cambium layer of wood at discrete time intervals over the growing season (Bowyer *et al.,* 2007, Punches, 2004, Wiedenholt, 2010). The distribution of water conducting tissue distinguishes conifer and broadleaf species. Whereas conifers possess tracheids for water conductance, the distinguishable feature of broadleaf tree species is that they possess vessels (Bowyer *et al.,* 2007, Punches, 2004). The size and distribution of vessels define whether or not a hardwood species is diffuse porous or ring porous (Bowyer *et al.,* 2007, Gates, 1991, Wiedenhoelt, 2010). Diffuse porous hardwoods possess vessels of uniform size on earlywood throughout the growing season, whereas ring porous species have larger vessels in the earlywood that decline in size later into the growing season before dormancy (Bowyer *et al.,* 2007, Coder, 1999).

Moisture content may be affected by the proportions of earlywood to latewood on annual growth rings. Earlywood has thin cell walls and large vessels typically formed in spring, whereas latewood has thicker cell walls and narrow vessels formed later in the growing season (Kern *et al.,* 2012, Punches, 2004). The formation of latewood is postulated to be based upon the availability and allocation of photosynthates throughout the growing season. Photosynthate is allocated to the apical meristem and shoot regions for foliage and cell development in cambial layers during the early growing season (Punches, 2004). Thereafter, with a reduction in day length and cessation of apical meristem extension, foliage matures and carbohydrates previously dedicated to foliage development in the growing season are allocated to cambial regions, giving latewood a darker appearance in comparison to earlywood due to thicker cell walls (Bowyer *et al.,* 2007, Josza and Middleton, 1994, Larson *et al.,* 2001, Punches, 2004, Wiedenhoelt, 2010).

Diffuse and ring porous hardwoods differ in relation to water conductance. Michalec and Niklasova (2006) found that diffuse porous species (alder, beech (*Fagus sylvatica* L.), birch and aspen) had higher radial and tangential water uptake in comparison to ring porous species in their experiment (ash and oak (*Quercus robur* L.). Ring porous species were found to have a greater proportion of latewood to earlywood than diffuse porous species, thus less frequent and narrow vessels that adversely affected the efficacy of water conductance. A shortcoming of Michalec and Niklasova's study was that they examined dry wood samples in a lab experiment setting, which is not reflective of the actual growing conditions of these species. Coniferous species and their water conduction are intermediate in their behaviour between diffuse and ring porous hardwood species (McCulloh *et al.*, 2009, Wiedenhoelt, 2010).

A number of investigations have been conducted into climatic effects on wood physiological processes. A number of authors have identified that annual radial growth (earlywood width, latewood width and total annual ring width) can be correlated to accumulated temperature, precipitation, soil moisture status and drought spatiotemporally (Gardiner, 2011, Hentonnen, 1984, Kern *et al.*, 2012, Michelot *et al.*, 2012). For example, Gardiner (2011) found that areas of higher rainfall in comparison to areas of lower rainfall have a positive effect on the radial growth of Sitka spruce. Premyslovska et al. (2008) found that higher accumulated temperatures, especially during the latter part of the growing season, extended latewood development in Norway spruce. Annual radial growth should therefore affect the water conductance and moisture content of different tree species spatiotemporally. However, Gartner (1995) highlighted that radial growth and its effect on xylem orientation and water movement is not well documented. Radial growth and its effects on other wood properties such as basic density have received considerable scrutiny (see Chapter 3, Section 3.3. for more details). In addition to spatiotemporal differences, investigations have also found moisture content variation between tree components.

2.3.2. Component variation of moisture content

Studies into the variation of moisture content between different tree components have been conducted by a number of authors. Manwiller (1975), studying 22 species, found irregular trends in moisture content differences between stem wood and branch wood. Fifteen of the 22 species in his study had higher moisture contents in the stem wood and stem bark than branch wood and branch bark. The remaining six species demonstrated an opposite trend, whereby branch wood and branch bark moisture content were higher than stem wood and stem bark. Similarly, Gibson et al. (1985) studied spatial and component variation. The authors found that moisture content was highest in root wood, intermediate in stem wood, and branch wood having the lowest moisture contents for all species and sites where sampling took place. The authors also sampled root bark, stem bark and branch bark, and found a similar trend to the wood components. In general bark is comparable to wood in its moisture content. However, this can be dependent on the ratio of inner and outer bark, as the inner sections are significantly more wet than wood

(Bowyer *et al.,* 2007). Branch wood varies in its vascular orientation in comparison to stem wood, generally containing a greater surface area for water conductance (Bowyer *et al.,* 2007). As branches and foliage are the most physiologically active tree parts in relation to water conductance and transpiration (Gates, 1991), they will be more prone to fluctuations in moisture content than stem wood.

Studies have also been conducted into the differences of moisture content within stems. Shotaffer and Brackley (1982) found that moisture content increased from the butt to top sections. Similar trends were found by Clark and Daniels (2000), as demonstrated in Figure 2.3.1.

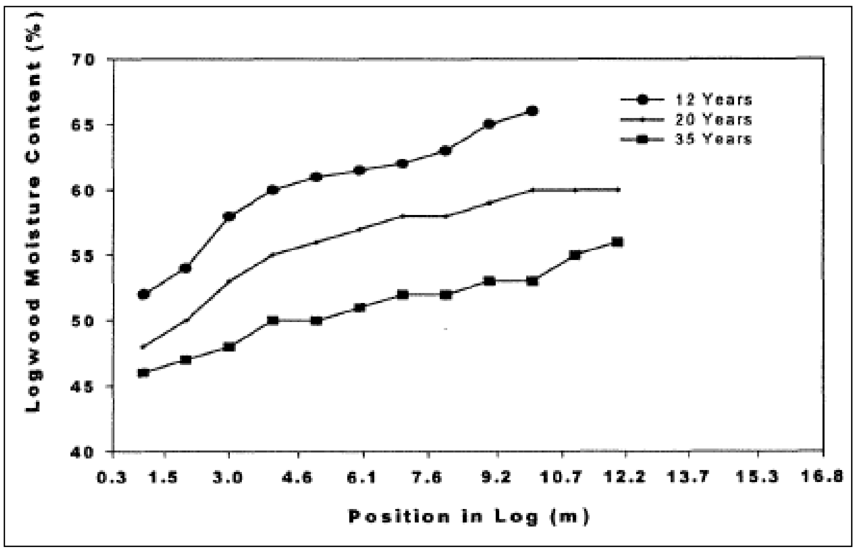

Figure 2.3.1. Differences in moisture content in relation to log sampling position of loblolly pine (*Pinus taeda*) (Clark and Daniels, 2000).

Another feature of Figure 2.3.1. is that samples of an older age had consistently lower moisture content than the younger material. These differences may due to sapwood and heartwood. Sapwood is located within the cambium layer and is involved with water conduction, among other functions such as the storage of photosynthates (Bowyer *et al.,* 2007, Jozsa and Middleton, 1994, Punches, 2004, Wiedenhoelt, 2010). Sapwood cells eventually die and cease in their conductance of moisture. Thus, heartwood begins to form over time, providing a structural support role in trees and acting as a repository of extractive substances (Bowyer *et al.,* 2007, Hoadley, 1990). It is because of this loss in conducting water, that heartwood is generally drier than sapwood, being especially pronounced with coniferous species (Bowyer *et al.,* 2007, Hoadley, 1990, Punches, 2004). The initiation of heartwood formation is species dependent, and the processes behind its development are largely theorised and have not been proven (Bowyer *et al.,* 2007, Taylor *et al.*, 2002). The ratio of heartwood to sapwood at various tree heights has also been shown to vary. For example, studying European larch (*Larix decidua* Mill.), Nawrot et al. (2008) found proportionately more sapwood and a reduction in heartwood with increasing stem height. Therefore, more sapwood and less heartwood with increasing stem height may contribute to increases of moisture content, as sapwood is active in the conductance of water. Another feature of Clark and Daniels (2000) study was the estimation of mean moisture content of stem length round wood using fewer samples than those originally taken. With this approach, the authors could then make recommendations as to how many samples were adequate to describe the moisture content of truckloads entering a weighbridge.

2.4. Methodology for the determination of moisture content

2.4.1. Field work

Four field visits were conducted in order to investigate temporal differences in moisture content. The purpose of visits across different seasons was in order to identify the optimum harvesting and seasoning windows for wood fuel under Irish conditions. An initial visit in the South East region was conducted during August 2011. The other field visits took place during dormancy/winter (January 2012), flushing/spring (May 2012) and the growing season/summer (July 2012). Flushing and the growing season are situated within the most suitable timeframe for seasoning wood for fuel (March-August), whereas dormancy is situated outside the most suitable timeframe (September-February). This has been found to be the case in temperate forest biomes (Alakangas, 2005, Filbakk *et al.,* 2011, Gigler *et al.,* 2000, Hakkila, 2004, Holt, 1967, Kofman and Kent, 2009a, Kofman and Kent, 2009b, Kofman and Kent, 2009c, Kofman and Kent, 2009d, M^{c}Minn, 1986, Mochan, 2006, Nord - Larsen *et al.,* 2011, Nurmi and Lehtimaki, 2010, Rolls, 2009, Roser *et al.,* 2010, Savill, 1979). In order to investigate spatiotemporal differences in moisture content, three regions were chosen. The South East (52^{o} N latitudinal zone), Midlands (53^{o} N latitudinal zone) and North West (54^{o} N latitudinal zone) of Ireland were the regions chosen. Tables 2.4.1 and 2.4.2 illustrate the site locations and climate data from each region and visiting period respectively.

Table 2.4.1. Site locations.

South East	**Location**	**Latitude**	**Longitude**	**Soil Type**
Ash	Castlelands, Lismore, County Waterford	52.13N	7.95W	Brown podzolic
Norway spruce and Sitka spruce	Deerpark North, Lismore, County Waterford	52.13N	7.91W	Brown podzolic
Lodgepole pine	Kilrossanty, County Waterford	52.18N	7.54W	Gley
Alder and Birch	Lemybrien, County Waterford	52.17N	7.52W	Gley
Midlands	**Location**	**Latitude**	**Longitude**	**Soil Type**
All six species	Bunakeeran, County Offaly	53.23N	7.69W	Cutaway peat
North West	**Location**	**Latitude**	**Longitude**	**Soil Type**
Norway spruce	Cleen, Knockvicar, County Roscommon	54.00N	8.18W	Gley
Lodgepole pine and Sitka spruce	Doobin, Glenties, County Donegal	54.76N	8.23W	Blanket peat
Alder, Ash and Birch	Carnowen, Raphoe, County Donegal	54.83N	7.63W	Brown earth

Table 2.4.2. Climate data for all the regions. Precipitation and solar radiation are totals of the months and year sampling took place. Temperature and soil temperature refer to the average values of the months and year sampling took place. Data were sourced from Met Eireann (2012).

South East Climate Data - Teagasc Oakpark Co. Carlow				
	Precipitation (mm)	**Temperature (^oC)**	**Soil Temperature (10 cm)**	**Solar Radiation (joule cm^{-2})**
August 2011	25.5	13.9	16.5	38946
January 2012	70.8	6.5	6.1	7420
May 2012	50.2	11.0	13.6	47734
Annual	674.9	10.6	11.9	302038
Averages (1981 - 2010)	840.2	10.2	9.5	N/A
Midlands Climate Data 2012 - Gurteen College Co. Offaly				
	Precipitation (mm)	**Temperature (^oC)**	**Soil Temperature (10 cm)**	**Solar Radiation (joule cm^{-2})**
January 2012	94.2	6.6	6.4	7029
May 2012	49.6	10.6	12.8	N/A
July 2012	103.0	15.6	16.9	41516
Annual	876.3	10.4	11.5	251476
Averages (1981 - 2010)	948.2	9.8	N/A	N/A
North West Climate Data 2012 - Markree Castle Co. Roscommon				
	Precipitation (mm)	**Temperature (^oC)**	**Soil Temperature (10 cm)**	**Solar Radiation (joule cm^{-2})**
January 2012	114.0	6.2	5.9	5494
May 2012	62.7	10.8	12.8	48746
July 2012	129.3	15.5	17.2	42279
Annual	973.3	10.0	11.5	300179
Averages (1981 - 2010)	1260.1	9.8	N/A	N/A

Inventories were taken in each trial stand, to evaluate infrastructure and the suitability of trees for sampling. The age of stands where sampling took place ranged from 12-17 years old. All stands were regularly stocked at the recommended commercial spacing, with the exception of birch in the South East that was growing wild due to invading a reforestation site of Sitka spruce. Table 2.4.3 illustrates the site details.

Table 2.4.3. Site characteristics. The initial stocking density recommended for birch (3300 stems ha^{-1}) was assumed for the site in the South East.

South East	Age	Area (ha)	Top Height (m)	QMDBH (cm)*	Stocking (ha^{-1})	YC ($m^{-3} \cdot ha^{-1} \cdot yr^{-1}$)	Volume per hectare ($m^3 \cdot ha^{-1}$)
Alder	14	0.3	8.8	9.0	2300	6	21.0
Ash	16	1.2	8.9	8.6	2883	6	26.0
Birch	15	N/A	7.6	8.8	3300	6	19.0
Lodgepole pine	12	1.3	9.3	12.1	2007	14	64.0
Norway spruce	17	1.7	14.7	15.0	1883	18	163.0
Sitka spruce	17	1.7	15.0	16.0	1950	26	251.0
Midlands	**Age**	**Area (ha)**	**Top Height (m)**	**QMDBH (cm)**	**Stocking (ha^{-1})**	**YC ($m^{-3} \cdot ha^{-1} \cdot yr^{-1}$)**	**Volume per hectare ($m^3 \cdot ha^{-1}$)**
Alder	16	0.2	7.7	10.3	2456	6	19.3
Ash	16	0.2	8.3	8.3	2245	6	11.5
Birch	16	1.2	7.7	11.3	1795	6	17.0
Lodgepole pine	16	0.3	9.3	14.0	2056	14	119.0
Norway spruce	16	0.7	8.8	13.0	2420	16	95.0
Sitka spruce	16	0.3	9.3	13.8	2346	22	150.0
North West	**Age**	**Area (ha)**	**Top Height (m)**	**QMDBH (cm)**	**Stocking (ha^{-1})**	**YC ($m^{-3} \cdot ha^{-1} \cdot yr^{-1}$)**	**Volume per hectare ($m^3 \cdot ha^{-1}$)**
Alder	12	0.6	11.1	9.7	2200	12	57.0
Ash	12	0.7	10.7	8.5	2250	10	40.6
Birch	12	0.8	11.9	9.7	2500	12	76.2
Lodgepole pine	16	1.3	8.8	11.7	2235	10	73.0
Norway spruce	17	3.1	11.8	17.9	2131	20	229.0
Sitka spruce	16	2.0	11.4	17.7	1590	20	200.0

*Quadratic mean DBH

Systematic samplings of trees within the diameter size distribution class of the quadratic mean diameter at breast height (QMDBH) were chosen. The total number of trees sampled was 270, 45 per species, 15 trees per region, and five trees per site visit. Sample trees were cut down at ground level and extracted to a landing. All branches were removed from stems and piled for weighing and sub sampling. The height at where the stem reached 7 cm diameter was noted and partitioned. The length and mid diameter of the main stem and top section less than 7 cm diameter were recorded and volume estimated using Equation 2.6., Huber's formula (Purser, 2000).

$$V = \frac{D^2 * \pi}{40000} \times L \qquad (2.6.)$$

V = Volume (m^3)

D = Midpoint diameter (cm)

L = Length (m)

Table 2.4.4. illustrates the attributes of the sample trees as an output of the latter approach.

Table 2.4.4. Sample tree attributes displaying the mean and range.

South East	**DBH (cm)**	**Total Height (m)**	**Merchantable Volume (m^3)**	**Tops Volume (m^3)**
Alder	8.3 (7-11)	8.7 (8-9)	0.018 (0.010-0.035)	0.009 (0.006-0.013)
Ash	9.1 (7-11)	9.8 (9-11)	0.022 (0.010-0.037)	0.007 (0.004-0.013)
Birch	8.9 (7-11)	7.8 (7-9)	0.018 (0.005-0.032)	0.006 (0.002-0.013)
Lodgepole pine	10.8 (9-13)	8.0 (6-10)	0.035 (0.023-0.062)	0.004 (0.001-0.007)
Norway spruce	15.4 (14-17)	12.6 (10-14)	0.117 (0.082-0.147)	0.005 (0.003-0.007)
Sitka spruce	16.0 (14-18)	13.1 (10-15)	0.128 (0.087-0.197)	0.005 (0.003-0.006)
Midlands	**DBH (cm)**	**Total Height (m)**	**Merchantable Volume (m^3)**	**Tops Volume (m^3)**
Alder	9.4 (7-12)	9.7 (8-11)	0.027 (0.009-0.041)	0.008 (0.003-0.012)
Ash	8.4 (7-10)	7.3 (6-8)	0.015 (0.008-0.030)	0.005 (0.002-0.008)
Birch	10.6 (8-12)	7.8 (7-9)	0.031 (0.015-0.045)	0.003 (0.001-0.006)
Lodgepole pine	13.7 (12-17)	9.8 (6-10)	0.056 (0.030-0.101)	0.005 (0.001-0.008)
Norway spruce	13.0 (11-15)	8.7 (8-10)	0.051 (0.035-0.071)	0.004 (0.002-0.007)
Sitka spruce	13.4 (12-17)	9.4 (8-11)	0.061 (0.036-0.106)	0.004 (0.002-0.005)
North West	**DBH (cm)**	**Total Height (m)**	**Merchantable Volume (m^3)**	**Tops Volume (m^3)**
Alder	8.6 (7-10)	11.0 (9-13)	0.023 (0.009-0.038)	0.011 (0.007-0.015)
Ash	8.2 (7-10)	10.9 (10-12)	0.016 (0.006-0.037)	0.012 (0.004-0.021)
Birch	8.0 (7-10)	10.8 (10-12)	0.023 (0.006-0.033)	0.010 (0.005-0.016)
Lodgepole pine	11.5 (9-15)	6.4 (6-8)	0.033 (0.015-0.062)	0.004 (0.002-0.006)
Norway spruce	16.5 (15-18)	11.5 (9-13)	0.114 (0.083-0.163)	0.004 (0.002-0.006)
Sitka spruce	16.2 (13-19)	9.1 (8-11)	0.081 (0.049-0.137)	0.003 (0.002-0.004)

Above ground biomass partitions were weighed after the measurement of heights and diameters. The merchantable stem, top section less than 7 cm, live branches and dead branches were weighed separately using OHAUS® bench scales to an accuracy of 0.1 kg. Five branches and one dead branch were taken at random from each sample tree; dead branches being those with no living foliage present (Brown, 1997, Carey, 1980, Green *et al.*, 2007, Repola *et al.*, 2007). After branch sub sampling, stem sections were placed onto a saw horse. Discs of 25-30 mm thickness were taken from the bottom of the stem and every metre up to 80% of total height, whilst also avoiding whorls. All discs were weighed fresh in the field using an OHAUS® Scout Pro SPU 4001 scales to an accuracy of 0.1 g. The total subsample size was ~ 4934; divided between stem discs, branch wood and foliage.

2.4.2. Moisture content analysis of subsamples

Subsamples were taken back to the lab. Disc samples were oven dried for 48-72 hours at 105^{o}C in accordance with the simplified procedure for determining moisture content (EN-14774-2, 2010). Moisture content for stem discs and branches were calculated on a wet weight basis using Equation 2.1. (Briggs, 1994, EN-14774-2, 2010). Branch wood and foliage were separated after oven drying and weighed separately (Brown, 1997).

$$\mathrm{MC\%_{wb}} = \frac{\mathrm{Ww} - \mathrm{Dw}}{\mathrm{Ww}} \text{ x } 100 \qquad (2.1.)$$

$\mathrm{MC\%_{wb}}$ = Moisture content on a wet weight basis expressed as a percentage

Ww = Wet weight of sample (kg)

Dw = Oven dry weight of sample (kg)

2.4.3. Statistical analysis of moisture content

Initial data entry was conducted using the Microsoft® Excel 2007 spreadsheet package. Statistical analysis was conducted using Minitab® 16 statistical software package. The scale of data was nominal, in terms of the species, partitions, locations and sampling period. The data scale was also continuous due to the contiguous nature of moisture content. For each species and partition, descriptive summary statistics of moisture content were compiled.

One way analysis of variance (ANOVA) tests were conducted to test for the significance of spatiotemporal and partition differences with the trial species for moisture content. Null hypothesis was that no statistically significant differences occurred between and within species on the basis of partitions spatiotemporally ($p \geq 0.05$). Alternative hypothesis was that statistically significant differences occurred ($p \leq 0.05$). Tukey's pairwise simultaneous confidence interval tests were used to determine what means differed when the null hypothesis was rejected ($p \leq 0.05$).

2.4.3.1. Prediction equations to determine stem wood moisture content

Single linear and multiple regression equations were constructed in order to estimate arithmetic mean stem wood moisture content using fewer samples than those originally taken. The samples chosen to construct the regression equations were the moisture content values recorded from the base, mid-point and top section of sample stems (0%, 50% and 80% of relative height). The regression models are illustrated in Equations 2.7.-2.9.

$$\mathrm{Y} = \mathrm{a} + \mathrm{b}\,(\mathrm{X}) \qquad (2.7.)$$

Y = Mean stem wood moisture content (%)

a = Intercept

b = Slope coefficient

X = Moisture content values recorded at the base of the stem (%)

$$Y = a + b\,(X_1) + c\,(X_2) \qquad (2.8.)$$

Y = Mean stem wood moisture content (%)

a = Intercept

b and c = Slope coefficients

X_1 = Moisture content values recorded at the base of the stem (%)

X_2 = Moisture content values recorded at the mid-point of the stem (%)

$$Y = a + b\,(X_1) + c\,(X_2) + d\,(X_3) \qquad (2.9.)$$

Y = Mean stem wood moisture content (%)

a = Intercept

b, c and d = Slope coefficients

X_1 = Moisture content values recorded at the base of the stem (%)

X_2 = Moisture content values recorded at the mid-point of the stem (%)

X_3 = Moisture content values recorded at 80% of relative height (%)

2.5. Results and discussion on moisture content

2.5.1. Summary of stem wood partitions

Table 2.5.1. Summary statistics of merchantable stem wood sections. Identical letters accompanying the mean values signify that no statistically significant difference occurred ($p \geq 0.05$). Different letters accompanying the mean values signify that a statistically significant difference occurred ($p \leq 0.05$).

Merchantable Stem Wood Moisture Content (%)							
Species	**Number of subsamples**	**Mean**	**Standard Error**	**Standard Deviation**	**Coefficient of Variation**	**Minimum**	**Maximum**
Alder	226	51.8 a	0.5	3.6	6.9	38.7	59.1
Ash	182	37.3 b	0.4	2.8	7.5	30.0	45.6
Birch	195	45.4 c	0.3	2.5	5.5	36.0	52.9
Lodgepole pine	232	58.9 d	0.6	4.4	7.5	47.2	69.2
Norway spruce	387	64.6 e	0.3	3.5	5.4	50.8	72.3
Sitka spruce	359	61.0 f	0.7	4.9	8.0	45.5	71.5

Table 2.5.2. Summary statistics of tops < 7 cm diameter stem wood sections. Identical letters accompanying the mean values signify that no statistically significant difference occurred ($p \geq 0.05$). Different letters accompanying the mean values signify that a statistically significant difference occurred ($p \leq 0.05$).

