# The UK's forest resource and its potential as a sustainable feedstock for bioenergy

**Douglas Phillips**

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Doctoral Training Centre in Low Carbon technologies, Energy Research Institute, School of Chemical and Process Engineering,

The University of Leeds

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*“you can mark my words, I’ll make changes to earth”*

*– Scott Hutchison –*

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# Abstract

The solutions for mitigating climate change are diverse, ranging from innovative technological advancements to national and international policy mechanisms, aimed at behavioural changes. Although rudimentary, the use of wood biomass in energy generation – as an important short- to mid-term transitional fuel – has continued to grow, forming a key component of global mitigation strategies. This is particularly apparent in the UK, which relies upon large volumes of imported wood pellets to supplement home-grown feedstocks. As the UK's forest resource is relatively small – when compared to the rest of Europe – the governments recently proposed afforestation schemes should prove beneficial; however, before initiating any major tree planting scheme, it is important to first fully understand the existing resource.

This interdisciplinary research – exemplifying the diverse nature of forestry – has investigated the UK's current forest feedstocks, focusing on samples sourced from different tree sections of UK-grown oak, birch, Scots pine and Sitka spruce. Their fundamental characteristics have been analysed, including the completion of Proximate, Ultimate and Lignocellulosic analysis, and the determination of their calorific values. Utilising these results – alongside data collated from extensive literature sources – the statistically significant differences that exist between wood feedstocks have been defined, inferring relationships that link their elemental, chemical and structural components. Consequently, the known heterogeneity of wood – and how this differs between species and tree sections – has been demonstrated, specific to UK-grown wood species.

These differences can have both negative and positive impacts upon woodfuel quality and the forest environment, particularly in relation to the blending of residues and stump wood with stem wood. In the case of UK-grown birch and Sitka spruce this could increase the volume and energy content of the produced woodfuel, however it will also result in a more reactive fuel, containing increased contents of nitrogen and potassium. An investigation into the costs of felling and extracting wood from UK forests – incorporating geospatial analysis of the UK's existing feedstocks – suggests it is currently economically viable to increase the supply of woodfuel from the nation's forests. This could produce an estimated

2,645 TJ $yr^{-1}$ of additional energy, specifically for domestic use in rural locations, situated close to the UK's forest resource. Although the continued expansion of the UK's woodfuel market is viable, it is important that the profitable production of fuel is balanced with the continued protection of our forest environments.

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# Abbreviations & Nomenclature

| | |
|---|---|
| $A$ | *Pre-exponential factor ($s^{-1}$)* |
| a.u. | *Arbitrary unit* |
| AAS | *Atomic Absorption Spectrometry* |
| ADF | *Acid Detergent Fibre* |
| ADL | *Acid Detergent Lignin* |
| ANOVA | *Analysis of Variance* |
| ANUDEM | *Australian National University Digital Elevation Model* |
| $\mathrm{Ar}_{\mathrm{i}}$ | *Calculated forested area* |
| BEIS | *Department for Business, Energy & Industrial Strategy* |
| BI | *Birch* |
| Ce | *Cellulose* |
| $c_i$ | *Supply route costs (£ $m^3$)* |
| $CI_1$ | *Lower confidence interval* |
| $CI_3$ | *Upper confidence interval* |
| CM | *Cellulose microfibril* |
| $\mathrm{CO}_{2\mathrm{e}}$ | *Carbon dioxide equivalent* |
| CTL | *Cut-To-Length* |
| daf | *Dry ash free* |
| db | *Dry basis* |
| DBH | *Diameter at Breast Height (cm)* |
| $df$ | *Degrees of Freedom* |
| $df_e$ | *Degrees of Freedom (population error variance)* |
| $df_t$ | *Degrees of Freedom (dependent variables population variance)* |
| dm/dt | *Rate of mass loss (Wt.% $s^{-1}$)* |
| DS | *Dataset* |
| DSS | *Decision Support System* |
| DTM | *Digital Terrain Model* |
| DUKES | *Digest of United Kingdom Energy Statistics* |
| E | *Relative experimental error* |
| $E$ | *Activation energy (kJ $mol^{-1}$)* |
| EC | *European Commission* |
| ECO | *Energy Company Obligation* |
| EF | *Extractive free* |
| $e_{\mathrm{i}}$ | *Individual experimental error* |
| EPC | *Energy Performance Certificate* |
| ESRI | *Environmental Systems Research Institute* |
| ETS | *Emissions Trading System* |
| EU | *European Union* |
| EUR | *Euro (€)* |
| $f(x)$ | *Function* |
| FC | *Forestry Commission* |
| FC | *Fixed carbon* |
| $F$-ratio | *Variability between groups (ANOVA)* |
| G | *Guaiacyl units* |
| GB | *Great Britain* |