Tops < 7 cm Diameter Moisture Content (%)							
Species	**Number of subsamples**	**Mean**	**Standard Error**	**Standard Deviation**	**Coefficient of Variation**	**Minimum**	**Maximum**
Alder	176	52.2 a	0.5	3.6	6.9	43.8	60.9
Ash	175	38.4 b	0.6	3.8	9.9	30.7	50.1
Birch	148	46.6 c	0.5	3.3	7.1	35.7	54.9
Lodgepole pine	140	61.7 d	0.5	3.2	5.2	51.0	70.6
Norway spruce	128	61.5 e	0.5	2.8	4.6	54.5	68.6
Sitka spruce	132	59.3 d	0.7	4.2	7.1	47.8	70.1

Table 2.5.3. Summary statistics of the whole stem (merchantable stem and tops < 7 cm diameter combined). Identical letters accompanying the mean values signify that no statistically significant difference occurred ($p \geq 0.05$). Different letters accompanying the mean values signify that a statistically significant difference occurred ($p \leq 0.05$).

Whole Stem Wood Moisture Content (%)

Species	Number of subsamples	Mean	Standard Error	Standard Deviation	Coefficient of Variation	Minimum	Maximum
Alder	402	52.0 a	0.4	3.6	6.9	38.7	60.9
Ash	357	37.8 b	0.3	3.4	9.0	30.0	50.1
Birch	343	45.9 c	0.3	2.9	6.3	35.7	54.9
Lodgepole pine	372	59.9 d	0.4	4.2	7.0	47.2	70.6
Norway spruce	515	64.6 e	0.3	3.6	5.6	50.8	72.3
Sitka spruce	491	60.9 f	0.4	4.7	7.7	45.5	71.5

2.5.2. Stem wood moisture content discussion

With all the stem wood partitions, ash had the lowest moisture contents, followed by birch, alder, lodgepole pine, Sitka spruce, and Norway spruce had the highest moisture contents. The differences between species are possibly a function of vascular tissue distribution. Ash is a ring porous species with larger, fewer vessels and has a propensity to allocate more latewood to annual growth rings than earlywood, thus inversely affecting water conductance as observed by Michalec and Niklasova (2006). The higher moisture contents of alder and birch in comparison to ash are reflective of their diffuse porous vascular distribution, having more void volume for water conductance on annual growth rings than ring porous species due to having more earlywood than latewood (Coder, 1999, Michalec and Niklasova, 2006). The three conifer species appeared to have more void volume for water conductance than the broadleaf species.

For practical purposes, moisture content helps describe a species suitability for wood fuel consumption. The three conifer species are situated within a range of moisture contents (60-65%) unsuitable for combustion, unsuitable for storage once processed into fuel such as wood chip, in addition to increasing fuel costs in transportation of wood intended for energy purposes (EN-14961-1, 2010, Hakkila, 2004, Sikanen, 2010). Alder and birch (46-52%) are situated within a lower range of moisture content than the conifers. Moreover, alder and birch are situated within an acceptable range of moisture contents suitable for combustion in large scale industrial condensing boilers of nominal boiler capacities > 100 kW_{th} (45-55%), but are still unsuitable for storage and the transportation costs at this moisture content will still be high (EN-14961-1, 2010, Hakkila, 2004, Kofman and Kent 2007, Obernberger *et al.,* 2006, Serup and Kofman, 2005, Sikanen, 2010). Ash (38%) is situated within a moisture content range suitable for commercial boilers of nominal boiler capacities of < 100 kW_{th}, but is above the range of moisture content percentages suitable for storage and combustion efficiency of small scale domestic wood burning of nominal boiler capacities of < 30 kW_{th} (EN-14961-1, 2010, Kent *et al.,* 2011). Overall, dependent on the scale of end user and boiler specifications for moisture content, seasoning schedules would need to be considered in all the examples mentioned.

2.6. Summary of branch wood partitions

Table 2.6.1. Summary statistics of branch wood. Identical letters accompanying the mean values signify that no statistically significant difference occurred ($p \geq 0.05$). Different letters accompanying the mean values signify that a statistically significant difference occurred ($p \leq 0.05$).

Branch Wood Moisture Content (%)

Species	Number of Subsamples	Mean	Standard Error	Standard Deviation	Coefficient of Variation	Minimum	Maximum
Alder	223	47.9 a	0.9	7.1	14.8	27.7	67.2
Ash	220	44.5 b	0.8	5.8	13	32.5	61.4
Birch	222	43.5 b	1.0	7.9	18.2	24.6	58.3
Lodgepole pine	225	53.5 c	0.8	6.2	11.6	29.0	79.6
Norway spruce	221	48.9 a	0.4	6.6	13.5	31.7	72.6
Sitka spruce	224	47.9 a	1.0	7.6	15.9	28.0	70.0

Table 2.6.2. Summary statistics of dead branch wood. Identical letters accompanying the mean values signify that no statistically significant difference occurred ($p \geq 0.05$). Different letters accompanying the mean values signify that a statistically significant difference occurred ($p \leq 0.05$).

	Dead Branch Wood Moisture Content (%)						
Species	**Number of Subsamples**	**Mean**	**Standard Error**	**Standard Deviation**	**Coefficient of Variation**	**Minimum**	**Maximum**
Lodgepole pine	30	24.4 a	1.5	8.2	33.7	12.9	43.2
Norway spruce	42	22.7 ab	1.4	9.0	39.7	9.3	43.0
Sitka spruce	37	19.2 b	1.1	6.8	35.7	9.4	38.6

2.6.1. Branch wood moisture content discussion

The moisture contents in live branches ranged from 44-54%. Birch had the lowest moisture content, followed by ash, alder, Sitka spruce, Norway spruce, and lodgepole pine had the highest moisture content. In addition, branch wood had a wide range of moisture contents, alder (40%), ash (29%), birch (34%), lodgepole pine (51%), Norway spruce (41%) and Sitka spruce (42%). As the branch wood partition included foliage, this may explain the high ranges of values encountered. Foliage moisture content alone can be 66-75% on a wet basis and can vary as a function of the time of day, being higher at night time and lowering during afternoon periods coinciding with transpiration (Gates, 1991). In their analysis of logging residue material derived from Sitka spruce, Hoyne and Thomas (2001) found moisture contents of 70% and 50% in foliage and wood respectively.

As discussed for stem wood in Section 2.5.2., the moisture content values help to describe the suitability of branches for wood fuel consumption. The range of moisture contents for branches (44-54%) are suitable for large scale industrial condensing boilers of nominal boiler capacities > 100 kW_{th} (45-55%), but are still unsuitable for storage and will affect transportation costs (EN-14961-1, 2010, Hakkila, 2004, Kofman and Kent 2007, Obernberger *et al.*, 2006, Serup and Kofman, 2005, Sikanen, 2010). However, irrespective of moisture content, another issue with the harvesting of branches for wood fuel is foliage. Foliage contains high concentrations of elements such as chlorine that can react with potassium and sodium to cause corrosion on heat transfer surfaces in boilers, in addition to higher concentrations of ash forming elements in comparison to other tree components such as stem wood and bark (Alakangas, 2005, Hakkila, 2004, Obernberger *et al.*, 2006, Roser *et al.*, 2010). It is necessary to develop operational strategies that aim to reduce foliage in wood fuel mixtures, as the removal of foliage can also have an adverse effect on the production potential of forests due to nutrient removals (Rauland-Rasmussen *et al.*, 2008). This can be achieved through seasoning wood fuel assortments that include branch wood, such as whole trees from first thinnings, and aboveground logging residues from clearfell areas (Kofman and Kent, 2007, Pettersson and Nordfjell, 2006).

2.7. Partition differences in moisture content

Table 2.7.1. Partition mean moisture content differences combining all regions and site visits. Identical letters in black signify that no statistically significant differences ($p \geq 0.05$) occurred within rows. Different letters in black signify that statistically significant differences occurred within rows ($p \leq 0.05$). Identical letters in red signify that no statistically significant differences ($p \geq 0.05$) occurred between species. Different letters in red signify that statistically significant differences occurred between species ($p \leq 0.05$).

Partition Analysis of Moisture Content (%)

	Merchantable Stem	Tops < 7 cm	Branch wood	Dead Branches
Alder	51.8 a a	52.2 a a	47.9 b a	N/A
Ash	37.3 a b	38.4 b b	44.5 c b	N/A
Birch	45.4 a c	46.6 a c	43.5 b b	N/A
Lodgepole pine	58.9 a d	61.7 b d	53.5 c c	24.4 d a
Norway spruce	64.6 a e	61.5 b e	48.9 c a	22.7 d ab
Sitka spruce	61.0 a f	59.3 a d	47.9 b a	19.2 c b

2.7.1. Partition moisture content discussion

When merchantable stem wood and top sections < 7 cm were partitioned for moisture content, three species (alder, birch, Sitka spruce) had no statistically significant differences ($p \geq 0.05$), whereby the remaining three species (ash, lodgepole pine, Norway spruce) had significant differences in moisture content ($p \leq 0.05$). Between all six species, moisture content of the merchantable stems was statistically significant ($p \leq 0.05$). There were no statistically significant differences in the tops < 7 cm diameter section between lodgepole pine and Sitka spruce ($p \geq 0.05$). With the exception of ash, branch wood moisture content was lower than the stem wood partitions. Other authors have also found similar idiosyncrasies between different tree components and species (Gibson *et al.*, 1985, Manwiller, 1975). There were no statistically significant differences with branch wood moisture content ($p \geq 0.05$) between ash and birch. There were also no statistically significant differences in branch wood moisture content between alder, Norway spruce and Sitka spruce. Dead branch wood moisture content was the lowest of all partitions for the conifer species, concurrent with that observed for Sitka spruce by Tobin and Nieuwenhuis (2007). The dead branch wood moisture content of lodgepole pine was not statistically significant from Norway spruce and Sitka spruce ($p \geq 0.05$). Broadleaf trees had no dead branches recorded in this study, possibly due to the fact that alder, ash and birch are typically self-pruning broadleaf tree species (Horgan *et al.*, 2003).

2.8. Temporal and spatial variation in the moisture content of the whole stem

Table 2.8.1. Temporal variation of whole stem moisture content. Identical letters in black signify that no statistically significant difference occurred within rows ($p \geq 0.05$). Different letters in black signify that a statistically significant difference occurred within rows ($p \leq 0.05$). Identical letters in red signify that no statistically significant difference occurred between species ($p \geq 0.05$). Different letters in red signify that a statistically significant difference occurred between species ($p \leq 0.05$).

Temporal Whole Stem Wood Moisture Contents (%)

South East	**Dormancy**	**Flushing**	**Growing Season**
Alder	48.1 a a	50.7 b a	49.3 ab a
Ash	35.1 a b	36.8 b b	38.7 c b
Birch	45.2 a c	47.4 b c	46.3 ab c
Lodgepole pine	62.3 a d	59.5 b d	58.9 b d
Norway spruce	64.2 a e	61.8 b e	62.9 ab e
Sitka spruce	59.5 a f	58.6 a d	60.0 a d
Midlands	**Dormancy**	**Flushing**	**Growing Season**
Alder	50.3 a a	51.5 a a	54.0 b a
Ash	33.7 a b	36.7 b b	41.0 c b
Birch	45.3 a c	43.9 a c	47.2 b c
Lodgepole pine	57.5 a d	59.0 ab d	60.4 b d
Norway spruce	64.2 a e	61.9 b e	64.0 a e
Sitka spruce	59.9 a f	57.4 b d	60.8 a d
North West	**Dormancy**	**Flushing**	**Growing Season**
Alder	54.4 ab a	55.1 a a	53.8 b a
Ash	35.8 a b	39.5 b b	42.3 c b
Birch	47.3 a c	45.3 b c	45.9 b c
Lodgepole pine	59.1 a d	60.4 a d	63.2 b d
Norway spruce	65.9 a e	67.3 b e	68.1 b e
Sitka spruce	63.9 a f	64.0 a f	65.5 a f

2.8.1. Temporal variation in the moisture content of the whole stem

In all regions, the only species to show a distinguishable trend in the fluctuation of moisture content over the periods sampled was ash. During flushing and the growing season, moisture content in ash was higher and significantly lower during dormancy. Between dormancy and the growing season, differences of four, seven and six percentage points were recorded in the South East, Midlands and North West respectively for ash. This is possibly reflective of ash's vascular distribution as a ring porous hardwood species. Ring porous hardwood species form larger vessels during the growing season, declining to a smaller size later on into dormancy due to an increase in the allocation of latewood to earlywood (Bowyer *et al.*, 2007, Coder, 1999, Michaelec and Niklasova, 2006).

In the other 15 instances, the remaining five species had no distinguishable fluctuations in stem wood moisture content. This compares with findings made by other authors (Peck, 1959, Shotaffer and Brackley, 1982), who found no distinguishable temporal fluctuations in moisture content over the course of seasons with stem sections sampled *in situ*. Only four incidences occurred where moisture content was not statistically significant between species. During flushing in the South East, lodgepole pine and Norway spruce were not statistically significant ($p \geq 0.05$). Similar trends occurred between lodgepole pine and Sitka spruce during the growing season in the South East. During flushing and the growing season in the Midlands, moisture content also did not vary between lodgepole pine and Sitka spruce.

2.8.2. Spatial variation in the moisture content of the whole stem

Table 2.8.2. Spatial variation of whole stem moisture content. Identical letters signify that no statistically significant difference occurred within rows ($p \geq 0.05$). Different letters signify that a statistically significant difference occurred within rows ($p \leq 0.05$).

Spatial Whole Stem Wood Moisture Contents (%)			
Dormancy	**South East**	**Midlands**	**North West**
Alder	48.1 a	50.3 b	54.4 c
Ash	35.1 a	33.7 b	35.8 a
Birch	45.2 a	45.3 a	47.3 b
Lodgepole pine	62.3 a	57.5 b	59.1 c
Norway spruce	64.2 a	64.2 a	65.9 b
Sitka spruce	59.5 a	59.9 a	63.9 b
Flushing	**South East**	**Midlands**	**North West**
Alder	50.7 a	51.5 a	55.1 b
Ash	36.8 a	36.7 a	39.5 b
Birch	47.4 a	43.9 b	45.3 b
Lodgepole pine	59.5 a	59.0 a	60.4 a
Norway spruce	61.8 a	61.9 a	67.3 b
Sitka spruce	58.6 a	57.4 a	64.0 b
Growing Season	**South East**	**Midlands**	**North West**
Alder	49.3 a	54.0 b	53.8 b
Ash	38.7 a	41.0 b	42.3 b
Birch	46.3 a	47.2 a	45.9 a
Lodgepole pine	58.9 a	60.4 a	63.2 b
Norway spruce	62.9 a	64.0 a	68.1 b
Sitka spruce	60.0 a	60.8 a	65.5 b

Over the three sampling periods, 16 cases out of 18 had at least two regions where no statistically significant difference ($p \geq 0.05$) occurred for whole stem wood moisture content. Lodgepole pine during flushing and birch during the growing season had three regions where no statistically significant occurred ($p \geq 0.05$) with whole stem wood moisture content. In the dormant season, alder and lodgepole pine had statistically significant differences between all three regions ($p \leq 0.05$).

During dormancy, the North West had the highest stem wood moisture contents recorded in five cases out of six. The only exception to this trend was lodgepole pine in the South East which recorded the highest moisture content. During flushing the North West recorded the highest stem wood moisture contents in four cases out of six. Lodgepole pine encountered no significant differences between regions. Birch in the South East recorded the highest moisture content between regions. During the growing season, the North West encountered the highest moisture contents in four cases out of six. Alder and birch in the Midlands recorded the highest moisture contents.

2.9. Temporal and spatial variation of branch wood moisture content

Table 2.9.1. Temporal variation of branch wood moisture content. Identical letters in black signify that no statistically significant difference occurred within rows ($p \geq 0.05$). Different letters in black signify that a statistically significant difference occurred within rows ($p \leq 0.05$). Identical letters in red signify that no statistically significant difference occurred between species ($p \geq 0.05$). Different letters in red signify that a statistically significant difference occurred between species ($p \leq 0.05$).

Temporal Branch Wood Moisture Contents (%)

South East	**Dormancy**	**Flushing**	**Growing Season**
Alder	50.5 a a	50.9 a a	44.0 b a
Ash	38.9 a b	49.5 b a	47.0 b a
Birch	46.0 a c	50.8 b a	33.3 c b
Lodgepole pine	54.7 a d	56.7 a b	46.8 b a
Norway spruce	49.0 a a	42.9 b c	45.3 b a
Sitka spruce	50.6 a a	46.1 b d	47.1 ab a
Midlands	**Dormancy**	**Flushing**	**Growing Season**
Alder	52.1 a a	37.4 b a	57.0 c a
Ash	41.2 a b	39.6 a ad	52.2 b bc
Birch	46.3 a c	34.4 b b	52.1 c bc
Lodgepole pine	55.1 a d	48.0 b c	54.5 a ab
Norway spruce	51.4 a b	41.6 b d	50.0 a cd
Sitka spruce	49.0 a e	40.7 b d	46.8 a d
North West	**Dormancy**	**Flushing**	**Growing Season**
Alder	54.5 a ac	41.3 b a	43.9 c ab
Ash	45.3 a b	44.2 a ab	42.6 a bc
Birch	52.0 a ac	37.1 b c	39.1 b c
Lodgepole pine	57.6 a ad	52.0 b d	56.3 a d
Norway spruce	59.5 a de	47.9 b be	52.8 c d
Sitka spruce	61.5 a e	42.5 b af	46.4 c ea

2.9.1. Temporal variation in the moisture content of branch wood

Branch wood had more pronounced temporal fluctuations in moisture content in comparison to stem wood. In the South East, moisture content was lower during flushing and reduced again during the growing season period in comparison to dormancy for Norway spruce and Sitka spruce. Alder and lodgepole pine branch wood had little change in moisture content between dormancy and flushing, but experienced a reduction during the growing season. Ash and birch branch wood had higher moisture content during flushing in comparison to dormancy, and experienced a significant reduction during the growing season.

The trends encountered in the South East were not entirely similar in the Midlands. With all six species, branch wood moisture content initially reduced at flushing in comparison to dormancy, only to rise again during the growing season. When moisture content rose again during the growing season, alder, ash and birch branch wood moisture content exceeded the dormancy values estimated. For lodgepole pine, Norway spruce and Sitka spruce, moisture content reached a level equal to the values recorded during dormancy.

Analogous to the Midlands, similar irregularities in branch wood moisture content fluctuations were encountered in the North West. All species encountered a reduction in branch wood moisture content between dormancy and flushing. Alder, birch, Norway spruce and Sitka spruce branch wood moisture content rose again during the growing season, but did not exceed the values estimated during dormancy. Ash and lodgepole pine moisture content rose again during the growing season, but was equal to the values recorded during dormancy.

In 14 cases out of 18, moisture content reduced at flushing in comparison to dormancy. This possibly indicates that with the general increase of physiological activity, increased temperatures and vapour pressure deficits, moisture content will reduce in branch sections (Gates, 1991, Keane and Sheridan, 2004). Where moisture content did not reduce at flushing, this may be due to foliage having not been partitioned before oven drying. Had foliage been partitioned before oven drying, different temporal trends may have been encountered, as foliage is most subject to fluctuations in moisture content in comparison to other tree parts (Gates, 1991). The situations where moisture content rose again during the growing season in comparison to flushing is less clear. This trend may be indicative of the reduction in apical meristem activity, shoot elongation and foliage maturation, potentially leading to a reduction of a tree’s demand for water in foliar regions (Bowyer *et al.,* 2007, Josza and Middleton, 1994, Larson *et al.*, 2001, Punches, 2004, Wiedenhoelt, 2010).

2.9.2. Spatial variation in the moisture content of branch wood

Table 2.9.2. Spatial variation of branch wood moisture content. Identical letters signify that no statistically significant difference occurred within rows ($p \geq 0.05$). Different letters signify that a statistically significant difference occurred within rows ($p \leq 0.05$).

Spatial Branch Wood Moisture Contents (%)			
Dormancy	**South East**	**Midlands**	**North West**
Alder	50.5 a	52.1 b	54.5 c
Ash	38.9 a	41.2 b	45.3 c
Birch	46.0 a	46.3 a	52.0 b
Lodgepole pine	54.7 a	55.1 a	57.6 b
Norway spruce	49.0 a	51.4 a	59.5 b
Sitka spruce	50.6 a	49.0 a	61.5 b
Flushing	**South East**	**Midlands**	**North West**
Alder	50.9 a	37.4 b	41.3 c
Ash	49.5 a	39.6 b	44.2 c
Birch	50.8 a	34.4 b	37.1 c
Lodgepole pine	56.7 a	48.0 b	52.0 c
Norway spruce	42.9 a	41.6 a	47.9 b
Sitka spruce	46.1 a	40.7 b	42.5 b
Growing Season	**South East**	**Midlands**	**North West**
Alder	44.0 a	57.0 b	43.9 a
Ash	47.0 a	52.2 b	42.6 c
Birch	33.3 a	52.1 b	39.1 c
Lodgepole pine	46.8 a	54.5 b	56.3 b
Norway spruce	45.3 a	50.0 b	52.8 c
Sitka spruce	47.1 a	46.8 a	46.4 a

For spatial variation in branch wood moisture content, eight cases out of 18 had two regions where no statistically significant difference occurred. Sitka spruce during the growing season was the only instance where no statistically significant difference occurred between regions. The remaining nine cases had statistically significant differences between all regions.

During dormancy the North West had the highest moisture contents, the range of differences during this period being 4% for alder, 6% for ash, 6% for birch, 3% for lodgepole pine, 11% for Norway spruce and 11% for Sitka spruce between all three regions.

During flushing the South East had the highest moisture contents with the exception of Norway spruce in the North West. The range of differences during flushing between all regions was 14% for alder, 10% for ash, 17% for birch, 9% for lodgepole pine, 6% for Norway spruce and 5% for Sitka spruce. The differences were stronger for this period than dormancy with alder, ash, birch and lodgepole pine and less for Norway spruce and Sitka spruce.

During the growing season the Midlands had the highest moisture contents for the broadleaf species. The North West was wettest for lodgepole pine and Norway spruce, whereas Sitka spruce had no differences between regions. The range of differences between regions was 13% for alder, 9% for ash, 19% for birch, 9% for lodgepole pine, 8% for Norway spruce and 1% for Sitka spruce.

2.10. Summary of the spatiotemporal trends in moisture content

The overall remit of this study was the application of results and their contribution to advancing knowledge into wood fuel supply chain optimisation. Identifying a time of year as to when moisture content would be naturally lower to advance seasoning schedules was the premise behind investigating temporal differences. The only species to demonstrate considerable temporal moisture content fluctuations in stem wood was ash. Ash had considerably lower moisture content in stem sections during dormancy in all locations. On one hand this provides a twofold advantage, but also has disadvantages. Lower moisture content and no foliage would prove to be advantageous if whole tree terrain chipping operations were intended for commercial and industrial scale applications. From a domestic point of view, lower moisture content in ash during winter may be a disadvantage if stem sections are harvested for firewood. Even though moisture content is lower, the conditions for seasoning to 20% moisture content during the dormancy period would not be ideal due to higher rates of precipitation, lower temperatures and higher relative humidity in the air, in addition to wind the latter three being key criterion to ensuring suitable conditions for natural drying of wood (Alakangas, 2005, Kofman and Kent, 2007). Spring and summer time are the preferred times of year for natural seasoning of wood intended for energy, taking advantage of lower precipitation, higher temperatures and lower relative humidity of air (Alakangas, 2005, Filbakk *et al.,* 2001, Kofman and Kent, 2007, Nord-Larsen *et al.,* 2011, Nurmi and Lehtimaki, 2010). Research has also confirmed in temperate forest biomes that the optimum time for harvesting wood for energy with a view to encourage natural seasoning before processing into wood fuel products is during spring time (March-April) up until August, as the period during September-February are not desired for harvesting and seasoning wood for energy (Alakangas, 2005, Filbakk *et al.*, 2011, Gigler *et al.*, 2000, Hakkila, 2004, Holt, 1967, Kofman and Kent, 2009a, Kofman and Kent, 2009b, Kofman and Kent, 2009c, Kofman and Kent, 2009d, M^c^Minn, 1986, Mochan, 2006, Nord-Larsen *et al.*, 2011, Nurmi and Lehtimaki, 2010, Rolls, 2009, Roser *et al.*, 2010, Savill, 1979).

Aside from ash, the other five species had no considerable rate of moisture content change over the periods sampled in stem sections. Thus, the ambient environment that favours natural seasoning conditions at the time of year trees are felled, as opposed to investigating fluctuations of the moisture content of tree parts *in situ* should receive more scrutiny. A practice employed in the latter regard is the operation of sour felling. Sour felling is a method where trees are felled during spring/summer and branches left intact, taking advantage of water withdrawal through foliage in order to reduce moisture content in the field before harvesting for round wood or whole trees (Alakangas, 2005, Filbakk *et al.*, 2011, Holt, 1967, M^c^Minn, 1986, Mochan, 2006, Nurmi and Lehtamaki, 2010). Another benefit to sour felling is that foliage begins to drop off branch sections after a period of seasoning to recycle back into soil. Alternatively, killing standing trees using herbicide is an operation that can be implemented. In this method, trees are later felled in a separate operation after a period of seasoning and to allow foliage to drop off (Holt, 1967, Kofman and Kent, 2009b). As branch wood moisture content in this study for the most part dropped significantly at the flushing period in comparison to dormancy in all the locations sampled, the withdrawal of water from branches within the context of sour felling's definition was certainly demonstrated. A reduction in branch wood moisture content at flushing would also prove beneficial if the intention is to season above ground logging residues on clearfell sites before bundling, as found by Pettersson and Nordfjell (2006).

Irrespective of the times of year most suitable for seasoning wood, the location where seasoning occurs is also another important factor to take into account. In the forest, because of a humid microclimate, Irish research has found that assortments such as Sitka spruce whole trees can only be seasoned to moisture content levels adequate only for industrial applications (45-55%) (Kofman and Kent, 2007). Other assortments, such as 3 m ash firewood lengths, have been found to season very little in forest environments under Irish conditions (Kent *et al.*, 2011). Dedicated terminals for seasoning conducive to ideal drying conditions (e.g. wind exposure), provided assortments are covered from rain, have proven to be effective in the seasoning of Sitka spruce round wood to moisture content levels as low as 30% (Kofman and Kent, 2009b). Exposed areas, such as clearfell sites, have also found to be effective for seasoning lodgepole pine whole tree assortments under Irish conditions (Kofman and Kent, 2009c).

2.11. Vertical dependence of stem wood moisture content

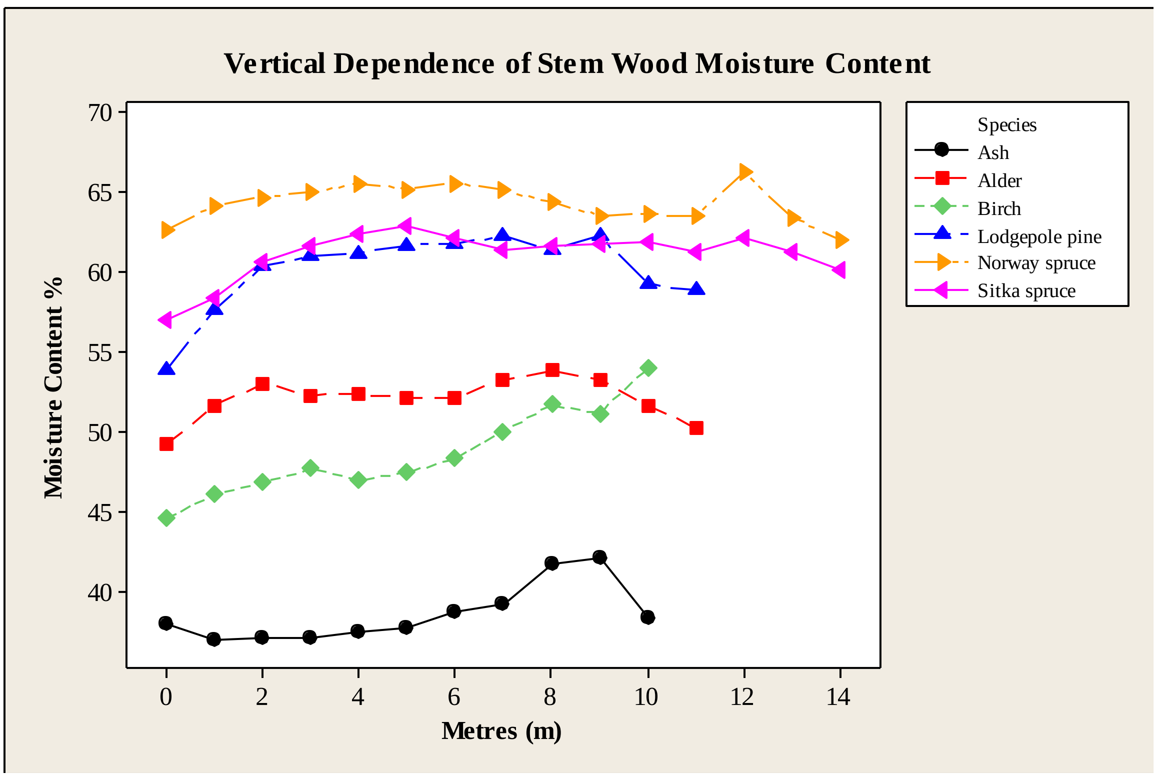

Figure 2.11.1. Vertical dependence trends of stem wood moisture content.

Table 2.11.1. Regression equations using one moisture content sample taken from the base of the stem to determine mean stem wood moisture content.

Species	Intercept (a)	b	R^2	Standard Error
Alder	-9.7	1.2	0.75	1.5
Ash	24.5	0.5	0.75	2.0
Birch	11.8	0.8	0.77	1.7
Lodgepole pine	49.1	0.2	0.10	2.6
Norway spruce	33.7	0.5	0.63	1.6
Sitka spruce	27.2	0.6	0.62	2.0

Table 2.11.2. Regression equations using two moisture content samples from the base and mid-point of stems to determine mean stem wood moisture content.

Species	Intercept (a)	b	c	Adjusted R^2	Standard Error
Alder	7.6	0.8	0.9	0.74	2.0
Ash	-3.3	0.3	0.8	0.96	0.6
Birch	-1.2	0.8	0.3	0.80	1.6
Lodgepole pine	29.9	-0.1	0.6	0.39	2.1
Norway spruce	16.3	0.3	0.4	0.79	1.2
Sitka spruce	12.8	0.3	0.5	0.78	1.5

Table 2.11.3. Regression equations using three moisture content samples at the base, mid-point and 80% of the relative height of stems to determine mean stem wood moisture content.

Species	Intercept (a)	b	c	d	Adjusted R^2	Standard Error
Alder	1.8	0.6	0.02	0.4	0.84	1.6
Ash	0.3	0.3	0.5	0.2	0.96	0.7
Birch	-2.8	0.7	0.2	0.2	0.82	1.5
Lodgepole pine	18.0	-0.1	0.4	0.4	0.51	1.9
Norway spruce	11.1	0.3	0.3	0.2	0.87	0.9
Sitka spruce	6.3	0.2	0.5	0.2	0.85	1.2

2.11.1. Vertical dependence trends in stem wood moisture content

Moisture content was lowest at the base of stems, gradually rising upwards. This trend in vertical dependence is concurrent with that found by others (Clark and Daniels, 2000, Shotaffer and Brackley 1982). This trend may be attributed to possible heartwood formation at different stem positions, which was not measured in this study. As found by Nawrot et al. (2008) for European larch, the proportions of heartwood on stem disc samples was found to decrease with an increase in stem height, whereas the proportions of sapwood increased. Heartwood is drier than sapwood, due to ceasing in its function to conducting water (Bowyer *et al.,* 2007). In addition, as stem disc samples were taken at one metre intervals along stem sections, they get smaller with increasing height. Discs taken from higher positions in stem sections are located closer to the apical meristem and crowns. This may have resulted in the discs from these higher positions in stems to possess more juvenile wood than adult wood. As juvenile wood is characteristic of having more earlywood than latewood and more lumen space than adult wood (Larson *et al.,* 2001, MacDonald and Hubert, 2002), this may also possibly explain why moisture content increases with stem height. However, juvenile wood in Norway spruce and Sitka spruce is typically denser than adultwood (Ní Dhubháin *et al.,* 2006, Jyske *et al.,* 2008). As a result, the increase of moisture content with stem height as a function of juvenile wood and lumen space may not apply in the case of Norway spruce and Sitka spruce.

With the exception of lodgepole pine, regression equations to determine mean stem wood moisture content had strong correlations. Potential multicollinearity with predictor variables was investigated for lodgepole pine. However, variance inflation factors added into the analysis were below the threshold indicator value for multicollinearity (< 10). The shortcomings in predicting mean moisture content for lodgepole pine may also be due to the selection of sample points. The moisture content samples chosen for this analysis were selected from the base, the midpoint and 80% of relative height. In the case of lodgepole pine, intermediately positioned sample points may prove more effective in predicting mean stem wood moisture content. The effects of using a mean weighted to disc volume and/or basal area may offer a solution to the problem with predicting mean stem wood moisture content for lodgepole pine. In general, such an approach can also formally identify what sample points yield the strongest coefficient of determination for mean stem wood moisture content for all the six species. For example, Clark and Daniels found that log large end diameter had a significant correlation to the weighted average moisture content for whole stem length logs.

Omitting lodgepole pine, 63-77% of variation could be explained using one sample point to determine mean moisture content for the other five species. Using two sample points to determine mean stem wood moisture content, the coefficients of determination for alder and birch reduced by 1 and increased by 3 percentage points. The coefficient of determination for ash, Norway spruce and Sitka spruce increased by 21, 16 and 16 percentage points. When three sample points were used to determine mean stem wood moisture content, ash had no increase in the coefficient of determination, whereas alder, birch, Norway spruce and Sitka spruce showed increases of 10, two, eight and seven percentage points respectively. Despite the successful determination of moisture content using less sample points, to verify the integrity of these regression equations, a labour intensive destructive sampling regime in the field would be required in order to do so. However, others have attempted sampling regimes to determine moisture content destructively in an industrial setting, in addition to sampling moisture content in a non-destructive manner. Clark and Daniels (2000) made recommendations as to how many sample points were required for the prediction of whole stem length round wood moisture content entering a weigh bridge. These recommendations included taking three core samples of chip from three whole stem length logs to determine the moisture content and oven dry tonnes of truckloads entering pulp mills. Purser (2000) illustrated appropriate sampling methods for the estimation of dry tonnes from pulp truckloads for the determination of moisture content and dry weight:fresh weight ratios. Dunnett (2012) successfully determined that one moisture content sample taken from round wood assortments at the mid-point is adequate to describe average round wood moisture content in a non-destructive manner using electrical resistance probed moisture meters. As non-destructive methods in the determination of moisture content have proven to compare favourably with the destructive method of oven drying (EN-14774-2, 2010, Mora *et al.,* 2011, Samuelsson *et al.*, 2006), non-destructive sampling techniques may have application in field based studies to determine stem wood moisture content. However, Dunnett (2012) highlighted that electrical resistance probe moisture meters are easily broken with regular use and lack resiliency. The use of near infrared spectroscopy technology in the prediction of moisture content has also proved to be promising (Mora *et al.*, 2011), but would require freshly cut stem discs for analysis. Testing non-destructive sampling regimes to determine moisture content in the field would however still require for destructive sampling to verify the validity of non-destructive methods.

2.12. Summary of moisture content

Comprehensive data on moisture content have been accumulated in this study. It is a variable characteristic; as it ranged from 38-65% between the six species in stem sections and 44-54% in branch sections. These six species represent 76% of the Irish forestry estate. Therefore parameter values ascertained from this study account for a large proportion of the commercial species grown under Irish conditions, albeit specific to a narrow range of ages (12-17 years old) and sizes of trees sampled. In all three regions, distinguishable spatiotemporal changes in stem wood moisture content were found only with ash. Ash stem wood moisture content was lower during dormancy and higher during flushing and the growing season. For the most part, moisture content in branch sections reduced significantly during flushing and in comparison to dormancy. Overall, the dataset accumulated in this study indicated that spring and summer (March-August) are the most suitable times of year for harvesting and seasoning wood for fuel, whereas autumn and winter (September-February) are less suitable. However, the optimisation of seasoning is also dependent on the length of time to reach the target moisture content specific to end user requirements, and where seasoning takes place. Sampling regimes using less sample points for the most part proved successful for determining mean stem wood moisture content. However, further work will be required to verify the integrity of the regression equations constructed.

3. CHAPTER 3 - AN INVESTIGATION INTO THE SPATIAL VARIATION OF STEM WOOD BASIC DENSITY DERIVED FROM FIRST THINNINGS

3.1. Definition of basic density

The methods for expressing dry matter in the total absence of water are desirable for estimating the energy content of wood. Basic density is expressed as the ratio of the oven dry weight of wood to its green volume, expressed as $g{\cdot}cm^{-3}$, $kg{\cdot}m^{-3}$ or $t{\cdot}m^{-3}$ (Bowyer *et al.,* 2007, Brown, 1997, Moore, 2011). Basic density of stem wood is calculated using Equation 3.1. (Moore, 2011).

$$\mathrm{BD} = \frac{\mathrm{DW}}{\mathrm{V}} \tag{3.1.}$$

Where BD = Basic density in $kg{\cdot}m^{-3}$

DW = Oven dry weight of sample (kg)

V = Fresh volume of sample (underbark or overbark) (m^3)

Oven dry in definition assumes that all free and bound moisture has been removed from cell lumens and cell walls (Bowyer *et al.,* 2007, Hoadley, 1990, Williamson and Wiemann, 2010). Thus, the method of oven drying is analogous to the procedures for the determination of moisture content (see Chapter 2, Section 2.1.). Alternative expressions include specific gravity. Specific gravity (SG) is the expression of the oven dry mass of wood to the density of pure water (1 $g{\cdot}cm^{-3}$, or 1000 $kg{\cdot}m^{-3}$) at 4^{o}C, expressed as $g{\cdot}cm^{-3}$ (Bowyer *et al.*, 2007, Briggs, 1994, Hoadley, 1990, Moore 2011, Williamson and Wiemann, 2010). The expressions used for specific gravity and basic density are interchangeable (Bowyer *et al.,* 2007).

The determination of sample volume for estimating density can be done in a number of ways. One such method is the volumetric procedure. Using 25-30 mm stem wood discs, green volume is determined with callipers to take diameter and thickness measurements (Aosaar *et al.*, 2011, Bowyer *et al.*, 2007, Brown, 1997, Snowdon *et al.*, 2002, Treacy *et al.*, 2000, West, 2004, Williamson and Wiemann, 2010). Basic density is then derived from the sample dry weight as a proportion of its green volume. Green volume is expressed on an over bark or under bark basis depending on the dimensions taken to estimate volume before oven drying (Picard *et al.*, 2012, Snowdon *et al.*, 2002). The volumetric procedure for basic density complements sub sampling regimes for moisture content, as discs are also used for the latter's determination.

3.2. Effects of basic density on wood fuel supply chains

In relation to wood fuel supply chains, the primary effects of wood basic density are on the energy yielded per unit volume (m^3). In general, tree species do not differ greatly in their energy content on an oven dry basis per unit mass. However, as hardwood species are typically denser than softwood species, they possess more energy content per unit volume due to a greater proportion of dry matter (Kofman, 2006a, Rolls, 2009, Roser *et al.*, 2008). Thus, more energy can be delivered using a smaller amount of material with more dense fuels as opposed to less dense fuels (Loibneggar, 2011). Basic density also affects the bulk density of fuel products such as wood chips.

Bulk density is a parameter that describes the proportion of mass per unit of a container volume under specific conditions, expressed as $kg{\cdot}m^{-3}$ loose volume, accounting also for air spaces (Equation 3.2.) (EN-14588, 2010, EN-15103, 2009).

$$BD_{ar}\,(M_{ar}) = \frac{(m_2 - m_1)}{V} \qquad (3.2.)$$

Where D_{ar} (at M_{ar}) = Bulk density as received to the nearest 0.1 $kg{\cdot}m^{-3}$ loose

M_{ar} = Moisture content as received at the time of measurement on a wet weight basis (%)

m_2 = Mass of filled container (kg)

m_1 = Mass of empty container (kg)

V = Net volume of container (m^3)

Furthermore, this definition pertains to bulk density as received, noting the influence of moisture content and demonstrated in Figure 3.2.1.

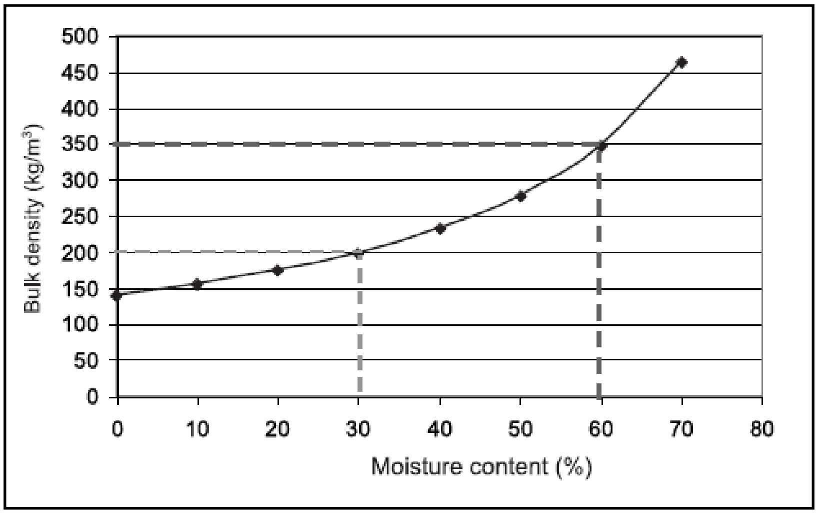

Figure 3.2.1. The relationship between moisture content and bulk density of Sitka spruce whole tree chip (Kofman and Kent, 2007).

Bulk density as received also has an influence upon the energy density of wood fuel, defined by Hakkila (2004) as the energy yielded per unit volume of truck loads and wood chip piles. Energy density as received is calculated using Equation 3.3. (Alakangas, 2005, EN-14961-1, 2010).

$$E_{ar} = \frac{1}{3600} \times q_{p,net,ar} \times BD_{ar} \qquad (3.3.)$$

Where E_{ar} = Energy density of the biofuel as received reported to the nearest 0.01 $MWh{\cdot}m^{-3}$

$q_{p,net,ar}$ = Net calorific value as received ($MJ{\cdot}kg^{-1}$) based on measured values or estimates

BD_{ar} = Bulk density as received ($kg{\cdot}m^{-3}$ loose) based on measured values or estimates

$^1/_{3600}$ = Conversion factor for energy units (MJ to MWh)

As a practicality, Kofman and Kent (2007) highlighted the importance of moisture content's effect on bulk density. Bulk densities in the upper range of Figure 3.2.1 (350 $kg{\cdot}m^{-3}$ at 60% moisture content) can compromise the weight limit of trucks with 100 m^3 containers. If moisture content were at the lower range of 30% and 200 $kg{\cdot}m^{-3}$ bulk density, a full truck load can be carried and also reduces fuel consumption (Kofman and Kent, 2007, Sikanen, 2010). Discounting moisture content completely, the bulk density on a dry basis is another expression used in order to calculate the energy content of delivered wood chip fuel (Hakkila, 2004). Bulk density on a dry basis is calculated using Equation 3.4. (EN-15103, 2009).

$$BD_d = BD_{ar} \text{ x } \frac{(100 - MC_{ar})}{100} \qquad (3.4.)$$

Where BD_d = Bulk density on a dry basis ($kg{\cdot}m^{-3}$)

BD_{ar} = Bulk density as received ($kg{\cdot}m^{-3}$)

MC_{ar} = Moisture content as received at the time of measurement (%)

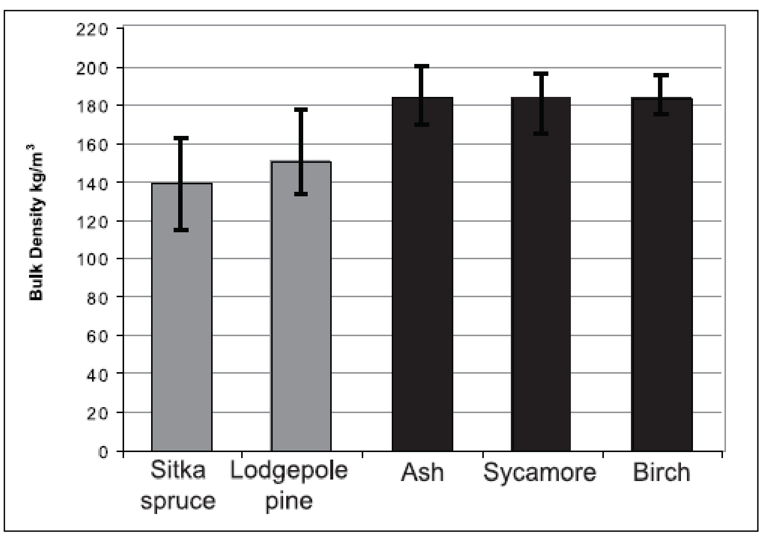

Figure 3.2.2. Mean dry bulk densities (bar indicates range) for different tree species studied on the Forest Energy Programme (Kofman and Kent, 2007).

Figure 3.2.2. demonstrates that hardwoods have a higher bulk density on an oven dry basis. Thus, broadleaf tree species possess a greater amount of energy content per unit volume than conifer species. However, as bulk density is a function of a tree species basic density, there are many variation sources that confound analysis into this wood fuel quality parameter.

3.3. Basic density variation

Ward and Gardiner (1976) summarised the variation encountered with wood basic density: *'Density is not a simple characteristic of wood, it is complex of the effect of several growth and physiological variables compounded into one fairly easily measured wood characteristic'.* Density in cell wall structures for all species is constant at approximately 1520 kg·m^{-3} (Bowyer *et al.,* 2007). Density is influenced by void volume. Void volume is defined as the proportion of cell wall substance to cell lumens (Bowyer *et al.,* 2007). Thus, as cell wall thickness increases and lumen volume decreases, the density of wood increases (Pinchot, 2005, Wiedenhoelt, 2010).