| | |
|---|---|
| GBP | *Pound sterling (£)* |
| GCV | *Gross Calorific Value* |
| GDP | *Gross Domestic Product* |
| GEC | *Gross Energy Consumption* |
| GHG | *Greenhouse Gases* |
| GIS | *Geographical Information System* |
| Gt | *billion ($10^9$) tonnes* |
| H | *ρ-Hydroxyphenyl units* |
| H:C | *Hydrogen and Carbon ratio* |
| $H_0$ | *Null hypothesis* |
| $H_1$ | *Proposed hypothesis* |
| ha | *Hectare* |
| $ha^{-1}$ | *per Hectare* |
| HDD | *Heating Degree Days* |
| He | *Hemicellulose* |
| $hr^{-1}$ | *per Hour* |
| HSD | *Honest Significant Difference* |
| HW | *Hardwood* |
| IBERS | *Institute of Biological, Environmental and Rural Sciences* |
| ICP-MS | *Inductively Coupled Plasma Mass Spectrometry* |
| IEA | *International Energy Agency* |
| IFT | *Interpreted Forest Types* |
| IPCC | *Intergovernmental Panel on Climate Change* |
| IQR | *Interquartile Range* |
| $k$ | *Reaction rate constant ($s^{-1}$)* |
| L:H | *Lignin and Holocellulose ratio* |
| LCA | *Lifecycle Assessment* |
| Li | *Lignin* |
| LSOA | *Lower Layer Super Output Area* |
| LULUCF | *Land Use, Land-Use Change and Forestry* |
| M | *Mean* |
| M ha | *Million hectares* |
| m.g.t | *Million green tonnes* |
| $m_\infty$ | *Terminal mass (Wt.%)* |
| $m_{ash}$ | *Mass of ash* |
| MC | *Moisture content* |
| $m_d$ | *Mass of dried sample* |
| $m_i$ | *Mass at a given point* |
| MSE | *Mean Square Error* |
| MSR | *Regression Mean Square* |
| Mt | *Million tonnes* |
| $m_{vm}$ | *Mass of sample (post-devolatilisation)* |
| $m_w$ | *Initial mass of sample* |
| MW | *Mixedwood* |
| $n$ | *Total number of values* |
| N:C | *Nitrogen and Carbon ratio* |
| NCV | *Net Calorific Value* |

| | |
|---|---|
| NDF | *Neutral Detergent Fibre* |
| NFI | *National Forest Inventory* |
| NIFS | *Northern Ireland Forest Service* |
| $n_x$ | *Mass fraction of structural component* |
| O:C | *Oxygen and Carbon ratio* |
| OK | *Oak* |
| OLS | *Ordinary Least Squares* |
| ONS | *Office for National Statistics* |
| OS | *Ordnance Survey* |
| OSNI | *Ordnance Survey Northern Ireland* |
| PAH | *Polyaromatic Hydrocarbons* |
| PL | *Payload* ($m^3$) |
| PM | *Particulate Matter* |
| $p$-value | *Probability value* |
| $Q_1$ | *Lower quartile* |
| $Q_3$ | *Upper quartile* |
| $r$ | *Radius* |
| R | *Gas constant* ($8.314\ kJ\ mol^{-1}.K^{-1}$) |
| $R^2$ | *Coefficient of Determination* |
| $\bar{R}^2$ | *Adjusted Coefficient of Determination* |
| RED | *Renewable Energy Directive* |
| RF | *Radiative Forcing* |
| RSD | *Relative Standard Deviation* |
| S | *Syringyl units* |
| SD | *Standard Deviation* |
| SEM | *Scanning Electron Microscope* |
| $SE_{pd}$ | *Standard error for productivity (p) and DBH (d)* |
| $SE_{\bar{x}}$ | *Standard error of the mean* |
| SP | *Scots pine* |
| spp. | *Species* |
| SPSS | *Statistical Package for the Social Sciences* |
| SS | *Sitka spruce* |
| $SS_{res}$ | *Residual Sum of Squares* |
| SSSI | *Sites of Specific Scientific Interest* |
| $SS_{tot}$ | *Total Sum of Squares* |
| SW | *Softwood* |
| T | *Temperature (°C)* |
| $T$ | *Temperature (K)* |
| $\mathrm{T}_1$ | *Temperature at initial mass loss (°C)* |
| $\mathrm{T}_2$ | *Temperature at burnout (°C)* |
| Tc | *Temperature at peak char combustion (°C)* |
| Ts | *Temperature at shoulder (°C)* |
| Tv | *Temperature at peak volatilisation (°C)* |
| TCY | *Theoretical Char Yield* |
| TGA | *Thermogravimetric Analysis* |
| $t_i$ | *Time at a given point (s)* |
| TWh | *Terawatt hours* |