Basic density has numerous variation sources. These variation sources include species, climatic effects on radial growth, presence of reaction wood, proportions of juvenile and adult wood, ratios of earlywood and latewood, between tree components, within stems, silvicultural practices and genetic sources (Bowyer *et al.,* 2007, Gardiner, 2011, Josza and Middleton, 1994, Jyske *et al.,* 2008, Kellomaki, 1979, Moore, 2011, Pinchot, 2005, Premyslovska *et al.,* 2007, Repola, 2006, Singh, 1984, Treacy *et al.,* 2000, Wiedenhoelt, 2010). In their study of basic density differences within Norway spruce stems, Jyske et al. (2008) found that basic density variation is caused by the following: between annual rings (11-27%), different heights in the stem (3-6%) and within annual rings (49-80%). The differences between and within annual growth rings are reflective of climatic variables and the allocation of photosynthates over the growing season that affect the timing of earlywood and latewood development. Thus, it has been found that accumulated temperatures, day length, drought periods and precipitation at various longitudes and latitudes between and within forest biomes are factors that affect basic density (Aosaar *et al.,* 2011, Bowyer *et al.,* 2007, Gardiner, 2011, Kellomaki, 1979, Kern *et al.,* 2012, Moore, 2011, Premyslovska *et al.,* 2007, Punches, 2004, Wiemann and Williamson, 2002). Latewood is generally denser than earlywood due to having thicker cell walls (Gryc *et al.,* 2011, Pinchot, 2005, Rikala, 2003, Wiedenhoelt, 2010). As tree species vary in their proportions of earlywood to latewood (Michalec and Niklasova, 2006), basic density should vary over locations in response to climatic factors as a function of radial growth and species.

Singh (1984) investigated the spatial variation in basic density of various tree species across three locations. Singh found no statistically significant differences with basic density between regions with the species in his study. However Singh did find significant differences with sampling positions. Repola (2006) applied the term vertical dependence for the differences in basic density within stems. Repola's (2006) findings on birch, Norway spruce and Scots pine (*Pinus sylvestris* L.) are illustrated in Figure 3.3.1.

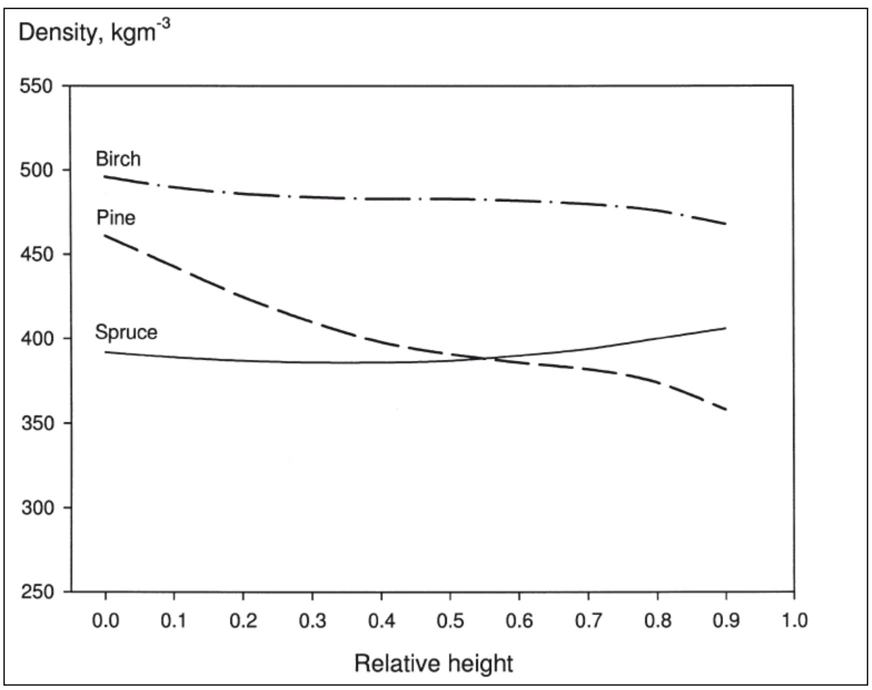

Figure 3.3.1. Vertical dependence of basic density in the stem wood of different tree species in Finland (Repola, 2006).

Repola (2006) found that birch and pine had strong vertical dependence, encountering a downward trend from base to tip. Spruce had a moderate level of vertical dependence in comparison. On the basis of vertical trends in basic density, some authors have attempted to develop means of predicting stem basic density using fewer samples than those originally taken, with mixed success. Singh (1984) successfully constructed single linear regression equations using discs derived from 1.3 m. Aosaar et al. (2011) adopted a similar approach, but failed to find a strong correlation. Rikala (2003) found that 3% of variation could be explained for basic density as a function of relative height sampling positions. Rikala also found that adding mean annual ring width and proportions of latewood as explanatory variables to regression analysis explained 31% of the variation in basic density.

As highlighted for moisture content (Chapter 2, Section 2.3.2), the proportions of sapwood and heartwood at different stem height positions may contribute to variations in moisture content. However, the basic density of sapwood and heartwood are not significantly different. This was confirmed through 500,000 tests for basic density on the heartwood and sapwood of various hardwood and softwood species by the United States Department of Agriculture (USDA, 1936). Instead, differences may be due to juvenile wood and adult wood. Juvenile wood is found at all stem height levels in the core region of trees, and also in crown sections (Larson *et al.*, 2001, MacDonald and Hubert, 2002). The development of cambium layers into adult wood begins at the bottom of stem sections (Punches, 2004). This development progresses upwards in stem sections with new growth increments (Larson *et al.*, 2001, Punches, 2004). The upper crown sections of trees maintain contact with the apical meristem and are characteristic of juvenile wood (Maeglin, 1987). Juvenile wood has low proportions of latewood and more earlywood, short tracheids/fibres/vessels with large lumens, lower densities, higher microfibril angles and poor dimensional stability (Bowyer *et al.*, 2007, Gryc *et al.*, 2011, Larson *et al.*, 2001, MacDonald and Hubert, 2002, Maeglin, 1987, Moore, 2011). The transition between juvenile and adult wood is species dependent, typically the first 5-25 growth rings (Bowyer *et al.*, 2007). As they vary in their quantities of earlywood and latewood, the transition of juvenile to adult wood will thus confound attempts to establish vertical dependence trends of basic density. This was confirmed by Jyske et al. (2008), who established that only 3-6% of the variation in basic density can be attributed to stem position differences, requiring more in depth analysis of growth rings.

In Ireland, investigations into basic density have concentrated on Sitka spruce with specific aims and objectives. Investigations included the effects of different tree spacing upon wood density (Gardiner and O'Sullivan, 1978, Javadi, *et al.*, 1983, Ward and Gardiner, 1976). Other investigations included an evaluation of genetic variation in relation to the physical and mechanical properties of Sitka spruce that included basic density (Treacy *et al.*, 2000). Two studies into carbon repositories and biomass allocations of Sitka spruce have been conducted, that included measuring for basic density (Green *et al.*, 2007, Tobin and Nieuwenhuis, 2007). Green et al. (2007) established a basic density of 0.38 $t{\cdot}m^{-3}$ for the purpose of converting standing volume to biomass in an unthinned Sitka spruce stand. Tobin and Nieuwenhuis (2007) ascertained basic densities in their assessment of carbon repositories within a Sitka spruce chronosequence over the course of a typical commercial rotation. The authors found that basic density declined with age. Mean basic density and standard deviations ascertained in their study included 475 ± 17.1 $kg{\cdot}m^{-3}$ at age nine, 375.3 ± 43.3 $kg{\cdot}m^{-3}$ at age 14, 389.3 ± 40.8 $kg{\cdot}m^{-3}$ at age 28, 378.5 ± 57.2 $kg{\cdot}m^{-3}$ at age 30, and 365.2 ± 19.25 $kg{\cdot}m^{-3}$ at age 45. Ní Dhubháin et al. (2006) investigated the impact of rotation length on the juvenile wood of Sitka spruce. The authors found juvenile wood in Sitka spruce was denser than adult wood. Basic density was also found to gradually reduce outwards from the pith to the adult wood zone. The transition of juvenile wood to adult wood was calculated at ring 14 where the lowest basic density value was calculated (Ní Dhubháin *et al.*, 2006). With a lengthening of rotation, the authors established that juvenile wood percentage lowers from 30.3% at age 30 to 13.7% at age 46. This also explains the decline of basic density in Sitka spruce as a function of increasing age by Tobin and Nieuwenhuis (2007).

3.4. Methodology for the determination of basic density

3.4.1. Field work

For an overview of the field work, please refer to Chapter Two, Section 2.4.1.

3.4.2. Basic density analysis of stem discs

After completion of field work, subsamples were taken back to the lab. Discs were measured for volume using callipers. Diameter and thickness measurements of disc samples were used to estimate volume (Brown, 1997, Snowden *et al.*, 2002, Treacy *et al.*, 2000, West, 2004). Disc samples were then oven dried for 48-72 hours at 105^{o}C in accordance with the simplified procedure for determining moisture content (EN-14774-2, 2010). Basic density was calculated using Equation 3.1. (Moore, 2011).

$$BD = \frac{DW}{V} \tag{3.1.}$$

Where BD = Basic density in $kg \cdot m^{-3}$

ODW = Oven dry weight of sample (kg)

V = Fresh volume of sample discs (m^3)

3.4.3. Statistical analysis of basic density

Initial data entry was conducted using the Microsoft® Excel 2007 spreadsheet package. Statistical analysis was conducted using the Minitab® 16 statistical software. The scale of data was nominal, in terms of the species, partitions, locations and sampling period. The data scale was also continuous. For each species, region and sampling period, descriptive summary statistics of basic density were compiled. One way analysis of variance (ANOVA) tests were conducted to determine the significance of spatial differences with basic density for the six species. The null hypothesis was that no statistically significant spatial differences occurred ($p \geq 0.05$). The alternative hypothesis was that statistically significant spatial differences occurred ($p \leq 0.05$). Tukey's pair wise simultaneous confidence interval tests were used when the null hypothesis was rejected ($p \leq 0.05$).

3.4.3.1. Prediction equations to determine stem wood basic density

Single linear and multiple regression equations were constructed in order to estimate arithmetic mean stem wood basic density using fewer samples than those originally taken. The samples chosen to construct the regression equations were the basic density values recorded from the base, mid-point and top section of sample stems (0%, 50% and 80% of relative height). The regression models are illustrated in Equations 3.5.-3.7.

$$Y = a + b\,(X) \qquad (3.5.)$$

Y = Mean stem wood basic density (kg·m^{-3})

a = Intercept

b = Slope coefficient

X = Basic density values recorded at the base of the stem (kg·m^{-3})

$$Y = a + b\,(X_1) + c\,(X_2) \qquad (3.6.)$$

Y = Mean stem wood basic density (kg·m^{-3})

a = Intercept

b and c = Slope coefficients

X_1 = Basic density values recorded at the base of the stem (kg·m^{-3})

X_2 = Basic density values recorded at the mid - point of the stem (kg·m^{-3})

$$Y = a + b\,(X_1) + c\,(X_2) + d\,(X_3) \qquad (3.7.)$$

Y = Mean stem wood moisture content (kg·m^{-3})

a = Intercept

b, c and d = Slope coefficients

X_1 = Basic density values recorded at the base of the stem (kg·m^{-3})

X_2 = Basic density values recorded at the mid - point of the stem (kg·m^{-3})

X_3 = Basic density values recorded at 80% of relative height (kg·m^{-3})

3.5. Basic density results and discussion

Table 3.5.1. Descriptive summary statistics of the basic density of the whole stem. Identical letters following the mean value indicates that no statistically significant differences occurred between species ($p \geq 0.05$). Different letters indicate that a statistically significant difference occurred between species ($p \leq 0.05$).

Basic Density of the Whole Stem ($kg \cdot m^{-3}$)							
Species	**Number of subsamples**	**Mean**	**Standard Error**	**Standard Deviation**	**Coefficient of Variation**	**Minimum**	**Maximum**
Alder	385	390.4 a	2.4	47.3	12.1	234.5	536.1
Ash	346	498.1 b	3.9	73.4	14.7	281.1	862.4
Birch	327	484.5 c	2.8	51.0	10.5	245.8	663.2
Lodgepole pine	368	376.7 d	2.1	41.7	11.1	266.3	501.5
Norway spruce	513	344.2 e	1.7	39.7	11.5	226.1	537.3
Sitka spruce	482	371.8 d	2.1	47.4	12.7	241.3	563.2

3.5.1. Basic density summary

Ash had the highest basic density at 498 $kg \cdot m^{-3}$, followed by birch (485 $kg \cdot m^{-3}$), alder (390 $kg \cdot m^{3}$), lodgepole pine (377 $kg \cdot m^{-3}$), Sitka spruce (372 $kg \cdot m^{-3}$), and Norway spruce being the least dense (344 $kg \cdot m^{-3}$). Only lodgepole pine and Sitka spruce showed no statistically significant difference between mean basic densities ($p \geq 0.05$). The higher density of ash in comparison to the other species is possibly due to being a ring porous species characteristic of possessing more latewood on annual growth rings (Michalec and Niklasova, 2006). Latewood possesses fewer, larger and narrower vessels. Latewood is also a product of the allocation of photosynthates to cell wall layers in the latter part of the growing season, thus leading to thicker cell walls (Bowyer *et al.,* 2007, Wiedenhoelt, 2010). Thicker cell wall layers leads to smaller proportions of void volume and give rise to higher basic densities in latewood as found by others (Gryc *et al.,* 2011, Pinchot, 2005, Rikala, 2003). Alder and birch are diffuse porous tree species that possess more earlywood than latewood (Michalec and Niklasova, 2006). Earlywood is less dense than latewood. Therefore, this would contribute to the lower basic densities of alder and birch in comparison to ash. This may also be the case with coniferous species, as research in Britain has found that Sitka spruce is subject to fluctuations in earlywood development over the course of the growing season due to climatic variables, whereas latewood development is not subject to climatic influences (Gardiner, 2011, Moore, 2011).

Standard errors ranged between 2 and 4 kg·m^{-3}. Basic density had high standard deviations and coefficients of variation for all species ranging between ± 40-73 kg·m^{-3} and 11-15% respectively. When comparing figures derived from this study to those cited from other sources, there are a number of factors to take into account. Williamson and Wiemann (2010) warned that one should be aware of the methodology employed to determine basic density, the definitions used, and from where samples are taken. The most recurrent problem highlighted by Williamson and Wiemann (2010) are the incorrect definitions of wood on an oven dry basis. Williamson and Wiemann (2010) found that some authors oven dry samples to 70^{o}C, which is not oven dry in definition. Oven dry wood is when all free and bound moisture has been removed by oven drying wood at 105^{o}C for 24-72 hours (Bowyer *et al.,* 2007, Briggs, 1994, Williamson and Wiemann, 2010). The samples used in this study to calculate basic density conformed to this definition. Another issue cited by Williamson and Wiemann was that some authors do not state the specific methodology they employed to calculate basic density.

Tobin and Nieuwenhuis (2007) found similar basic densities (expressed on an oven dry basis per unit green volume from stem discs) and standard deviations for Sitka spruce to the figures in this study. The most relevant values from Tobin and Nieuwenhuis' study were a 14 year old stand with a value of 375.3 ± 43.3 kg·m^{-3}. The overall mean for Sitka spruce in this study was 371.8 ± 47.4 kg·m^{-3} (between the ages of 16-17). In addition, when the mean basic density for Sitka spruce is converted to t·m^{-3}, the 0.37 t·m^{-3} ascertained in this study compares with the 0.38 t·m^{-3} found by Green et al. (2007) for an unthinned 19 year old stand of Sitka spruce. However, Green et al. (2007) dried core samples to 70^{o}C. This may lead to potential differences in the basic density estimation, as Green et al. (2007) may have derived a different estimate for basic density had they dried samples to 105^{o}C. Lodgepole pine specific gravities sourced from America ranged between 0.38-0.43 g·cm^{-3} or 380-430 kg·m^{-3} (Alden, 1997, Zischke, 1956), and compares with the mean and standard deviation of this study (377 ± 41.7 kg·m^{-3}). However, the lodgepole pine figures quoted do not elaborate upon where they have been derived and the methodologies employed to determine basic density. Goff et al. (2004) found specific gravities ranging between 0.551-0.606 g·cm^{-3} or 551-606 kg·m^{-3} from a 34 year old stand of ash in North Eastern France. These figures are higher than the basic density derived for ash in this study (498.1 kg·m^{-3}). The difference is may be due to Goff et al. (2004) sampling older material that was more developmentally mature in terms of adult wood and latewood development. The study by Goff et al. (2004) is an example of the prudence that must be paid to quoting basic density figures from elsewhere, as the authors did not state to what temperatures wood samples were oven dried to. Kiaei and Samariha (2011) ascertained oven dry basic densities for alder and ash, by oven drying samples at 105^{o}C. The authors found average basic densities of 490 kg·m^{-3} for alder, and 654 kg·m^{-3} for ash. These estimates are higher than those found in this study (390.4 kg·m^{-3} and 498.1 kg·m^{-3}). However, Kiaei and Samariha (2011) sampled more developmentally mature material that ranged between the ages of 40-46 years old. Johansson (2005) quoted an average basic density of 427 kg·m^{-3} for alder in Sweden, in line with the appropriate oven drying methodology, albeit on an underbark basis. In addition, Johansson sampled from an older age class of material than this study (48 years on average ranging from 22-92 years). Hakkila (2004) quoted typical basic densities on an oven dry basis of small sized birch in Finland to be between 450-500 kg·m^{-3}. This range compares with the basic density derived for birch in this study (484.5 kg·m^{-3}). For Norway spruce, Rikala (2003) found an average basic density of 379.0 ± 33.9 kg·m^{-3} on an oven dry basis, derived from ten stands ranging between 61-128 years of age in Finland. However, despite the age ranges, Rikala’s figures compare with the 344.1 ± 39.6 kg·m^{-3} for Norway spruce ascertained in this study on the basis of the large standard deviation.

3.5.2. Spatial variation of basic density

Table 3.5.2. Spatial variation of basic density. Identical letters in black indicate that no statistically significant differences occurred within rows ($p \geq 0.05$). Different letters in black indicate that statistically significant differences occurred within rows ($p \leq 0.05$). Identical letters in red indicate that no statistically significant differences occurred between species ($p \geq 0.05$). Different letters in red indicate that statistically significant differences occurred between species ($p \leq 0.05$).

Spatial Variation of Basic Density (kg·m^{-3})

Species	South East	Midlands	North West
Alder	412.4 a a	407.4 a a	351.5 b bd
Ash	543.5 a b	480.2 b b	463.9 b a
Birch	512.9 a c	484.6 b b	461.4 c a
Lodgepole pine	384.0 a d	377.5 ab c	367.5 b b
Norway spruce	363.3 a e	348.3 b d	322.2 c c
Sitka spruce	381.6 a d	375.0 a c	351.0 b d

3.5.3. Spatial trends in basic density

Three species (alder, ash, Sitka spruce) had no statistically significant differences in mean basic density between the South East and Midlands. Lodgepole pine basic density in the Midlands was not statistically different from the South East or North West. Birch and Norway spruce had statistically significant differences in all regions. Lodgepole pine and Sitka spruce did not vary significantly in basic density between each other in the Midlands and North West. Ash and birch did not vary between each other in the Midlands and North West. Alder did not vary between lodgepole pine and Sitka spruce in the North West.

The most distinguishable spatial trend for all species was the decrease of density with increasing latitude. These results are concurrent with those found by Bryan and Pearson (1955) in the UK for Sitka spruce cited by Moore (2011). Bryan and Pearson (1955) found that density decreased by 10 kg·m^{-3} with every one degree increase in latitude. Also cited by Moore (2011), Jeffers and Dowden (1964) found a decrease of 6 kg·m^{-3} in Sitka spruce with every one degree increase in latitude from 34 sites sampled in the UK. The effects of latitude on basic density have been identified by other authors to be a function of mean annual temperatures and precipitation.

Wiemann and Williamson (2002) investigated wood specific gravity of broadleaf species in tropical and temperate forest biomes. The authors found an increase in specific gravity with decreasing latitude due to increases in mean annual temperatures. The authors also found a decrease of specific gravity within areas of higher precipitation than areas of lower precipitation within the two biomes studied. Aosaar et al. (2011) found that grey alder (*Alnus incana* (L.) Moench), and hybrid alder (*Alnus hybrida* A. Br.) wood basic density increased in Nordic regions at more southerly latitudes with a corresponding increase in annual temperatures. Premyslovska et al. (2007) confirmed that increases in accumulated temperatures during the latter parts of the growing season leads to extended latewood development and a higher overall basic density from data collected in the Czech Republic.

Analysis of weather patterns over the course of this study found equitable temperatures in all regions based on the annual average and the 30 year average (10^{o}C) (see Chapter two, Table 2.4.2). Rather than temperature in this study, precipitation may possibly better explain the latitudinal reductions in basic density, concurrent with Wiemann and Williamson (2002). The North West region, where basic density was lowest for all species, experiences a higher amount of annual precipitation than the other two study regions. Higher precipitation in western areas as opposed to eastern areas of Britain was found by Gardiner (2011) to increase earlywood growth in Sitka spruce. Moore (2011) outlined that the effects of increased radial growth in Sitka spruce leads to an increase in the allocation of earlywood to annual growth rings, whereas latewood formation is normally constant in its development and is not influenced by climatic variables. Thus, this increase in earlywood allocation would affect overall basic density, possibly explaining why basic density decreased in the North West due to higher precipitation for the six species. Climatic effects as an indicator of the differences in basic density between the six species in this study may not be sufficient. As the sources of variation in wood basic density are innumerable, more sophisticated analysis of the deeper anatomy of wood (e.g. radial growth and maturity status in development) would be a requirement to find specific answers, whilst also paying cognisance towards other factors that can influence variations in basic density (e.g. silvicultural factors).

3.5.4. Vertical dependence of stem wood basic density

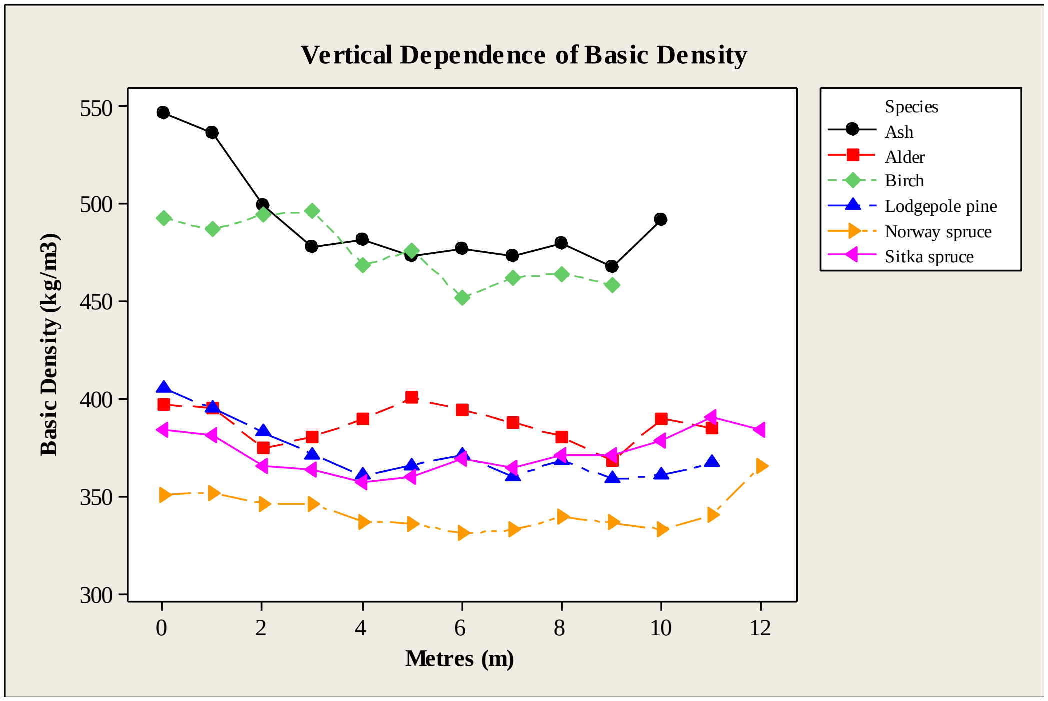

Figure 3.5.1. Vertical dependence of stem wood basic density.

Table 3.5.3. Regression equations using one basic density sample taken from the base of the stem to determine mean stem wood basic density.

Species	Intercept (a)	b	R^2	Standard Error
Alder	187.7	0.5	0.60	24.7
Ash	225.8	0.5	0.59	0.8
Birch	250.5	0.5	0.61	23.9
Lodgepole pine	176.0	0.5	0.63	17.5
Norway spruce	202.9	0.4	0.55	17.8
Sitka spruce	180.5	0.5	0.67	19.6

Table 3.5.4. Regression equations using two basic density samples taken at the base and mid - point to determine mean stem wood basic density.

Species	Intercept (a)	b	c	Adjusted R^2	Standard Error
Alder	100.3	0.4	0.4	0.74	19.9
Ash	86.7	0.4	0.4	0.82	21.6
Birch	122.8	0.4	0.3	0.75	19.1
Lodgepole pine	59.5	0.4	0.4	0.80	13.0
Norway spruce	124.2	0.3	0.4	0.69	14.6
Sitka spruce	120.1	0.4	0.3	0.75	17.1

Table 3.5.5. Regression equations using three basic density samples taken at the base, mid - point and 80% of relative height to determine mean stem wood basic density.

Species	Intercept (a)	b	c	d	Adjusted R^2	Standard Error
Alder	82.2	0.2	0.2	0.4	0.88	13.5
Ash	45.8	0.4	0.3	0.2	0.92	15.2
Birch	123.0	0.3	0.2	0.2	0.86	14.6
Lodgepole pine	-13.8	0.3	0.3	0.4	0.90	8.8
Norway spruce	80.6	0.2	0.3	0.2	0.79	11.9
Sitka spruce	75.7	0.3	0.3	0.2	0.84	13.5

3.5.5. Vertical dependence trends of stem wood basic density

Ash and birch demonstrated vertical dependence, reducing in basic density with an increase in stem height. The trend in birch is concurrent with Repola's (2006) findings on the decline in basic density with increasing tree height. Alder and the three conifer species had moderate fluctuations. Repola (2006) also found moderate vertical dependence with Norway spruce. Rikala (2003) found that basic density remained constant for Norway spruce up until samples reached a relative height of 75%, and encountered an increase in density after this height position. Regression equations using less sample points than those originally taken were successful. When more sample points were added, there was an increase in the coefficient of determination. However, standard error estimates in the prediction of mean basic density were high in the majority of equations (1-25%). Another disadvantage of these regression equations is the requirement for destructive sampling to verify their utility. Other authors have found mixed success in using predictive regression equations in the determination of mean stem basic density. Singh (1984) successfully constructed regression equations using less sample points than those originally taken. Singh used discs sampled from 1.3 m in his regression equations to determine mean stem wood basic density. Aosaar et al. (2011) failed to find correlations when attempting to construct predictive regression equations. Jyske et al. (2008) found that 3-6% of the variation in basic density is explained by the height where samples are taken, whereas the remainder of variation was attributed to between (11-27%) and within (49-80%) annual growth rings. Rikala (2003) found that 3% of the variance could be explained for basic density as a function of relative height sampling position. Rikala also found that adding mean annual ring width and proportions of latewood as explanatory variables to regression analysis explained 31% of the variation in basic density. Cruzado and Soalleiro (2011) determined that mean stem wood basic density could be determined from samples taken at 30-35% of height, due to the greater weighting effect of sample discs from the lower section of sample stems. As discussed for moisture content (see Chapter 2, Section 2.11.1), calculating the weighted mean stem wood basic density may lead to determining the optimum locations and frequency of stem discs to be sampled. Analogous to the spatial trends with basic density, more sophisticated anatomical analysis of annual growth rings would be required to truly ascertain why variation occurs within stems.

3.6. Summary of basic density

Analogous to moisture content, basic density is a highly variable wood fuel property. Basic densities ranged from 344-498 kg·m^{-3} for the six species in this study, representing 76% of the Irish forestry estate, albeit restricted to narrow range of ages (12-17 years old). Basic density for all species reduced with increase in latitude, postulated to be due to increased rainfall in the North West region in comparison to the South East and Midlands. Reduced sampling regimes to determine mean stem basic density using fewer samples than those originally taken proved successful, although high standard errors were recorded.

4. CHAPTER 4 - QUANTIFICATION AND ESTIMATION OF TOTAL ABOVE GROUND BIOMASS AND ENERGY CONTENT FROM FIRST THINNINGS

4.1. Overview of biomass estimation

Quantifying oven dry biomass provides a means to ascertain the energy content of wood. However, the estimation of biomass is not exclusive to research into the use of wood for energy. As wood's elemental composition is generally 50% carbon, investigations into the cycle of carbon in forest ecosystems have been conducted worldwide in order to quantify the sink and reservoir capacities of forests (Briggs, 1994, Brown, 1997, Brown, 2002, FAO, 2000). Biomass is also measured in situations where wood is sold on a per weight basis. Wood products sold on a weight basis include pulpwood, firewood and short rotation coppice for energy (West, 2004). Various methods are employed to quantify forest biomass.

The conversion of standing merchantable volume from inventory data, based upon merchantable stem wood volumes to a specified top diameter (7 cm), provides a baseline to estimating biomass and also to account for components (branches, foliage, stumps) that are not easily measured, or have not been measured to any extent in the past (Albrekston, 1980, Brown, 1997, Brown, 2002, Edwards and Christie, 1981, Miao and Li, 2007, Repola, 2008, Repola, 2009, West, 2004). Stand volume data are widely available worldwide, due to facilitating commercial forestry remits that are based upon purchasing round wood on the basis of size rather than mass (Miao and Li, 2007, West, 2004). However, despite the practical application of converting standing volume to biomass, there are shortcomings to this procedure. Volume inventories typically only account for the measurement of trees suitable for round wood processing, and usually do not account for trees below commercial sizes (e.g. trees ≤ 7 cm) (Black *et al.*, 2004, Miao and Li, 2007). Investigations into the biomass and carbon concentrations of small sized trees have been conducted by a number of authors (Neumann and Jandl, 2005, Peichl and Altaf Arain, 2007, Peichl *et al.*, 2012, Tobin and Green, 2006, Tobin and Nieuwenhuis, 2007). This has particular relevance to Ireland, due to a significant land bank that contains trees below commercial sizes (Tobin and Green, 2006). The methods used in the conversion of standing volume per unit area to biomass per unit area include biomass expansion factors (BEFs) and allometric regression equations. The preferred method depends on the type of information collected in national forest inventories (Brown, 1997, Brown, 2002, Levy *et al.*, 2004, Snowdon *et al.*, 2002, Zianis and Mencuccini, 2004). BEFs are defined as the ratio of biomass components to the oven dry biomass of merchantable stems recorded from standard inventory procedures (Equation 4.1.) (Brown, 1997). However the expression of BEFs can vary from study to study and cognisance should be paid to what components authors have included to construct BEFs.

$$\text{Total AGB}\cdot\text{ha}^{-1} = \text{Vol}\cdot\text{ha}^{-1} * \text{BD} * \text{BEF} \quad (4.1.)$$

Where Total AGB·ha^{-1} = Total above ground biomass in oven dry tonnes per hectare (odt·ha^{-1})

Vol·ha^{-1} = Merchantable volume per hectare (m^3)

BD = Basic density (t·m^{-3})

BEF = Biomass Expansion Factor

Caution must be exercised with the utility of BEFs. BEFs are sensitive to species, age, productivity, climatic conditions, locations, diameter size classes and proportions of merchantable stem biomass, in addition to what biomass partitions are included in the expansion factor (Black *et al.*, 2004, Brown, 1997, Brown, 2002, Pajtik *et al.*, 2008, Peichl and Altaf Arain, 2007, Tobin and Nieuwenhuis, 2007, Uri *et al.*, 2012, Zianis *et al.*, 2005). Equation 4.1. also demonstrates an application of wood basic density. As species differ in their basic density, this would require basic density values appropriate to different tree species (Ilic *et al.*, 2000).

Another approach to biomass estimation is the use of allometric regression equations. Allometry is defined as the relationship between one dimension of an organism to its whole (Picard *et al.*, 2012, West, 2004). These equations are typically a function of DBH and/or total height to estimate biomass. Sample trees are typically stratified on the basis of diameter size class or canopy status to construct allometric regression equations (Johansson, 1999, Johansson, 2005). Mean tree methods for the selection of sample trees can also be used (Johansson, 1999). However, mean tree methods in the selection of sample trees are discouraged if the research objectives are to construct allometric regression equations. Stratification of sample trees are necessary for the development of allometric regression equations (Zianis *et al.*, 2005). This approach also avoids potential errors and bias when upscaling biomass estimates to a stand level (Snowdon *et al.*, 2002). In addition to DBH and total height, basic density can also be incorporated into allometric regression equations (Overman *et al.*, 1994). However, DBH alone is preferred for estimating biomass (Liu, 2009). For example, using diameter and total height together can lead to collinearity in the prediction of biomass components. Using diameter alone to predict biomass has proven sufficient, which is more easily measured than total height (Pajtik *et al.*, 2008). On the contrary, Black et al. (2004) determined that the using DBH and total height together to predict biomass leads to a higher coefficient of determination and reduced standard error estimates of trees that were the same DBH. Equations 4.2 and 4.3 are the most common allometric regression equations employed to determine biomass (Uri *et al.*, 2012, West, 2004, Zianis and Mencuccini, 2004).

$$M = aD_{1.3}^{b} \quad (4.2.)$$

$$M = aD_{1.3}^{\ b}\, TH^{c} \quad (4.3.)$$

Where M = Total aboveground biomass (kg)

$D_{1.3}$ = DBH (cm)

TH = Total height (m)

a, b and c = Equation parameters

Both the dependent and independent variables of these allometric regression equations are transformed by logarithms. Logarithms allow for the use of parametric least squares regression (Sprugel, 1983). Other means of regression analysis can also be used, including logarithmic transformations of single and multiple regression equations (M^{c}Carthy and Keogh, 1983, Wharton and Douglas, 1995). Logarithmic transformations are typically applied to linearise the relationships between the dependent and independent variables, and to reduce error variance across observations (Black *et al.,* 2004, Liu, 2009, Sprugel, 1983).

4.1.1. Methods to estimate biomass

The most accurate means of sampling biomass components is through the destructive complete weighing method (FAO, 2009, Liu, 2007, Snowdon *et al.,* 2002, Ximenes *et al.,* 2008). This method is conducted by weighing different tree components in the field, taking a representative subsample, oven drying subsamples at 105^{o}C, and subsequent up scaling to convert total component fresh weight through the use of dry weight:fresh weight ratios to determine total component dry weight (Brown, 1997, Carey, 1980, Chave *et al.,* 2005, Green *et al.,* 2007, Liu, 2009, Liu and Westman, 2009, Matthews and Mackie, 2006, Miksys *et al.,* 2007, Peichl and Altaf Arain, 2007, Repola *et al.,* 2007, Repola, 2008, Repola, 2009, Snowdon *et al.,* 2002, Tobin and Nieuwenhuis, 2007, Ximenes *et al.,* 2008). Dry matter mass provides a baseline to determining carbon concentrations and energy content in wood, and is also a more consistent value than fresh mass. Fresh mass is influenced by moisture content, which is subject to fluctuations due to a number of variation sources including biomass components (West, 2004).

4.1.1.1. Component sampling

In terms of sampling for different biomass components, a number of methods can be used for sampling branches. These methods include sampling at least five branches of nominal top sizes < 10 cm, taken either at random from each whorl, or whorls situated within quartile subdivisions of equal length relative to total height (Brown, 1997, Liu, 2009, Neumann and Jandl, 2005). Live and dead branches are treated separately (Repola *et al.,* 2007). Dead branches constitute those without any living foliage (Carey, 1980, Green *et al.,* 2007). Other options for branch sampling include taking a proportion (5-10%) of the total partition weight (Liu, 2009, Snowdon *et al.,* 2002). Liu and Westman (2009) successfully developed regression equations for branch biomass by recording branch neck diameter and length as predictor variables. The oven drying methodology for the determination of moisture content is used to estimate branch and foliage dry matter (Brown, 1997). Branch wood and foliage are separated and weighed before or after oven drying (Brown, 1997, Liu, 2009, Picard *et al.*, 2012).

Disc samples of 25-30 mm are used in the estimation of stem biomass using dry weight : fresh weight ratios (Brown, 1997, Peichl and Altaf Arain, 2007, Picard *et al.,* 2012, Snowdon *et al.,* 2002). The sampling intensity of stem discs depends upon how much is known about the variation of moisture content and basic density in stems (Cruzado and Soalleiro, 2011, Ilic *et al.*, 2000, Picard *et al.,* 2012, Repola, 2006). If the variation within stems is unknown, a more intensive sampling regime is recommended (Repola, 2006). Repola's (2006) vertical dependence model in determining basic density included sampling stem discs at one metre intervals in sample stems. Cruzado and Soalleiro (2011) sampled stem discs at 0.5 m intervals. The authors determined that mean stem basic density can be explained using only samples derived from 30-35% of the height of shining gum (*Eucalyptus nitens*). Analogous to estimating biomass components, regression equations are also used to predict moisture content and basic density of stem wood. Singh (1984) constructed single linear regression equations of the function Y = a + b (X) for the estimation of average stem wood basic density utilising discs sampled from 1.3 m. In contrast, Aosaar et al. (2011) found no such correlations in their attempt to determine mean stem basic density using fewer samples than those taken in the field. Clark and Daniels (2000) compiled regression equations in their determination of whole stem length moisture content. The authors implemented an intensive sampling regime of discs from stem length round wood and constructed single and multiple regression equations.

Implementing methods that use easily measured parameters to determine other characteristics not so easily measured is the premise behind constructing predictive regression equations for biomass estimation, as biomass sampling is a laborious, time consuming and expensive endeavour (Brown, 1997, Liu, 2009, Miao and Li, 2007, Picard *et al.*, 2012, Repola, 2008, Repola, 2009, Snowdon *et al.,* 2002, West, 2004).

4.2. Methodology to determine biomass

4.2.1. Field work

For an overview of the field work, please refer to Chapter Two, Section 2.4.1.

4.2.2. Lab methodology

After completion of field work, subsamples were taken back to the lab. Disc and branch samples and branches were oven dried for 48-72 hours at 105^{o}C in accordance with the simplified procedure for determining moisture content (EN-14774-2, 2010). Branch wood and foliage were separated after oven drying and weighed separately (Brown, 1997). Dry weight:fresh weight ratios were used for the conversion of the fresh mass to oven dry mass for merchantable stem sections, tops < 7cm, and branch wood during dormancy for the broadleaf species (Equation 4.4). Dry weight:dry weight ratios were calculated for the wood and foliage components after the oven drying of conifer branches for all sampling periods, and broadleaf branches during flushing and the growing season (Equation 4.5.).

$$\mathrm{DM} = \frac{\mathrm{DW}}{\mathrm{FW}} \qquad (4.4.)$$

Where $\mathrm{DM} = \text{Dry weight : fresh weight ratios}$

$\mathrm{DW} = \text{Component dry weight (kg)}$

$\mathrm{FW} = \text{Component fresh weight (kg)}$

$$DM = \frac{CDW}{BDW} \qquad (4.5.)$$

Where DM = Dry weight : dry weight ratios

CDW = Component dry weight (wood or foliage) (kg)

BDW = Branch dry weight (including wood and foliage) (kg)

4.2.3. Statistical analysis of biomass

Initial data entry was conducted using the Microsoft® Excel 2007 spreadsheet package. Statistical analysis was conducted using the Minitab® 16 statistical software. The scale of data was nominal, with reference to the species, partitions, locations and sampling period. The data scale was also continuous due to the random nature of biomass. For each species, region and sampling period, descriptive summary statistics were compiled for fresh and oven dry biomass.

4.2.3.1. Energy content analysis of biomass partitions

The fresh weight of partitions were converted to energy content ($MJ \cdot kg^{-1}$) using moisture content, reference net calorific values (Table 4.2.1), and Equation 4.6. from European solid biofuel Standards (EN-14961-1, 2010). Moisture contents recorded for the mean partition values of the six species was used for this analysis (see Chapter two, Table 2.8.1.). Energy content on an oven dry weight basis was calculated by multiplying the oven dry kilograms of species and partitions by standard reference values (Table 4.2.1).

Table 4.2.1. Reference net calorific values for species and partitions on an oven dry basis (EN-14961-1, 2010).

Species and Study Partitions		
Alder, ash and birch	**Standard Definition**	**Net calorific values ($MJ \cdot kg^{-1}$)***
Merchantable stem and tops < 7 cm	Broadleaf wood	18.9
Live branches and leaves	Broadleaf logging residue	18.7
Lodgepole pine, Norway spruce and Sitka spruce	**Standard Definition**	**Net calorific values ($MJ \cdot kg^{-1}$)***
Merchantable stem and tops < 7 cm	Coniferous wood	19.1
Live branches, needles and dead branches	Conifer logging residue	19.2

* Typical European Standard values.

$$q_{p,net,ar} = q_{p,net,d} \times \left(\frac{100 - MC\%_{wb}}{100}\right) - 0.02443 \times MC\%wb \quad (4.6.)$$

Where $q_{p,net,ar}$ = Net calorific value at constant pressure (p) as received (ar) in $MJ \cdot kg^{-1}$

$q_{p,net,d}$ = Net calorific value at constant pressure (p) on an oven dry basis (d) in $MJ \cdot kg^{-1}$

$MC\%_{wb}$ = Moisture content on a wet weight basis (%)

0.02443 = Correction factor for the enthalpy of vaporisation for water at 25°C

Table 4.2.2. Net calorific values as received, for species and partitions.

	Net Calorific Values as Received ($MJ \cdot kg^{-1}$)					
Partition	**Alder**	**Ash**	**Birch**	**Lodgepole pine**	**Norway spruce**	**Sitka spruce**
Merchantable Stem	7.8	10.9	9.2	6.4	5.1	6.0
Tops	7.8	10.7	9.0	6.0	5.5	6.0
Branch Wood and Foliage	8.6	9.3	9.5	7.6	8.6	8.8
Dead Branches	0.0	0.0	0.0	13.9	14.3	15.0

4.2.3.2. *Extrapolation of biomass and energy content estimates*

The basic density data was converted from $kg \cdot m^{-3}$ to $t \cdot m^{-3}$ and was parameterised following a procedure described by Bowyer et al. (2007). Basic density in $t \cdot m^{-3}$ was multiplied by the coefficient of variation and a Z-score of 1.96, assuming a 95% confidence interval. BEFs were calculated using Equation 4.7. (Brown, 1997).

$$\mathrm{BEF} = \frac{\mathrm{Total\ AGB}}{\mathrm{MSB}} \qquad (4.7.)$$

Where BEF = Biomass Expansion Factor

Total AGB = Total Above Ground Biomass of all components (merchantable stem, tops < 7 cm, live branches, foliage and dead branches) (kg)

MSB = Merchantable Stem Biomass (kg)

Mean basic density ($t \cdot m^{-3}$) and BEFs were multiplied into the volume per hectare calculated from inventory data to calculate total above ground biomass in oven dry tonnes per hectare ($odt \cdot ha^{-1}$). The GROWFOR® software was used for the conifers to estimate volume per hectare ($Vol \cdot ha^{-1}$). For broadleaves, volume per hectare was calculated following procedures documented by Booth et al. (2006). This analysis first involved calculation of mean tree volume (Equation 4.8.), and multiplying the mean tree volume by the stand stocking density per hectare (Equation 4.9.) To calculate form height for this analysis, a general table for sycamore, ash and birch (SAB) was referred to (Matthews and Mackie, 2006). No main crop form height tables were available for alder. As a result, the SAB table was also used for alder. As the area for birch in the South East could not be quantified, the regular initial stocking density recommended for birch (3300 stems ha^{-1}) was assumed for this analysis (Horgan *et al.*, 2003).

Table 4.2.3. Main crop form heights for broadleaves. Derived from Matthews and Mackie (2006).

Alder	**Top Height (m)**	**Main Crop Form Height (m)**
South East	8.8	1.45
Midlands	7.7	0.95
North West	11.1	3.52
Ash	**Top Height (m)**	**Main Crop Form Height (m)**
South East	8.9	1.45
Midlands	8.3	0.95
North West	10.7	3.15
Birch	**Top Height (m)**	**Main Crop Form Height (m)**
South East	7.6	0.95
Midlands	7.7	0.95
North West	11.9	4.15

$$\mathrm{MTV} = \mathrm{QMDBH}^2 \text{ x } \frac{\pi}{40000} \text{ x MCFH} \tag{4.8.}$$

Where MTV = Mean Tree Volume (m^3)

QMDBH = Quadratic Mean DBH (cm)

MCFH = Main Crop Form Height (m)

$$\mathrm{Vol} \cdot \mathrm{ha}^{-1} = \mathrm{MTV} \text{ x } \mathrm{Stocking} \cdot \mathrm{ha}^{-1} \tag{4.9.}$$

Where Vol·ha^{-1} = The volume per hectare of broadleaf stands (m^3)

MTV = Mean tree volume (m^3)

Stocking·ha^{-1} = The stocking rate per hectare of the broadleaf stands

Biomass in oven dry tonnes per hectare was calculated using Equation 4.1. (Brown, 1997). The oven dry tonnes per hectare were further converted to gigajoules per hectare ($GJ \cdot ha^{-1}$) using standard reference values (Table 4.2.1.).

$$\text{Total AGB} \cdot ha^{-1} = Vol \cdot ha^{-1} * BD * BEF \quad (4.1.)$$

Where Total $AGB \cdot ha^{-1}$ = Total above ground biomass in oven dry tonnes per hectare ($odt \cdot ha^{-1}$)

$Vol \cdot ha^{-1}$ = Volume per hectare (m^3)

BD = Basic density ($t \cdot m^{-3}$)

BEF = Biomass Expansion Factor

4.3. Results and discussion on biomass sampling

4.3.1. Fresh and oven dry biomass

Table 4.3.1. Fresh mass of components (mean ± standard deviation) combining all regions and site visits for sample trees.

Fresh Mass of Components on a per Tree Basis (kg)

Partition	Alder	Ash	Birch	Lodgepole pine	Norway spruce	Sitka spruce
Merchantable Stem	21.0 ± 9.2	17.8 ± 7.8	22.8 ± 9.9	45.0 ± 16.8	99.8 ± 34.8	89.4 ± 32.3
Tops < 7 cm	8.2 ± 2.5	7.8 ± 3.0	7.0 ± 3.4	5.6 ± 1.6	5.1 ± 1.2	5.4 ± 1.1
Branch Wood and Foliage	6.9 ± 4.6	11.2 ± 6.1	13.6 ± 6.9	40.4 ± 17.7	42.8 ± 13.4	42.9 ± 18.4
Dead Branches	0.0	0.0	0.0	3.0 ± 4.6	6.2 ± 3.9	5.7 ± 4.5

Table 4.3.2. Oven dry mass of components (mean ± standard deviation) combining all regions and site visits for sample trees.