| | |
|---|---|
| UK | *United Kingdom* |
| UN | *United Nations* |
| UNFCCC | *United Nations Framework Convention on Climate Change* |
| $V$ | *Stated standardised DBH value* |
| VM | *Volatile matter* |
| VOC | *Volatile Organic Compounds* |
| $w_i$ | *Normalised weighting* |
| X | *Mean value* |
| $\bar{X}_c$ | *Calculated mean cost of wood harvesting (£ $m^3$)* |
| $\bar{X}_{pd}$ | *Mean for productivity (p) and DBH (d)* |
| $\bar{X}_s$ | *Standardised mean for productivity ($m^3$ $h^{-1}$)* |
| $x_c$ | *Mean of specific independent variable* |
| $x_i$ | *Independent variable* |
| $x_{max}$ | *Largest value within a dataset* |
| $x_{min}$ | *Smallest value within a dataset* |
| $x_s$ | *Standardised value* |
| $y_c$ | *Mean of specific dependent variable* |
| $y_i$ | *Dependent variable* |
| $yr^{-1}$ | *per Annum* |
| $\alpha$ | *Y-intercept* |
| $\beta$ | *Vector (slope)* |
| $\varepsilon_i$ | *General experimental error* |
| $\mu m$ | *Micrometre* |
| $\mu_x$ | *Population mean of group (x)* |
| $\sigma$ | *Standard Deviation* |
| $\sigma_p$ | *Pooled Standard Deviation* |
| %E | *Total % relative experimental error* |
| $\%e_i$ | *Individual % error (experimental)* |
| $\neq$ | *Statistically Significantly Different* |

## Our Priceless Resource

*What was once a mere seedling*
*is now fully grown,*
*a part of the canopy*
*no longer alone.*

*Magnificent, glorious,*
*a beauty, profound!*
*With deep roots and high branches,*
*sustains life underground.*

*There is strength in a forest:*
*a unified force,*
*a diverse ecosystem,*
*oh what a resource!*

*An assorted society*
*Copper beech, birch and oak.*
*Lifeline for humanity,*
*through fire and smoke.*

*Sunlight, water, rivalry,*
*forms a stem straight and true.*
*Stores carbon, makes oxygen,*
*benefits that accrue.*

*There is strength in our forest:*
*our unified force,*
*our diverse ecosystem,*
*our priceless resource.*

# Chapter 1. Introduction

*"To light a candle is to cast a shadow" – Ursula K. Le Guin*

## 1.1. Introduction

The development and progression of mankind – from our archaic ancestry to today's modern humans – has been driven by major events throughout history. From the first evidenced control of fire to the creation of the internet, our history is littered with key triggers that have advanced human development. Of these, the Industrial Revolution has proved to be one of the most important turning points; where British technological innovation influenced manufacturing and engineering processes throughout Great Britain and across Europe [1]. Indeed, the reverberations of Europe's industrialisation, which started more than 250 years ago, are still felt today. Improvements to living standards, 21st Century technological comforts and access to diverse transport infrastructures – which are often taken for granted – are just a few of the benefits that exist as a direct result of the Industrial Revolution.

However, the successful industrialisation of Europe required major changes to the amounts of energy available for use. By the end of the Industrial Revolution the annual gross energy consumption of England and Wales had increased by nearly 800%, with the majority of this attributed to coal as the energy source [2]. As an energy-rich carbonaceous fuel, coal possessed the potential to significantly reduce production costs in industrial operations. It therefore became both a substitute for wood as a direct source of heating and, eventually, a core component of iron ore smelting and glass and brick manufacture. Clearly the utilisation of abundant fossil fuel sources, such as coal, resulted in a wealth of tangible benefits; however, just as a lit candle casts a shadow, those benefits have associated negative consequences. The combustion of organic fuels produces by-products – such as carbon dioxide, water vapour and other trace gases and aerosol emissions – which impact upon on health, air quality and the climate [3]. This ever-growing dependence on fossil fuels for energy creation prompted an interest into the implications that consequently emerged – an interest that still remains today.