Oven Dry Mass of Components (kg)						
Partitions	**Alder**	**Ash**	**Birch**	**Lodgepole pine**	**Norway spruce**	**Sitka spruce**
Merchantable Stem	10.1 ± 4.3	12.2 ± 6.7	12.2 ± 5.8	21.0 ± 8.0	35.2 ± 12.1	36.0 ± 14.6
Tops < 7 cm	3.9 ± 1.1	4.8 ± 1.8	3.7 ± 1.8	2.8 ± 1.7	1.9 ± 0.5	2.1 ± 0.5
Branch Wood	3.0 ± 1.9	5.1 ± 3.0	6.5 ± 3.7	10.8 ± 5.3	11.3 ± 4.0	12.7 ± 6.8
Foliage	0.7 ± 0.9	0.8 ± 1.0	1.2 ± 1.2	7.8 ± 3.5	10.3 ± 3.3	9.3 ± 3.7
Dead Branches	0.0	0.0	0.0	2.3 ± 3.5	4.6 ± 2.6	4.6 ± 4.7

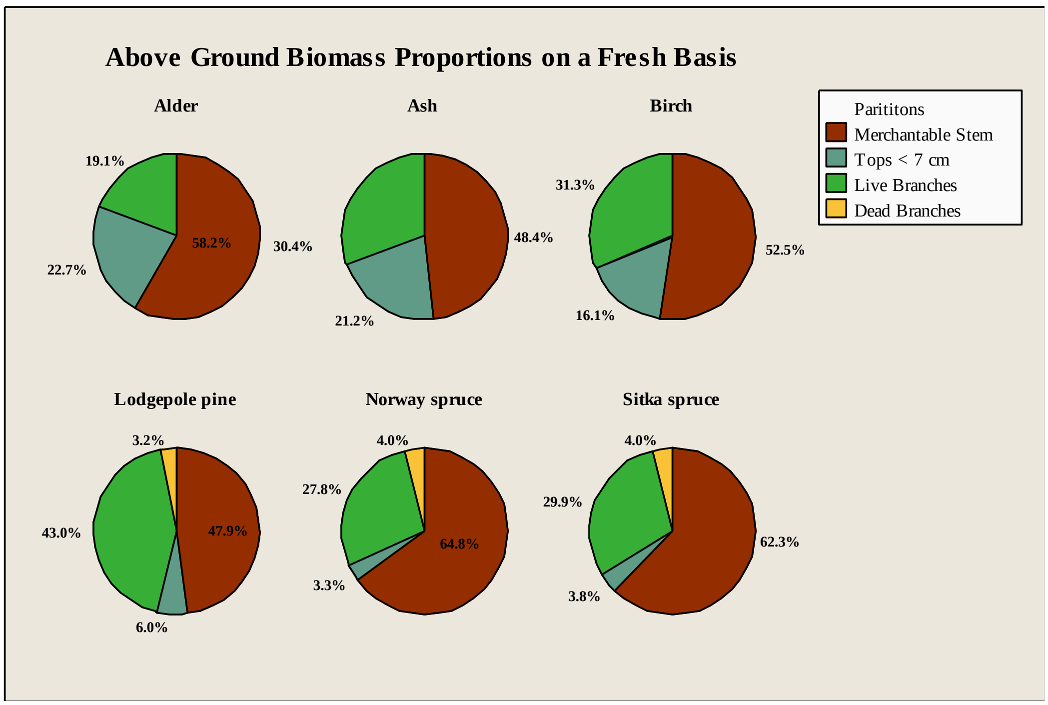

Figure 4.3.1. Fresh mass proportions of total above ground biomass.

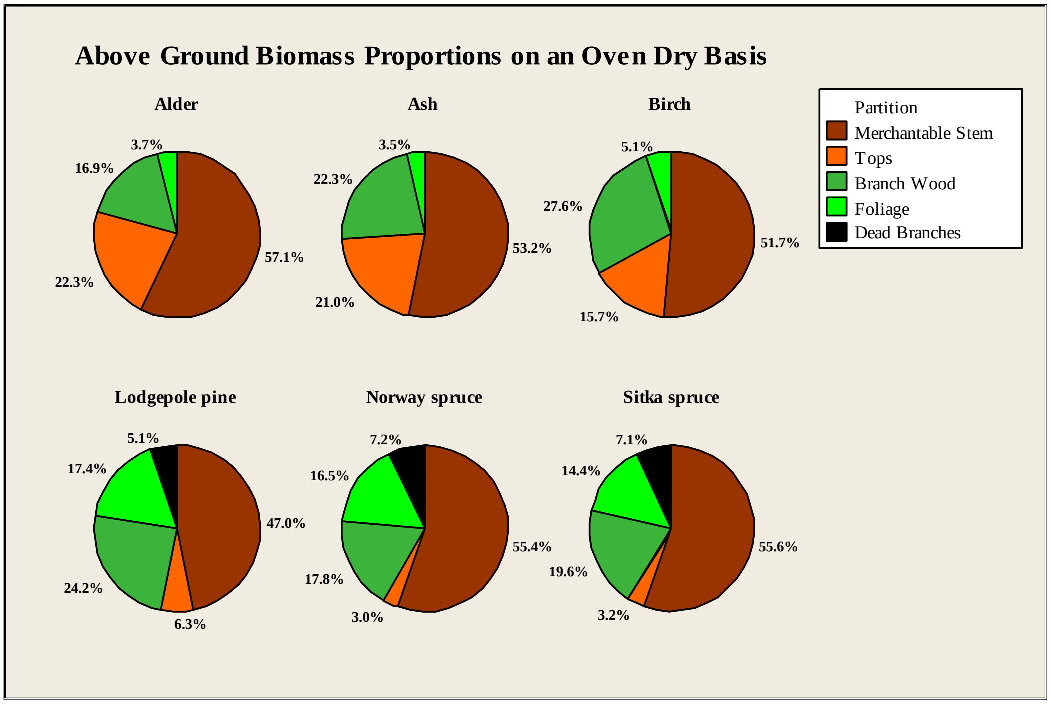

Figure 4.3.2. Oven dry mass proportions of total above ground biomass.

4.3.2. Discussion on the proportions of total above ground biomass

The conifer species had two-three times more total above ground biomass than the broadleaf species on a fresh and oven dry basis. The majority of above ground biomass was located in the stem sections for all species on a fresh and oven dry basis. The results for Sitka spruce are concurrent with previous research conducted in Ireland which also found that the majority of total above ground biomass was located in stem sections (Carey, 1980, Carey and O'Brien, 1979, Green *et al.*, 2007). The total amount of residual material (tops < 7 cm, branch wood, foliage and dead branches) accumulated to 43%, 47%, 48%, 53%, 45% and 44% for alder, ash, birch, lodgepole pine, Norway spruce and Sitka spruce respectively on an oven dry basis. Broadleaf species had a greater proportion of tops > 7 cm than the conifer species, yielding less merchantable stem material because of the smaller tree sizes. Proportions of live branch wood ranged from 17-28% for all species. Foliage proportions ranged from 4-5% and 14-17% respectively for the broadleaf and conifer species. Dead branch proportions of the total above ground biomass of the three conifer species ranged from 5-7%. For an overall comparison, published above ground dry matter figures from four 19-year old Sitka spruce trees of DBH 12, 13, 15 and 18 cm (Green *et al.*, 2007) were compared with the overall proportions of the Sitka spruce findings in this study which also had a similar range of diameters (12-19 cm). The results proved comparable, as Green et al. (2007) established figures of 62% in the whole stem, 19% in branches, 12% in foliage and 17% dead branches. This study determined figures of 59% in the whole stem, 20% in branches, 14% in foliage and 7% dead branches. In general, if whole trees were harvested from all six species, this can potentially lead to a 43-53% increase in the biomass that can be harvested from whole trees, in contrast to harvesting only merchantable stem sections. This concurs with research findings into whole tree terrain chipping trials previously conducted in Ireland (Kofman and Kent, 2007, Kent *et al.*, 2011).

4.3.3. Energy content of biomass

Table 4.3.3. Energy content of species and partitions (mean ± standard deviation) on a fresh basis combining all seasons and regions for sample trees.

Energy Content (MJ) of Biomass Components on a Fresh Basis						
Partitions	**Alder**	**Ash**	**Birch**	**Lodgepole pine**	**Norway spruce**	**Sitka spruce**
Merchantable Stem	163.8 ± 71.8	194.0 ± 85.0	209.8 ± 91.1	288.0 ± 107.5	509.0 ± 177.5	536.4 ± 193.8
Tops < 7cm	64.0 ± 19.5	83.5 ± 32.1	63.0 ± 30.6	33.6 ± 9.6	28.1 ± 6.6	32.4 ± 6.6
Branch Wood and Foliage	59.3 ± 39.6	104.2 ± 56.7	129.2 ± 65.6	307.0 ± 134.5	368.1 ± 115.2	377.5 ± 161.9
Dead Branches	0.0	0.0	0.0	41.7 ± 63.9	88.7 ± 55.8	85.5 ± 67.5

Table 4.3.4. Energy content of species and partitions (mean ± standard deviation) on an oven dry basis combining all seasons and regions for sample trees.

Energy Content (MJ) of Biomass Components on an Oven Dry Basis						
Partitions	**Alder**	**Ash**	**Birch**	**Lodgepole pine**	**Norway spruce**	**Sitka spruce**
Merchantable Stem	190.9 ± 81.3	230.6 ± 126.6	230.6 ± 109.6	401.1 ± 152.8	672.3 ± 231.1	687.6 ± 278.9
Tops < 7 cm	73.7 ± 20.8	90.7 ± 34.0	69.9 ± 34.0	53.5 ± 32.5	36.3 ± 9.6	40.1 ± 9.6
Branch Wood	56.7 ± 35.5	95.4 ± 56.1	121.6 ± 69.2	207.4 ± 101.8	217.0 ± 63.4	242.4 ± 129.8
Foliage	13.1 ± 16.8	15.0 ± 18.7	22.4 ± 22.4	149.8 ± 67.2	197.8 ± 76.8	178.4 ± 70.7
Dead Branches	0.0	0.0	0.0	44.2 ± 67.2	88.3 ± 49.9	88.3 ± 90.2

4.3.4. Energy content discussion

As already identified in Section 4.3.2., the conifer species in this study had two-three times more total above ground biomass than the broadleaf species in this study. As a result, the conifer species had more energy content per unit fresh and oven dry mass. The larger quantities of fresh and dry matter in conifers are reflective of their production potential in terms of mass and volume. This is especially reflected in the merchantable stem sections, despite conifers generally having a higher moisture content in merchantable stem sections than the broadleaves (see Chapter 2, Section 2.6.). The tops sections of broadleaf species however possessed more energy content on a fresh and oven dry basis. On a fresh basis, this was due to lower moisture contents in broadleaves. On an oven dry basis, this was due to broadleaves having more unmerchantable stem material than the conifer species. Branch wood energy content was greater in the conifer species in comparison to the broadleaves on a fresh and oven dry basis, again due to a greater amount of mass. With the conifer species, dead branches had the highest net calorific values on a fresh basis due to lower moisture contents in comparison to the other partitions.

A shortcoming in this study was that foliage alone was not analysed for calorific value on a fresh and oven dry basis, as it was not separated before oven drying. Branch wood moisture contents recorded in this study included both the wood and foliage components. Foliage may have had higher moisture content than wood (Gates, 1991, Hoyne and Thomas, 2001). In addition, European Standard reference values and definitions for the calorific value of logging residues are ambiguous (EN-14961-1, 2010). Logging residues are defined as including tree tops and branches either fresh or seasoned (EN-14961-1, 2010). The ambiguity arises from the fact that the estimated net calorific values do not distinguish from the possible differences that may exist between wood and foliage. For example, Nurmi (1997) ascertained net calorific values for Norway spruce and birch foliage. The foliage net calorific value (19.2 $MJ \cdot kg^{-1}$) for Norway spruce from Nurmi's study compares with the typical value (19.1 $MJ \cdot kg^{-1}$) for conifer logging residues (EN-14961-1, 2010). However the net calorific value for birch foliage ascertained by Nurmi (19.8 $MJ \cdot kg^{-1}$) is higher than the standard reference value for broadleaf logging residues (18.7 $MJ \cdot kg^{-1}$).

Nurmi (1993) stated that the quantities of wood fuel that can be harvested and moisture content are among the most important parameters conducive to the needs of end users for wood fuel. The products that can be harvested from the above ground biomass of first thinnings, and the type of combustion applications that can tolerate differing ranges of moisture content will ultimately determine management strategies. Exploiting as much biomass as possible to reduce harvesting and processing costs is of interest to industrial scale end users whose boilers can tolerate moisture contents of 45-55% (Hakkila, 2004, Nurmi, 1993, Obernberger *et al.*, 2006). This would certainly be the case with coniferous species as they possess more mass, and once seasoned to the appropriate moisture content, wood net calorific value does not differ significantly between tree species (Nurmi, 1993, Rolls, 2010, Roser *et al.*, 2008).

Conversely, for small scale domestic and commercial situations, the use of broadleaf species would be preferred, due to lower initial moisture contents and higher basic densities (see Chapters two and three, sections 2.6. and 3.5. respectively on findings). Lower initial moisture contents gives rise to shorter seasoning schedules for broadleaf species. Irish and Scandinavian research has found that eight months is needed to reach the desired moisture content of 20% if broadleaves are felled during the summer period for the consumption of firewood, as opposed to 16-24 months for conifers (Alakangas, 2005, Kofman and Kent 2009a, Nord-Larsen *et al.*, 2011). This is provided that firewood has been cut, split, and sheltered from rain (Kofman and Kent, 2009a). The higher basic density of broadleaf species can deliver more energy per unit volume from cut, split, seasoned and stacked firewood in comparison to coniferous species (Rolls, 2009, Roser *et al.*, 2008). Broadleaves would also have a higher energy density than the coniferous species if harvested for wood chip (Kofman and Kent, 2007). However, despite the benefits of utilising wood fuel derived from broadleaves, the three conifer species are more widespread in Ireland than the three broadleaf species, in addition to their majority contribution to future round wood supply scenarios (93%) (NFI, 2007, Phillips, 2011). Therefore, the conifer species will feature more prominently in future industrial-scale energy supply scenarios than broadleaves. The forest products industry is the majority consumer of wood energy at 55-60% of total consumption (O'Driscoll, 2011), of whom for the majority utilise small sized round wood derived from the three coniferous species, in addition to by-products and wastes as a result of wood processing for energy purposes.

Broadleaf species on the otherhand may be reserved purely for domestic and commerical wood fuel consumption. The majority of broadleaf planting has been conducted in the private sector (Short and Radford, 2008). There has been an increase in private sector first thinnings in recent years (Knaggs and O'Driscoll, 2012b). A large proportion of these thinnings have been used for domestic firewood consumption (Knaggs and O'Driscoll, 2012b), either for a landowner's own consumption and/or sold locally. Privately owned forest plantations are small on average, and there are innumerable issues associated with the mobilisation of thinnings (Byrne and Legge, 2008, Casey and Ryan, 2012, Maguire *et al.*, 2010). Although first thinnings from broadleaf stands would make for an ideal source of wood fuel for the range of different end users (domestic, commercial, industrial), the consistency and reliability of ensuring *en masse* supplies are questionable. Ensuring supplies will vary on a case-by-case basis with individual landowners and regional grower groups in terms of what markets are available for thinnings, be it for conventional end uses or energy.

4.3.5. Methods to extrapolate biomass and energy content estimates per hectare

Table 4.3.5. Basic density converted from kg·m^{-3} to t·m^{-3}

Basic Density (t·m^{-3})				
South East 52°N	**Density (t·m^{-3})**	**Coefficient of Variation (%)**	**Z – Score**	**Range***
Alder	0.41	10.0	1.96	0.33 - 0.49
Ash	0.54	11.8	1.96	0.42 - 0.67
Birch	0.51	9.7	1.96	0.41 - 0.61
Lodgepole pine	0.38	10.5	1.96	0.30 - 0.46
Norway spruce	0.36	10.8	1.96	0.29 - 0.44
Sitka spruce	0.38	10.6	1.96	0.30 - 0.46
Midlands 53°N	**Density (t·m^{-3})**	**Coefficient of Variation (%)**	**Z – Score**	**Range**
Alder	0.41	9.8	1.96	0.33 - 0.49
Ash	0.48	16.4	1.96	0.33 - 0.63
Birch	0.48	9.3	1.96	0.40 - 0.57
Lodgepole pine	0.38	9.1	1.96	0.31 - 0.44
Norway spruce	0.35	8.9	1.96	0.29 - 0.41
Sitka spruce	0.38	11.2	1.96	0.29 - 0.46
North West 54°N	**Density (t·m^{-3})**	**Coefficient of Variation (%)**	**Z – Score**	**Range**
Alder	0.35	9.2	1.96	0.29 - 0.41
Ash	0.46	11.9	1.96	0.36 - 0.57
Birch	0.46	9.5	1.96	0.38 - 0.55
Lodgepole pine	0.37	13.7	1.96	0.27 - 0.47
Norway spruce	0.32	10.8	1.96	0.25 - 0.39
Sitka spruce	0.35	14.4	1.96	0.25 - 0.45
All Regions	**Density (t·m^{-3})**	**Coefficient of Variation (%)**	**Z – Score**	**Range**
Alder	0.39	12.1	1.96	0.30 - 0.48
Ash	0.50	14.7	1.96	0.35 - 0.64
Birch	0.48	10.5	1.96	0.38 - 0.58
Lodgepole pine	0.38	11.1	1.96	0.29 - 0.46
Norway spruce	0.35	11.5	1.96	0.27 - 0.42
Sitka spruce	0.37	12.7	1.96	0.28 - 0.46

*Within the limits of the coefficient of variation ascertained in this study

Table 4.3.6. Biomass expansion factors (BEFs).

Biomass Expansion Factors (BEFs)						
South East	**Count**	**Mean**	**Standard Deviation**	**Standard Error**	**Minimum**	**Maximum**
Alder	15	2.2	0.9	0.5	1.1	4.5
Ash	15	1.9	0.4	0.2	1.4	2.6
Birch	15	2.7	0.9	0.5	1.4	4.3
Lodgepole pine	15	2.2	0.7	0.4	1.4	3.8
Norway spruce	15	1.6	0.1	0.1	1.3	1.8
Sitka spruce	15	1.7	0.2	0.1	1.4	2.0
Midlands	**Count**	**Mean**	**Standard Deviation**	**Standard Error**	**Minimum**	**Maximum**
Alder	15	1.7	0.3	0.2	1.4	2.4
Ash	15	1.9	0.4	0.2	1.5	2.9
Birch	15	1.7	0.3	0.2	1.3	2.3
Lodgepole pine	15	2.0	0.3	0.1	1.6	2.5
Norway spruce	15	2.1	0.2	0.1	1.8	2.4
Sitka spruce	15	1.8	0.2	0.1	1.6	2.3
North West	**Count**	**Mean**	**Standard Deviation**	**Standard Error**	**Minimum**	**Maximum**
Alder	15	1.9	0.5	0.2	1.3	2.9
Ash	15	2.4	0.7	0.3	1.6	3.7
Birch	15	2.2	0.8	0.4	1.6	4.1
Lodgepole pine	15	2.6	0.8	0.4	2.1	5.2
Norway spruce	15	1.8	0.2	0.1	1.5	2.3
Sitka spruce	15	2.1	0.3	0.1	1.7	2.5
All Regions	**Count**	**Mean**	**Standard Deviation**	**Standard Error**	**Minimum**	**Maximum**
Alder	45	1.9	0.7	0.2	1.1	4.5
Ash	45	2.1	0.6	0.2	1.4	3.7
Birch	45	2.2	0.8	0.2	1.3	4.3
Lodgepole pine	45	2.3	0.7	0.2	1.4	5.2
Norway spruce	45	1.9	0.3	0.1	1.4	2.4
Sitka spruce	45	1.9	0.3	0.1	1.4	2.5

Table 4.3.7. Calculation of biomass per hectare and energy content per hectare using the mean basic density and BEFs for each region.

Alder	**Age**	**YC ($m^{-3}\cdot ha^{-1}\cdot yr^{-1}$)**	**Vol·ha^{-1}**	**Basic Density ($t\cdot m^{-3}$)**	**BEF**	**Biomass odt·ha^{-1}**	**GJ·ha^{-1}**
South East	14	6	21.0	0.41	2.2	18.9	358.8
Midlands	16	6	19.3	0.41	1.7	13.5	254.7
North West	12	12	57.0	0.35	1.9	37.9	716.4
Ash	**Age**	**YC ($m^{-3}\cdot ha^{-1}\cdot yr^{-1}$)**	**Vol·ha^{-1}**	**Basic Density ($t\cdot m^{-3}$)**	**BEF**	**Biomass odt·ha^{-1}**	**GJ·ha^{-1}**
South East	16	6	26.0	0.54	1.9	26.7	503.7
Midlands	16	6	11.5	0.48	1.9	10.5	198.6
North West	12	10	40.6	0.46	2.4	44.8	847.4
Birch	**Age**	**YC ($m^{-3}\cdot ha^{-1}\cdot yr^{-1}$)**	**Vol·ha^{-1}**	**Basic Density ($t\cdot m^{-3}$)**	**BEF**	**Biomass odt·ha^{-1}**	**GJ·ha^{-1}**
South East	15	6	19.0	0.51	2.7	26.2	495.3
Midlands	16	6	17.0	0.48	1.7	13.9	262.5
North West	12	12	76.2	0.46	2.2	77.1	1456.6
Lodgepole pine	**Age**	**YC ($m^{-3}\cdot ha^{-1}\cdot yr^{-1}$)**	**Vol·ha^{-1}**	**Basic Density ($t\cdot m^{-3}$)**	**BEF**	**Biomass odt·ha^{-1}**	**GJ·ha^{-1}**
South East	13	14	64.0	0.38	2.2	53.5	1021.9
Midlands	16	14	119.0	0.38	2.0	90.4	1726.6
North West	16	10	73.0	0.37	2.6	70.2	1340.8
Norway spruce	**Age**	**YC ($m^{-3}\cdot ha^{-1}\cdot yr^{-1}$)**	**Vol·ha^{-1}**	**Basic Density ($t\cdot m^{-3}$)**	**BEF**	**Biomass odt·ha^{-1}**	**GJ·ha^{-1}**
South East	17	18	163.0	0.36	1.6	93.9	1793.5
Midlands	16	16	95.0	0.35	2.1	69.8	1333.2
North West	17	20	229.0	0.32	1.8	131.9	2519.3
Sitka spruce	**Age**	**YC ($m^{-3}\cdot ha^{-1}\cdot yr^{-1}$)**	**Vol·ha^{-1}**	**Basic Density ($t\cdot m^{-3}$)**	**BEF**	**Biomass odt·ha^{-1}**	**GJ·ha^{-1}**
South East	17	26	251.0	0.38	1.7	162.1	3097.0
Midlands	16	22	150.0	0.38	1.8	102.6	1959.7
North West	17	20	200.0	0.35	2.1	147.0	2807.7

4.3.1. Discussion on extrapolation methods

4.3.1.1. Basic density in t·m^{-3}

This basic density data could be used to ascertain stem wood biomass of first thinning material. If wood fuel products from first thinning such as firewood and round wood chip are desired from stem sections, these basic densities may prove useful in their application to convert volume per hectare to get an estimate of stem wood biomass per hectare. Adjustments can be made can be made on the basis of latitudinal zones if desired (see discussion in Chapter three, Section 3.5.2. for more details). However, caution should be exercised with the utility of these basic densities. First, these basic densities are specific to an age range (12-17 years old). Second, these basic densities are also specific to a diameter size class within the age range of the material sampled. Third, the basic density expressions in this study are over bark. Finally, the methods used to derive basic density for this study were estimated from disc samples that were oven dried at 105^{o}C.