## 1.2. A Changing Climate

Historical records indicate that the Earth's natural climate has been in a continued state of fluctuation, highlighting levels of variability that span hundreds of thousands of years. The basic principle dictating the changes in global temperature – and the consequent weather and climate variations that occur – relate to the balance of radiated solar energy absorbed by the Earth and its atmosphere, and the amount that is radiated back out into space [4].

### 1.2.1. Climate Change Science

On average, the net incoming solar radiation equates to 342 $Wm^{-2}$, some of which is initially reflected back by the Earth's clouds and atmosphere. Around half of the thermal radiation that makes it to the surface is absorbed before later returning to the atmosphere as infrared radiation, predominantly via evapotranspiration. The thermal energy that is not absorbed by the Earth's surface is reflected back towards the atmosphere and clouds – some of which is radiated out to space, while some returns back towards the surface [4]. Neither the nitrogen or oxygen that exist within the atmosphere absorb or emit thermal radiation; this process instead occurs due to the existence of greenhouse gases (GHGs) – water vapour ($H_2O$), carbon dioxide ($CO_2$), ozone ($O_3$), methane ($CH_4$) and nitrous dioxide ($N_2O$) – within the atmosphere. GHGs help regulate the Earth's average surface temperature at ~15°C, which is about 20°C warmer than it would be without them. Referred to as the natural greenhouse effect, this is a process that is vital for human life to flourish and continue [4].

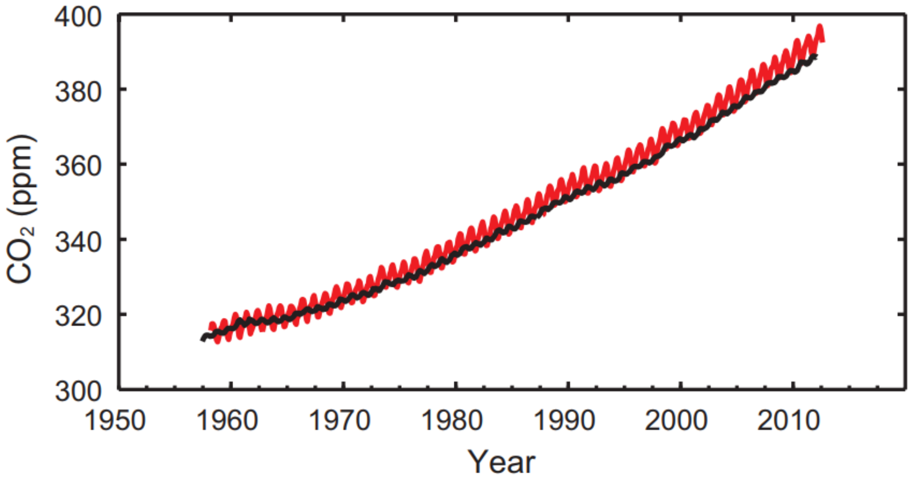


Figure 1.1 – **Measured atmospheric concentrations of carbon dioxide ($CO_2$) at the Mauna Loa Observatory (red) and the South Pole (black), since 1958 [5]**

The existence of naturally occurring GHGs in the Earth's atmosphere are essential, however there is now an almost unequivocal consensus that anthropogenic activities – such as fossil fuel combustion – have directly impacted these levels and, as a result, the Earth's climate. Since the start of the Industrial Revolution the concentrations of $CO_2$ have increased by 40%, with the current atmospheric concentrations of $CO_2$, $CH_4$ and $N_2O$ reaching their highest levels in the last 800,000 years [5]. Figure 1.1 details the measured atmospheric concentrations at two sites – the first is located in Hawaii, while the second is found at the South Pole. This highlights that $CO_2$ has continued to increase at different global locations during the last 50 years. Furthermore, the rates at which concentrations have increased during the last century are also at unprecedented levels, reaching their highest levels in the last 22,000 years [5].