4.3.1.2. Biomass expansion factors

In relation to BEFs, results are concurrent with trends noted by Tobin and Nieuwenhuis (2007), who observed that less merchantable stem material yields a higher BEF. BEFs are not reflective of the actual mass of the six species and therefore should not be compared against each other. This is due to the various ages and quantities of volume and mass accumulated between each of the six species. Similar to the trends with the sample trees, the three conifer species for the most possessed more biomass and energy content per hectare in comparison to the broadleaves. However there were exceptions. Birch in the North West possessed more mass and energy content than lodgepole pine in the South East and North West, and Norway spruce in the Midlands.

With the exception of Sitka spruce, the BEFs in this study are the first reported for Irish conditions for alder, ash, birch, lodgepole pine and Norway spruce. However, these BEFs have been derived from a narrow range of ages. Other authors have found that BEFs exponentially reduce with age in an inverse non-linear fashion, eventually stabilising at stand maturity (Black *et* *al.*, 2004, Brown, 2002, Pajtik *et al.*, 2008). The sampling of trees within the quadratic mean diameter distribution in trial stands prevented the construction of allometric regression equations. The stratification and sampling of trees within the range of diameter size class distributions was required for the construction of allometric regression equations (Brown, 1997, Chave *et al.*, 2005, Overman *et al.*, 1994, Snowdon *et al.*, 2002, Zianis and Mencuccini, 2004, Zianis *et al.*, 2005). This study has proven that sampling trees of an average dimension (i.e. QMDBH) should not be implemented if the research objective is to construct allometric regression equations. This is concurrent with others who discouraged such an approach (Snowdon *et al.*, 2002, Zianis *et al.*, 2005). Nonetheless, although data are restricted to the diameter size class of the QMDBH, there is considerable variation within the relatively narrow range of diameter sizes sampled. Sample trees were selected on the basis of diameter alone. Other authors have found that canopy status can be a considerable source of variation within trees of the same diameter that are sampled for biomass (Cruzado and Soalleiro, 2011, Liu, 2009).

Analogous to the methodology for determining basic density in $t \cdot m^{-3}$ (see Section 4.3.1.1.), the utilisation of BEFs from this study must be exercised with caution because of their restriction to the age and sizes of trees sampled. These BEFs are inclusive of above ground biomass only. Future research into the above ground biomass of first thinning material could incorporate the raw data generated from this study, as dry matter findings were comparable with those of Green et al. (2007) for Sitka spruce.

Trends concerning stand inventory parameters with BEFs were also found in this study. Black et al. (2004) stated that for Sitka spruce stands of the same age, BEFs were higher in stands of a high yield class than those of lower yield class. This trend was encountered with Norway spruce in the North West in comparison to the South East. However, in all other cases, a higher yield class gave rise to a lower BEF. This was especially pronounced for Sitka spruce. Black et al. (2004), however, also stated that BEFs were not a function of yield class, but rather a function of the allometric allocations of trees. This would appear to be the case with lodgepole pine. Lodgepole pine in the South East and Midlands were of the same yield class. However, as lodgepole pine in the South East was three years younger than in the Midlands, it was possibly less developmentally mature and as a result yielded a higher expansion factor due to having less merchantable stem mass.

As basic density in t·m^{-3} and BEFs are typically used in the conversion of standing volume per hectare to a specified top diameter (7 cm) into biomass per hectare (Brown, 1997, Brown, 2002, Edwards and Christie, 1981), this approach was most suited to the coniferous species. Standardised inventory procedures and growth prediction models have been designed to cater for coniferous species under Irish conditions (Purser and Lynch, 2012). In addition, the parameters for calculating the volume per hectare for the broadleaf species used form heights derived from British data (Matthews and Mackie, 2006). These form heights also refer to a general table for sycamore, ash and birch. As a result, improvisations were made in the analysis of alder conforming to this form height table. The suitability of using parameters such as form height for broadleaves to predict volume per hectare growing under Irish conditions is unknown. However, in time, stand volume models for broadleaf species will become available for Irish conditions as an output of the next National Forest Inventory for Ireland (Redmond, 2012), in addition to the development of a GROWFOR dynamic yield model for ash (Purser and Lynch, 2012).

Another shortcoming to this study was that some of the sites where were less than a hectare. As a result, assumptions were made that sites were of at least one hectare to calculate volume per hectare, which may not be truly representative of stand growing conditions. Overall, any future studies to determine biomass should incorporate sampling the range of diameter distributions. Sampling the range of tree sizes encountered in stands reduces bias and error when biomass estimates are upscaled to the stand level (Snowdon *et al.*, 2002).

Ultimately, the utility of biomass estimation methods from this study could be validated through operations research into the harvesting of biomass components for wood fuel (e.g. whole tree terrain chipping). This would be a measure to compare how accurate estimation methods are in relation to the removals of biomass for wood energy consumption

4.4. Summary of biomass sampling

This study confirmed that if whole trees are harvested, there is a 43-53% potential increase in the biomass that can be harvested, as opposed to the harvesting merchantable stem sections only. However, these percentages are ambiguous due to the findings that showed conifers possess greater mass and energy content on a per tree basis, and on a per hectare basis in most cases. The utility of parameters such as basic density ($t \cdot m^{-3}$) and BEFs that are used to convert standing volume per hectare to biomass and energy content per hectare were demonstrated. BEFs ranged from 1.9-2.3 between the six species. However, their utility must be interpreted with caution, as they are restricted to a narrow age and size of trees sampled, in addition to including only above ground biomass components.

5. CHAPTER 5 – CONCLUSIONS

5.1. Original aims and objectives

The original aims and objectives were as follows:

- First, to characterise moisture content and investigate spatiotemporal and partition variation.
- Second, to characterise basic density and spatial variation of stem sections.
- Third, to quantify above ground biomass and energy content.

5.2. Objective 1 - Moisture content

Moisture content was characterised for the six tree species (ash, alder, birch, lodgepole pine, Norway spruce, and Sitka spruce) in this study. These species represent 76% of the Irish forestry estate. However the sampling was restricted to a narrow range of ages and size of trees sampled (12-17 years). Moisture content ranged from 38-65% in the stem wood sections between the six tree species. Branch wood moisture content ranged between 44-54%. Ash was the only species to demonstrate distinguishable spatiotemporal fluctuations in stem wood moisture content. Ash stem wood moisture content was lower during dormancy, higher during flushing and higher again during the growing season in all locations. This was possibly due to ash' vascular distribution as a ring porous hardwood tree species, which have a larger vessels for water conductance during the growing season, and a smaller vessels over the course of dormancy (Bowyer *et al.,* 2007, Coder, 1999). Ring porous species develop more latewood over the latter period of the growing season before dormancy. As a result, latewood has an inverse effect on water conductance, as found by others (Michalec and Niklasova, 2006). The other species were relatively inert with changes in stem wood moisture content spatiotemporally. This concurs with research by others who investigated temporal trends in stem wood (Peck, 1959), and spatiotemporal trends (Shotaffer and Brackley, 1982). These trends may also be attributed to vascular distribution, as species such as alder; birch and Sitka spruce possess more earlywood than latewood on annual growth rings (Michalec and Niklasova, 2006, Moore, 2011). Earlywood is more conducive to conducting water than latewood (Michalec and Niklasova, 2006).

In the majority of cases, branch wood moisture content reduced at flushing in comparison to dormancy. Despite the *in situ* fluctuations of moisture content, the time of year harvesting and seasoning of wood for fuel should take precedence. This most optimum period for harvesting and seasoning wood for fuel in temperate forest biomes is between March-August, due to higher temperatures, lower rainfall and lower relative humidity of air. The period of September-February is not suitable for harvesting and seasoning wood for fuel due to lower temperatures, higher rainfall and higher relative humidity of air. This has been confirmed by a number of authors who examined optimum seasoning periods for different wood fuel assortments in temperate forest biomes (Alakangas, 2005, Filbakk *et al.,* 2011, Gigler *et al.,* 2000, Hakkila, 2004, Holt, 1967, Kofman and Kent, 2009a, Kofman and Kent, 2009b, Kofman and Kent, 2009c, Kofman and Kent, 2009d, M^{c}Minn, 1986, Mochan, 2006, Nord-Larsen *et al.,* 2011, Nurmi and Lehtimaki, 2010, Rolls, 2009, Roser *et al.,* 2010, Savill, 1979). However, the optimisation of seasoning is also dependent on the length of time to reach the target moisture content specific to end user requirements, and where seasoning takes place. Seasoning in the forest reduces moisture content to a level suitable for industrial applications (45-55%) (Kofman and Kent, 2007), whereas clearfell areas and dedicated terminals for seasoning with a high level of wind exposure have proven to be effective for drying moisture content to levels as low as 30% (Kofman and Kent 2009b, Kofman and Kent, 2009c, Pettersson and Nordfjell, 2006).

The reduction of moisture content in branches at flushing is reflected in the practice of sour felling. Sour felling is a seasoning method that takes advantage of the water withdrawal capacity of branches during spring time to reduce moisture content in trees, and to reduce foliage in fuel mixtures if branches are harvested (Alakangas, 2005, Filbakk *et al.,* 2011, Holt, 1967, M^{c}Minn, 1986, Mochan, 2006, Nurmi and Lehtamaki, 2010). Potential trials could investigate the practice of sour felling in terms of its efficacy for seasoning wood for fuel under Irish conditions. In addition, such trials could also incorporate biomass sampling to ascertain the rate of foliage losses from branches, as the effects of nutrient removals as a result of harvesting whole trees from first thinnings has not been studied in Ireland.

5.3. Objective 2 - Basic density

The basic density of stem sections was characterised for the six species in this study. Basic density ranged from 344-498 kg·m^{-3}. The most significant trend from a spatial perspective was a decrease of basic density with an increase in latitude. Others have attributed such trends to climatic influences. These climatic influences have included a reduction of basic density in areas of higher precipitation than areas of lower precipitation. Trees that grow in areas of high precipitation develop more earlywood than latewood on annual growth rings (Gardiner, 2011, Moore, 2011, Wiemann and Williamson, 2002). Earlywood is less dense than latewood (Pinchot, 2005), and thus contributes to lower basic densities. Other authors have found that increases in accumulated temperatures with decreasing latitude leads to an increase in basic density, due to extended growing seasons and latewood development (Aosaar *et al.*, 2011, Premyslovska *et al.*, 2007). In this study, precipitation may be the indicator to explaining the spatial trends in basic density, as there was a decrease of basic density in areas of higher precipitation than areas of lower precipitation. Annual temperatures on the otherhand were equal on average in all the locations trees were sampled. Future studies could further study spatial variations in basic density. However, others have found that to truly ascertain the variations in basic density, analysis of the differences between and within annual growth rings are necessary, as this is where the majority of variation with basic density is encountered (Jyske *et al.*, 2008).

5.4. Objective 3 - Biomass

Total above ground biomass was quantified for the six tree species in this study. It was found that if whole trees are harvested, this can lead to an increase of 43-53% in the biomass that can potentially be harvested, in contrast to harvesting merchantable stem sections only. The three conifer species in this study has two-three times more biomass than the broadleaf species, and thus more energy content. The utility of this biomass data was also demonstrated with BEFs. BEFs are multiplication ratios that account for residual biomass components (tops < 7 cm diameter, branch wood, and foliage) that are not measured in standard inventory practice. BEFs in this study ranged from 1.9-2.3 between the six species. BEFs were used in tandem with the basic density data (in t·m^{-3}) to convert the standing volume per hectare of the trial stands to biomass and energy content per hectare. However, the utility of these parameters should be interpreted with caution. The basic densities used were samples oven dried to 105^{o}C, included bark, and are restricted to a narrow range of ages and tree sizes. The BEFs are also restricted to a narrow age and size of trees sampled. BEFs were also constructed from a single diameter size class distribution. As a result there may be errors and bias associated with upscaling methods to determine biomass per hectare, as it is recommended that the range of tree diameter sizes encountered should be sampled (Snowdon *et al.,* 2002). Future trials could test the validity of these parameters in estimating biomass against the actual removals through wood fuel harvesting operations, but should only be used in stands conforming to the ages and tree sizes of the biomass sampled in this study, as BEFs reduce with age (Black *et al.,* 2004, Brown, 2002, Pajtik *et al.,* 2008).

5.5. Conclusion

The objectives were fulfilled for the physical characterisation and quantification of the total above ground biomass for the six tree species in this study. The moisture content and basic density data generated from this study can be supplemented with similar datasets for other species and wood biomass fuels. Future work will aim to characterise ash forming elements and calorific values of the above ground biomass partitions measured in this study. Overall, the data accumulated from this study are restricted to a narrow range of age and sizes of tree sampled, particularly where the quantification of biomass is concerned through the use of basic densities and BEFs. However, limiting the sampling to the six species in this study ensured that the majority of potentially commercially available biomass for energy in Ireland would be characterised, as the six species in this study represent 76% of the Irish forestry estate, and are within a range of ages that represent two thirds of forest cover in Ireland at present (NFI, 2007).

This study is part of an initial phase to develop a fuel property database of forest biomass fuel sources under Irish conditions. The premise behind this database is to evaluate the suitability of different forest biomass fuel sources for energy consumption in Ireland, particularly fuel sources that have not been harvested in the past (e.g. whole trees from first thinnings and logging residues from clearfell areas). Once data on the fuel properties of different biomass fuel sources under Irish conditions have been collated, results will be made available to wood fuel producers and the general public through dissemination outputs. These outputs will be in the form of project reports, peer reviewed papers and an online database with a user query interface. It is envisioned that the dissemination of this information will increase awareness towards how to control for wood fuel quality, and instil an increased sense of confidence towards the use of an emerging source of energy in Ireland.

REFERENCES

AE BIOM. (2008). *Wood fuels handbook. Quality, requirements, trading.* Legnaro: AIEL Italian Agriforestry Energy Association.

Alakangas, E. (2005). *Properties of wood fuels used in Finland-BIOSOUTH project.* Jyvaskyla: Technical Research Centre of Finland, VTT processes.

Alakangas, E., Valtanen, J., & Lavlin, J. (2006). CEN technical specifications for solid biofuels. *Biomass & Bioen., 30* (11), 908-914.

Albrekston, A. (1980). Relations between tree biomass fractions and conventional silvicultural measurements. *Ecological Bulletins No. 32. Structure and function of Northern coniferous forests: An ecosystem study, 32,* 315-327.

Alden, H. (1997). *Softwoods of North America.* Madison: USDA Forest Products Laboratory.

Aosaar, J., Varik, M., Lohmus, K., & Uri, V. (2011). Stemwood density in young grey alder (*Alnus incana* (L.) Moench) and hybrid alder (*Alnus hybrida* A. Br.) stands growing on abandoned agricultural land. *Baltic For., 17* (2), 256-261.

Baker, A. (1983). *Wood fuel properties and fuel products from woods.* East Lansing: Michigan State University.

BIONORM. (2004). *BIONORM Projec - Final Technical Report.* European Standards Committee.

Black, K., Tobin, B., Saiz, G., Byrne, K., & Osborne, B. (2004). Improved estimates of biomass expansion factors for Sitka spruce. *Irish For., 61* (1), 50-65.

Booth, A., Ryan, T., & Whelan, D. (2006). Irish thinning protocol. A complete step-by-step guide to the requirements and implementation of thinning systems in Ireland. Dublin: Department of Agriculture and Food.

Bórd na Mona. (2012). Bórd na Mona annual report 2012. Newbridge: Bórd na Mona.

Bowyer, J., Haygreen, J., & Shmulsky, R. (2007). *Forest Products and Wood Science: An Introduction* (5th ed.). Iowa: Iowa State Press University/AMES.

Byrne, K., & Legge, T. (2008). Sustainability of Irish forestry - current status and future prospects. *Irish For., 65*, 47-59.

Briggs, D. (1994). *Forest products measurements and conversion factors: With special emphasis on the U.S. Pacific Northwest.* Washington, USA: College of Forest Resources, University of Washington.

Brown, S. (1997). *Estimating biomass and biomass change of Tropical forests. A primer.* Rome: FAO - Food and Agriculture Organisation of the United Nations.

Brown, S. (2002). Measuring carbon in forests: current status and future challenges. *Environ. Poll., 116* (3), 363-372.

Bryan, J., & Pearson, F. (1955). The quality of Sitka spruce grown in Britain. *Emp. For. Rev.*, 144-149.

Carey, M. (1980). Whole tree harvesting of Sitka spruce. Possibilities and implications. *Irish For., 38* (1), 48-63.

Carey, M., & O'Brien, D. (1979). Biomass, nutrient content and distribution in a stand of Sitka spruce. *Irish For., 36* (1), 25-35.

Casey, J., & Ryan, M. (2012). *Situation and Outlook for Forestry 2011/2012.* Athenry: Teagasc Forestry.

CEN. (2010). *EN-14778: 2010. Solid biofuels - Sampling.* Dublin: National Standards Authority of Ireland.

CEN. (2010). *EN-14961-1: 2010. Solid biofuels - Fuel specifications and classes - Part 1 : General requirements.* Dublin: National Standards Authority of Ireland.

CEN. (2011). *EN-15234-1: 2011. Solid biofuels - Fuel quality assurance - Part 1 : General requirements.* Dublin: National Standards Authority of Ireland.

CEN. (2010). *EN-14588: 2010. Solid biofuels - Terminology, definitions and descriptions.* Dublin: National Standards Authority of Ireland.

CEN. (2010). *EN-14774-2: 2010. Solid biofuels - Determination of moisture content - Oven dry method - Part 2: Total Moisture - Simplified Method.* Dublin: National Standards Authority of Ireland.

CEN. (2009). *EN-15103: 2009. Solid biofuels - Determination of bulk density.* Dublin: National Standards Authority of Ireland.

Chave, J., Andalo, C., Brown, S., Cairns, M., Chambers, J., Eamus, D., et al. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia, 145* (1), 87-99.

Clark, A., & Daniels, R. (2000). *Estimating moisture content of tree-length roundwood.* Georgia: USDA.

Coder, K. (1999). *Tree ring porosity in hardwoods.* Athens: University of Georgia.

COFORD Round Wood Demand Group. (2011). *All Ireland roundwood demand forecast 2011-2028.* Dublin: COFORD.

Coggins, K. (1996). An integrated study on the viability of using slash for domestic energy in the form of briquettes. *Irish For., 53,* 36-44.

Cruzado, C., & Soalleiro, R. (2011). Improvement in accuracy of aboveground biomass estimation in *Eucalyptus nitens* plantations: Effects of bole sampling intensity and explanatory variables. *For. Ecol. Man., 261,* 2016-2028.

Deasy, J.J. 1947. Notes on the extraction of firewood. *Irish For., 4* (2), 63.

Demirbus, A. 2004. Combustion characteristics of different biomass fuels. *Prog. in Ener. Combust. Sci., 30* (2), 219-230.

Dennehy, E., Howley, M., & O'Gallachóir, B. (2011). *Energy security in Ireland. A statistical overview. 2011 Report.* Dublin: Sustainable Energy Authority of Ireland.

Dennehy, E., Howley, M., O'Gallachóir, B., & Holland, M. (2012). *Renewable Energy in Ireland 2011*. Dublin: Sustainable Energy Authority of Ireland.

Department of Communications, Marine and Natural Resources. (2007a). *Delivering a sustainable energy future for Ireland. The energy policy framework 2007-10.* Dublin.

Department of Communications, Marine and Natural Resources. (2007b). *Bioenergy action plan for Ireland. Report to the ministerial task force on bioenergy.* Dublin.

Department of Finance. (2010). *Finance Bill 2010.* Dublin.

Department of Finance. (2012). *Finance Bill 2012.* Dublin.

Donovan, T. (1946). Notes on the construction and handling of small portable units for firewood cutting. *Irish For.*, *3* (1), 40-45.

Dunnett, A. (2012, June 6th). Rapid and low cost methods of wood fuel moisture determination. GIFT (Green Innovation and Future Technologies) wood fuel quality event. Ramada Hotel Waterford City.

Edwards, P. N., & Christie, J. M. (1981). *Yield models for forest management.* London: HMSO.

FAO. (2009). *Assessment of the status of the development of the standards for the terrestrial essential climate variables.* Rome: FAO.

FAO. (2000). *Global forest resource assessment 2000.* Rome: FAO.

Fennessy, J. (2005). *Rural Ireland 2025. Foresight Perspectives.* Dublin: COFORD.

Filbakk, T., Hoibo, O., & Nurmi, J. (2011). Modelling natural drying efficiency in covered and uncovered piles of whole broadleaf trees for energy use. *Biomass & Bioen., 35* (1), 454-463.

Gardiner, B. (2011). Climate change, tree growth and timber properties. Newcastle: Forest Research.

Gardiner, J., & O'Sullivan, P. (1978). The effect of wide espacement on wood density in Sitka spruce (*Picea sitchesis* (Bong.) Carr.). *Irish For., 35* (1), 45-51.

Gargan, E. (2012). *Reflections on the implementation of the carbon tax in Ireland.* Dublin: The Department of Finance.

Gartner, B. L. (1995). Patterns of xylem variation within a tree. In *Plant Stems* (p. 142). London: Academic Press Inc.

Gates, D. (1991). Water Relations of Forest Trees. *IEEE Transactions on Geoscience and Remote Sensing., 29* (6), 836-842.

Gibson, M., McMillin, C., & Shoulders, E. (1985). Moisture content and specific gravity of four major southern pines under the same age and site conditions. *Wood Fib. Sci., 18* (3), 428-435.

Gigler, J., van Loon, W., van den Berg, J., Sonnevald, C., & Meerdink, G. (2000). Natural wind drying of willow stems. *Biomass and Bioen., 19* (3), 153-163.

Goff, N., Granier, A., Ottorini, J., & Peiffer, M. (2004). Biomass increment and carbon balance of ash (*Fraxinus excelsior*) trees in an experimental stand in northeastern France. *Ann. For. Sci., 61* (6), 1-12.

Gorenson, C. (2002). Whole-Stem Water Relations in White Oak. MSc. Thesis. Athens, United States of America: University of Georgia.

Government of Ireland. (2007). *National Climate Change Strategy 2007-2012.* Dublin: Department of the Environment, Heritage and Local Government.

Green, C., Tobin, B., O'Shea, M., Farrell, E., & Byrne, K. (2007). Above and belowground biomass measurements in an unthinned stand of Sitka spruce (*Picea sitchensis* (Bong) Carr.). *Eur. Jour. For. Res., 126*, 179-188.

Gryc, V., Vavrcik, H., & Horn , K. (2011). Density of juvenile and mature wood of selected coniferous species. *Jour. For. Sci., 57*, 123-130.

Hakkila, P. (2004). *Developing technology for large scale production of forest chips. Wood Energy Technology Programme 1999-2003.* Helsinki: TEKES.

Henttonen, H. (1984). The dependence of annual ring indices on some climatic factors. *Acta Forestal. Fenn.,186*, 1-38.

Hernandez, E. (2012). *A review on natural drying of biofuels.* Joensuu: COST Forest Energy Observer.

Hillring, B. (2006). World trade in forest products and wood fuel. *Biomass and Bioen., 30* (10), 815-825.

Hoadley, R. (1990). *Identifying wood. Accurate results with simple tools* (1st ed.). Newtown: The Taunton Press.

Holt, H. (1967). *Pre harvest measures to reduce the weight of second growth Douglas fir.* Corvallis: Unpublished MSc Thesis. Oregon State University.

Horgan, T., Keane, M., McCarthy, R., Lally, M., & Thompson, D. (2003). *A Guide to Forest Tree Species and Selection and Silviculture in Ireland*. (J. O'Carroll, Ed.) Dublin: COFORD.

Hoyne, S., & Thomas, A. (2001). *Forest residues. Harvesting, storage and fuel value.* Dublin: COFORD.

Ilic, J., Boland, D., McDonald, M., Downes, G., & Blakemore, P. (2000). *Wood density - Phase 1 state of knowledge.* Canberra: Autralian Greenhouse Office.

Javadi, Z., MacSiúrtáin, M., & Gardiner, J. (1983). The effect of tree espacement upon wood density in Sitka spruce (*Picea sitchesis* (Bong.) Carr.). *Irish For., 40* (2), 92-97.

Jeffers, J., & Dowden, H. (1964). Moisture content and specific gravity of freshly-felled conifers: analysis of weighted tree means. *Forestry Commission statistics section paper 70*.

Jensen, R., & Davis, J. (1953). *Seasonal Moisture Variations in Aspen.* School of Forestry, University of Minnesota.

Johansson, T. (1999). Biomass equations for determining fractions of pendula and pubescent birches growing on abandoned farmland and some practical implications. *Biomass and Bioen., 16* (3), 223-228.

Johansson, T. (2005). Stem volume equations and basic density for grey alder and common alder in Sweden. *Forestry, 78* (3), 249-262.

Josza, L., & Middleton, G. (1994). *A discussion of wood quality attributes and their practical implications.* Vancouver: Forintek Canada Corporation.

Jyske, T., Makinen, H., & Saranpaa, P. (2008). Wood Density within Norway spruce stems. *Silva Fenn., 42* (3), 439-455.

Karltun, E., Saarsalmi, A., Ingerslev, M., Mandre, M., Andersson, S., Gaitnieks, T., Ozolincius, R. & Varnagiryte-Kabasinskeine, I. (2008). Wood ash recycling - Possibilities and risks. In *Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic regions.* Eds. Roser, D., Asikainen, A., Rauland-Rasmussen, K. and Stupak, I., Springer Science + Business Media, The Netherlands, pp. 79-101.

Karsenty, A., Blanco, C., & Dufour, T. (2003). *Instruments related to the United Nations Framework Convention on Climate Change.* Rome: FAO.

Keane, T., & Sheridan, T. (2004). Climate of Ireland. In T. Keane, & J. Collins, *Climate, Weather and Irish Agriculture* (2nd ed., pp. 27-58). Dublin: AGMET.

Kellomaki, S. (1979). On geoclimatic variation of basic density of Scots pine wood. *Silva Fenn., 13* (1), 55-64.

Kent, T. (2009). Wood Fuel Quality Testing Methodologies. Presentation made at: Wood fuel Quality and Quality Assurance Workshop, January 21st 2009. Dublin: Sustainable Energy Authority of Ireland & COFORD.

Kent, T. (2012). Leveraging additional biomass from the forest resource. *National Bioenergy Conference 2012. Growing the Bio-Economy.* Athlone: Teagasc.

Kent, T., Coates, E., & Kofman, P. (2011). *Harvesting wood for energy. An investigation into cost effective wood fuel supply chains from Irish forestry.* Dublin: COFORD.

Kern, Z., Patko, M., Kazmer, M., Fekete, J., Kele, S., & Palyi, Z. (2012). Multiple tree ring proxies (earlywood width, latewood width and ɗ13^{C} from penduncculate oak (*Quercus robur* L.), Hungary. *Quarten. Inter., 293,* 257-267.

Kiaei, M., & Samarihu, A. (2011). Fibre dimensions, physical and mechanical properties of five important hardwood plants. *Indian Jour. Sci. Tech., 4* (11), 1460-1464.

Klasnja, B., Kopitovic, S., & Orlovic, S. (2002). Wood and bark of some poplar and willow clones as fuelwood. *Biomass & Bioen., 23* (6), 427-432.

Knaggs, G., & O'Driscoll, E. (2008). *An overview of the Irish wood-based biomass sector.* Dublin: COFORD.

Knaggs, G., & O'Driscoll, E. (2010). *An overview of the Irish wood-based biomass sector in 2007 - 2009.* Dublin: COFORD.

Knaggs, G., & O'Driscoll, E. (2012a). *Woodflow and forest-based biomass energy use on the island of Ireland (2010).* Dublin: COFORD.

Knaggs, G., & O'Driscoll, E. (2012b). *Woodflow and forest-based biomass energy use on the island of Ireland (2011).* Dublin: COFORD.

Kofman, P. (2006a). *Firewood.* Dublin: COFORD.

Kofman, P. (2006b). *Quality wood chip fuel.* Dublin: COFORD.

Kofman, P., & Kent, T. (2007). *Harvesting and Processing Forest Biomass for Energy Production. The Forest Energy 2006 Programme.* Dublin: COFORD.

Kofman, P., & Kent, T. (2009a). *Forest storage and seasoning of conifer and broadleaf whole trees.* Dublin: COFORD.

Kofman, P., & Kent, T. (2009b). *Long term storage and seasoning of conifer energy wood.* Dublin: COFORD.

Kofman, P., & Kent, T. (2009c). *Production of wood chip from premature clearfelling of lodgepole pine on cutaway peat.* Dublin: COFORD.

Kofman, P., & Kent, T. (2009d). *Storage and seasoning of conifer and broadleaf firewood.* Dublin: COFORD.

Kofman, P. (2010). *Preview of European standards for solid biofuels.* Dublin: COFORD.

Kofman, P. (2012, July). Development of International solid biofuel standards. *Forestry and Wood Update Newletter, Volume 12 - No. 2.* Dublin: COFORD.

Larson, P., Kretschmann, D., Clark, A., & Isebrands, J. (2001). *Formation and properties of juvenile wood in Southern pines. A synopsis.* Madison: Forest Products Laboratory.

Levy, P. E., Hale, S. E., & Nicoll, B. E. (2004). Biomass expansion factors and root:shoot ratios for coniferous tree species in Great Britain. *Forestry, 77* (5), 421-430.

Li, X., Koseki, H., & Momota, M. (2006). Evaluation of danger from fermentation - induced spontaneous ignition of wood chips. *Jour. Haz. Mat., 135* (1-3), 15-20.

Liu, C. (2009). From a tree to a stand in Finnish Boreal forests: biomass estimation and comparison of methods. Helsinki: University of Helsinki.

Liu, C., & Westman, C. (2009). Biomass in a Norway spruce-Scots pine forest: a comparison of estimation methods. *Bor. Environ. Res., 14*, 875-888.

Loibneggar, T. (2011). *Roadmap for implementing standards.* Graz: Intelligent Energy Europe.

MacDonald, E., & Hubert, J. (2002). A review of the effects of silviculture on timber quality of Sitka spruce. *Forestry, 75* (2), 107-138.

Maeglin, R. (1987). Juvenile wood, tension wood and growth stress effects on processing hardwoods. Memphis: Hardwood Research Council.

Magner, D. (2012, November 3rd). Record levels of felling license applications by private growers. *Irish Farmers Journal*, p. 30.

Maguire, K., Ní Dhubháin, Á., & Farrelly, N. (2010). The suitability of the private forest estate in Ireland for first thinning. *Irish For., 67*, 21-37.

Manwiller, F. (1975). *Wood and bark moisture contents of small diameter hardwoods growing on southern pine sites.* Pineville: United States Department of Agriculture.

Matthews, R., & Mackie, E. (2006). *Forest mensuration. A handbook for practitioners* (2nd ed.). Edinburgh: British Forestry Commission.

McCarthy, R. (1979). The energy potential of forest biomass in Ireland. *Irish For., 36* (1), 7-18.

McCarthy, R., & Keogh, R. (1983). The potential contribution of state forests to the supply of energy. *Irish For., 40* (2), 98-109.

McCulloh, K., Sperry, J., Lachenbrach, B., Meinzer, F., Reich, P., & Voelker, S. (2010). Moving water well: comparing hydraulic efficiency in twigs and trunks of conifers, ring porous and diffuse porous saplings from temperate and tropical forests. *New Phytologist.*

McKendry, P. (2002a). Energy production from biomass (Part 1): Overview of biomass. *Biores. Tech., 83* (1), 37-46.

McKendry, P. (2002b). Energy production from biomass (Part 2): Conversion technologies. *Biores. Tech., 83* (1), 47-54.

McMinn, J. (1986). *Transpirational drying of Piedmont hardwoods.* Georgia Forestry Commission Research Division.

Met Eireann. (2012). *Monthly Data*. Retrieved November 4th, 2012, from www.met.ie: http://www.met.ie/climate/monthly-data.asp?Num=1475

Miao, Z., & Li, C. (2007). *Biomass estimates for major Boreal forest species in west central Canada.* Edmonton: Canadian Forest Service.

Michalec, J., & Niklasova, S. (2006). *Water uptake of hardwoods.* Vaxjo University.

Michelot, A., Breda, N., Damesi, C., & Dufrene, E. (2012). Differing growth responses to climatic variations and soil water deficits of *Fagus sylvatica, Quercus petrea, Pinus sylvestris* in a temperate forest. *For. Ecol. Man., 265*, 161-171.

Miksys, V., Varnagiryte-Kabasinkiene, I., Stupak, I., Armolaitis, K., Kukkola, M., & Wójcik, J. (2007). Above-ground biomass functions for Scots pine in Lithuania. *Biomass & Bioen., 31* (10), 685-692.

Mochan, S. (2006). Sourfelling trial results - a pilot study. Forest Research, the research branch of the British Forestry Commission.

Moore, J. (2011). *Wood properties and uses of Sitka spruce in Britain. Forestry Commission research report.* Edinburgh: Forestry Commission.

Mora, C., Schimleck, L., Yoon, S., & Thai, C. (2011). Determination of moisture content and basic density of loblolly pine wood disks using a near infrared hyperspectral imaging system. *Jour. Near. Infra. Spec., 19* (5), 401-409.

Nawrot, M., Pazdrowski, W., & Szymanski, M. (2008). Dynamics of heartwood formation and axial and radial distribution of sapwood and heartwood in stems of European larch (*Larix decidua* Mill.). *Jour. For. Sci., 54* (9), 409-417.

Neumann, M., & Jandl, R. (2005). Derivation of locally valid estimators of the aboveground biomass of Norway spruce. *Eur. J. For. Res., 124*, 125-131.

National Forest Inventory. (2007). *National Forest Inventory: Results.* Forest Service. Dublin: Government Publications.

Ní Dhubháin, A., Magner, D., & Nieuwenhuis, M. (2006). Juvenile wood in Irish grown Sitka spruce and the impact of rotation length. *Irish For., 63*, 26-36.

Nord-Larsen, T., Bergstedt, A., Farver, O., & Heding, N. (2011). Drying of firewood - the effect of harvesting time, tree species and shelter of stacked wood. *Biomass and Bioen., 35*, 2993-2998.

North, P., & Healion, K. (2003). *COFORD strategic study - Maximising the potential of wood use for energy*. Dublin: COFORD.

NREAP. (2010). *National Renewable Energy Action Plan for Ireland.* Dublin: Department of Communications Marine and Natural Resources.

NSAI. (2009). National Working Agreement 4 : 2009 : Woodfuel Quality Assurance - Requirements. Dublin: National Standards Authority of Ireland.

Nurmi, J. (1993). Heating values of the above ground biomass of small sized trees. *Acta For. Fenn., 236*, 30p.

Nurmi, J. (1997). Heating values of mature trees. *Acta For. Fenn., 256*, 2-28.

Nurmi, J., & Lehtimaki, J. (2010). Debarking and drying of downy birch (*Betula pubescens*) and Scots pine (*Pinus sylvestris*) fuelwood in conjunction with multi-tree harvesting. *Biomass & Bioen., 35* (8), 3376-3382.

Obernberger, I., Brunner, T., & Barnthaler, G. (2006). Chemical properties of solid biomass - significance and impact. *Biomass & Bioen., 30* (11), 973-982.

O'Driscoll, E. (2011). *UNECE Timber Commitee Marketing Report for Ireland 2011.* Dublin: Department of Agriculture Fisheries and Food.

O'Halloran, J. (2010, August). Ecotoxicological and growth promoting properties of wood ash. *Forestry and Wood Update Newletter, Volume 10 - No. 8.* Dublin: COFORD.

O'Halloran, J. (2012). Biomass to Mega Watts. *National Bioenergy Conference 2012. Growing the Bio - Economy.* Athlone: Teagasc.

O’Rourke, F., Boyle, F., & Reynolds, A. (2009). Renewable energy resources and technologies applicable to Ireland. *Renew. and Sus. Ener. Rev., 13* (8), 1975-1984.

Overman, J., Witte, H., & Saldarriga, J. (1994). Evaluation of regression models for above-ground biomass determination in Amazon rainforest. *Jour. Trop. Ecol., 10* (2), 207-218.

Pajtik, J., Konopka, B., & Lukac, M. (2008). Biomass functions and expansion factors in young Norway spruce trees (*Picea abies* (L.) Karst.). *For. Ecol. Man., 256* (5), 1096-1103.

Peck, E. (1959). *The sap or moisture in wood.* Madison: USDA Forest Products Laboratory.

Peichl, M., & Altaf Arain, M. (2007). Allometry and partitioning of above and below ground tree biomass in an age-sequence of white pine forests. *For. Ecol. Man., 253* (1-3), 68-80.

Peichl, M., Leava, N., & Kiely, G. (2012). Above and belowground ecosystem biomass C and N allocation in recently afforested grassland and adjacent intensively managed grassland. *Plant Soil , 344* (1-2), 281-296.

Pettersson, M., & Nordfjell, T. (2006). Fuel quality changes during seasonal storage of compacted logging residues and young trees. *Biomass and Bioen., 31* (11-12), 782-792.

Phillips, H. (2011). *All Ireland roundwood production forecasts 2011-2028.* Dublin: COFORD.

Picard, N., Saint - André, L., & Henry, M. (2012). *Manual for building tree volume and biomass allometric equations.* Montpellier: FAO.

Pinchot, G. (2005). *Measurement of earlywood and latewood properties in loblolly pine.* Madison: Forest Products Laboratory.

Pitman, R.M. (2006). Wood ash use in forestry - A review of the environmental impacts. *Forestry, 79* (5), 563-588.

Premyslovska, E., Slezingeroua, J., & Gandelova, L. (2007). Tree ring width and basic density of wood in different forest types. *Proceedings of DENDROSYMPOSIUM* (pp. 118-122). Riga: TRACE - Tree rings in archaeology, climatology and ecology.

Punches, J. (2004). *Tree growth, forest management and their implications for wood quality.* Corvallis: Oregon State University.

Purser, P. (2000). *Timber measurement manual. Standard procedures for the measurement of round timber for sale purposes in Ireland.* Dublin: COFORD.

Purser, P., & Lynch, T. *Dynamic yield models used in Irish forestry*. Dublin: COFORD.

Radford, T., & Short, I. (2008). *Silvicultural guidelines for the tending and thinning of broadleaves.* Athenry: Teagasc.

Ragland, K., Aerts, D., & Baker, A.J. (1991). Properties of wood for combustion analysis. *Biores. Tech., 37* (2), 161-168.

Rauland-Rasmussen, K., Stupak, I., Clarke, N., Callesen, I., Hellmisaari, H.S. & Karltun, F. (2008). Effects of very intensive forest biomass harvesting on short and long term site productivity. In *Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic regions.* Eds. Roser, D., Asikainen, A., Rauland-Rasmussen, K. and Stupak, I., Springer Science + Business Media, The Netherlands, pp 29-70.

Redmond, J. (2012). Personal communication.

Reeb, J. (2009). *Wood and moisture relationships.* Corvallis: Oregon State University.

REFIT III. (2012). *A competition for electricity generation from biomass technologies.* Dublin: Government of Ireland.

Reilly, J. (2010). The co - firing market for biomass. *National Forestry Conference 2010. Generating revenue from your woodlands.* Kilkenny: COFORD.

Repola, J. (2008). Biomass equations for birch in Finland. *Silva Fenn.*, *42* (4), 605-624.

Repola, J. (2009). Biomass equations for Scots pine and Norway spruce in Finland. *Silva Fenn.*, *43* (4), 625-647.

Repola, J. (2006). Models for vertical wood density of Scots pine, Norway spruce and birch stems and their application to determine average wood density. *Silva Fenn.*, *40* (4), 673-685.

Repola, J., Ojansuu, R., & Kukkola, M. (2007). *Biomass functions for Scots pine, Norway spruce and birch in Finland.* Joensuu: Metla.

Revenue Commissioners. (2013). Guidance on solid fuel carbon tax. Revenue Commissioners, Dublin.

Rikala, J. (2003). *Spruce and pine on drained peatlands - wood quality and suitability for the sawmill industry*. Helsinki: University of Helsinki Department of Forest Resource Management Publications No. 35.

Rolls, W. (2009). *Wood as a fuel.* Forestry Commission England.

Rolls, W. (2010). *Wood as a fuel technical supplement.* Edinburgh: British Forestry Commission.

Roser, D., Asikainen, A., Stupak, I., & Pasanen, K. (2008). Forest Energy Resources and Potential. In *Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic regions*. Eds. Roser, D., Asikainen, A., Rauland-Rasmussen, K. and Stupak, I., Springer Science + Business Media, The Netherlands, pp 29-70.

Roser, D., Erkkila, A., Mola-Yodego, B., Sikanen, L., Prinz, R., Heikkinen, A., et al. (2010). *Natural drying methods to promote fuel quality enhancement of small energywood systems.* Joensuu: TEKES.

Rothpfeffer, C., & Karltun, E. (2007). Inorganic elements in tree compartments of *Picea abies* - concentrations versus stem diameter in wood and bark and concentrations in needles and branches. *Biomass and Bioen.*, *31* (10), 717 - 725.

Saarsalmi, A., Smolander, A., Kukkola, M., Moilanen, M., & Saramaki, J. (2012). 30 - Year effects of wood ash and nitrogen fertilisation on soil chemical properties, soil microbial processes and stand growth in a Scots pine stand. *For. Ecol. Man., 278,* 63-70.

Samuelsson, R., Burvall, J., & Jirjis, R. (2006). Comparisons of different methods for the determination of moisture content in solid biomass. *Biomass & Bioen., 30* (11), 929-934.

Savill, P. (1979). Rate of weight loss of small round timber. *Irish For., 36* (1), 48-56.

Savoleinen, V., & Berggren, H. (2000). *Wood fuels basic information pack.* Jyvaskyla: Finland.

Schulze, J., Cermak, R., Matyssek, M., Penka, R., Zimmermann, F., Vasicek, W., et al. (1985). Canopy transpiration and water fluxes in the xylem of *Larix* and *Picea* trees - a comparison of xylem flow, porometer and cuvette measurements. *Oceologia*, *66*, 474-483.

Senelwa, K., & Sims, R. (1999). Fuel characteristics of short rotation forest biomass. *Biomass & Bioen.*, *17* (2), 127-140.

Serup, H., & Kofman, P. (2005). *Wood for Energy Production, Irish edition.* Dublin: COFORD.

Shotaffer, J., & Brackley, A. (1982). *An analysis of moisture content variation in eastern spruce and balsam fir in Maine.* Orono: University of Maine.

Sikanen, L. (2010). Effect of moisture content on the financial and environmental cost of forest biomass. (Metla, Compiler) Trento.

Singh, T. (1984). Variation in the ovendry wood density of ten prarie species. *The Forestry Chronicle, 60* (4), 217-221.

Snowdon, P., Raison, J., Heather, K., Ritson, P., Grierson, P., Adams, M., et al. (2002). *Protocol for sampling tree and stand biomass.* Canberra: Australian Greenhouse Office.

Solid Standards. (2011). Enhancing the implementation of quality and sustainability standards and certification schemes for solid biofuels (EIE/11/218). Utrecht University: The Netherlands.

Sprugel, D. (1983). Correcting for bias in log-transformed allometric equations. *Ecology*, *64* (1), 209-210.

Stupak, I., Asikainen, A., Roser, D. & Pasanen, K. (2008). Review of recommendations for forest energy harvesting and wood ash recycling. In *Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic regions.* Eds. Roser, D., Asikainen, A., Rauland-Rasmussen, K. and Stupak, I., Springer Science + Business Media, The Netherlands, pp 155-191.

Swithenbank, J., & Chen, Q., Zhang, X., Sharifi, V., Pourkashanian, M. (2011). Wood would burn. *Biomass & Bioen., 35* (3), 999-1007.

Taylor, A., Gartner, B., & Morrell, J. (2002). Heartwood formation and natural durability - a review. *Wood Fib. Sci., 34* (4), 587-611.

Teagasc. (2012). A guide to forest owner groups in Ireland. Athenry: Teagasc.

Tobin, B., & Nieuwenhuis, M. (2007). Biomass expansion factors for Sitka spruce (*Picea sitchensis* (Bong.) Carr). *Eur. J. For. Res., 126*, 189-196.

Tobin, B., & Green, C. (2006). Biomass stocks in young Sitka spruce and lodgepole pine stands. In K. Black & E.P. Farrell (Eds.), *Carbon sequestration and Irish forest ecosystems* (pp. 55-57). Dublin: COFORD.

Traver, E., Ewers, B., Mackay, D., & Loranty, M. (2010). Tree transpiration varies spatially in response to atmospheric but not edaphic conditions. *Func. Ecol., 24* (2), 273-282.

Treacy, M., Evertsen, J., & Ní Dhubháin, A. (2000). *A comparison of mechanical and physical wood properties of a range of Sitka spruce provenances.* Dublin: COFORD.

United Nations. (1998). *Kyoto protocol to the United Nations Framework Convention on Climate Change.* United Nations.

Uri, V., Varik, M., Aosaar, J., Kanal, A., Kukumagi, M., & Lohmus, K. (2012). Biomass production and carbon sequestration in a fertile silver birch (*Betula pendula* Roth.) forest chronosequence. *For. Ecol. Man., 267*, 117-126.

USDA. (1936). *Differences between heartwood and sapwood.* Madison: Forest Products Laboratory.

Ward, D., & Gardiner, J. (1976). The influence of tracheid length and density in Sitka spruce. *Irish For., 33* (1), 39-56.

Werkelin, J., Skrifvars, B., & Hupa, M. (2005). Ash - forming elements in four Scandinavian wood species. Part 1: Summer harvest. *Biomass & Bio., 29* (6), 451-466.

West, P. (2004). *Tree and forest measurement.* Berlin: Springer.

Wharton, E., & Douglas, M. (1995). *Estimating total forest biomass in Maine, 1995.* Radnor: USDA.

Wiedenhoelt, A. (2010). Structure and function of wood. In U. S. Forest Service (Ed.), *Wood handbook. Wood as an engineering material.* Madison: Forest Products Laboratory.

Wiemann, M., & Williamson, G. (2002). Geographic variation in wood specific gravity: effects of latitude, temperature and precipitation. *Wood Fib. Sci., 34* (1), 96-107.

Williamson, G., & Wiemann, M. (2010). Measuring wood specific gravity... Correctly. *Amer. Jour. Bot., 97* (3), 519-524.

Xiemes, F., Gardiner, W., & Kathuria, A. (2008). Proportion of above-ground biomass in commercial logs and residues following the harvest of five commercial tree species in Australia. *For. Ecol. Man., 256* (3), 335-346.

Zianis, D., & Mencuccini, M. (2004). On simplifying allometric analyses of forest biomass. *For. Ecol. Man., 187*, 311-322.

Zianis, D., Muukkonen, P., Makipaa, R., & Mencuccini, M. (2005). Biomass and stem volume equations of tree species in Europe. *Silva Fennica Monographs 4*, 63p.

Zischke, D. (1956). *Lodgepole pine.* Madison: USDA.