The increase in atmospheric GHGs – caused by human activity – has resulted in changes to radiative forcing (RF); this is the quantification of the changes that occur in average net radiation at the top of the troposphere. The climate's response to RF stimulates a restoration of balance between the incoming and outgoing radiation. Consequently, a positive RF will result in the warming of the Earth's surface, while a negative RF will lead to its cooling [4, 5]. Although a complex area of research – in which different agents can account for positive and negative RF estimates – the existing scientific evidence strongly indicates that the continuation of GHG emissions will result in sustained warming, which will in turn increase the threats to the environment and mankind's safety.

### 1.2.2. Climate Change Policy

Evidence compiled by the Intergovernmental Panel on Climate Change (IPCC), using a range of modelled simulations, indicate that by the end of the 21st Century the global surface temperature is likely to exceed a 1.5°C increase, when compared to the mean temperatures between 1850-1900 [5]. A warmer climate brings with it an array of threats. Some of these are unique – specific to individual ecosystems and cultures – while others have a greater range of impact, such as extreme weather events like heat waves and coastal flooding. Worryingly, the distribution of these risks are estimated to greater impact those within society who are already the most disadvantaged [6]. The acceptance by the majority of the scientific community – that current climatic changes are primarily a result of sustained anthropogenic emissions – has prompted the world's political leaders to confront and attempt to deal with climate change.

#### 1.2.2.1. Global Consensus

In 1992, driven by concerns over the anthropogenic influence on atmospheric concentrations of GHGs, the United Nations Framework Convention on Climate Change (UNFCCC) was formed. The key objective of the convention – which today consists of 197 nations – is to combat climate change, specifically by stabilising atmospheric GHG concentrations at a level that prevents dangerous manmade interference with the Earth's climate system [7]. With a desire to define a long-term goal for climate change policy, the Kyoto Protocol was adopted in December 1997, containing legally binding emission targets for industrialised countries, during defined commitment periods [8, 9]. Although eventually ratified in 2005, the refusal of the United States of America to sign the protocol raised questions over the influence it would have in combatting climate change.

In 2016, the ratification of the Paris Agreement – which was the culmination of decades of work – represented a key moment in the political and global acceptance that mankind has a responsibility to combat climate change. By achieving the UNFCCC's objective of uniting nations, the long-term goal of keeping the global average temperature increase well below 2°C was agreed. This also contained further recognition that efforts should be made to limit this to 1.5°C above pre-industrial levels [10]. Donald Trump's accession to President has since prompted the United States' declaration of withdrawal from the agreement, however the targets – and the overriding desire to combat climate change – still remain.

### 1.2.2.2. European Targets & Policy

This climate change commitment is evident within the European Union (EU) and it's Member States; their independently-set domestic emissions target is to, by 2020, reduce their $CO_{2e}$ (equivalent) emissions by 20% and then by a minimum of 40% by 2030, when compared to the 1990 baseline levels. Current projections indicate that the 2020 target will be met, however to achieve their 2030 target then additional policies are required. Importantly, the EU's total emissions for 2015/16 reduced by 0.7% while their economy rose by 1.9% during the same time, solidifying the decoupling of emissions from GDP [11, 12].

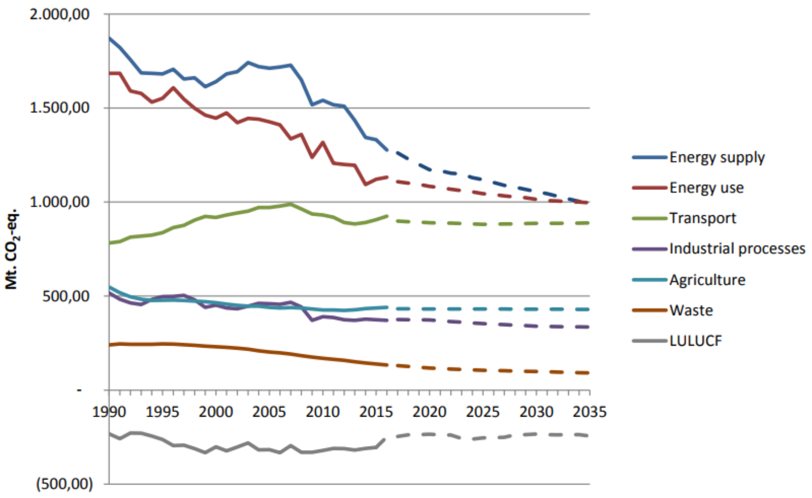


Figure 1.2 – **Historical data and projections of GHG emissions ($CO_{2e}$) of different sectors of the combined EU-28 nations [11]**

Figure 1.2 shows the sector breakdown of GHG emissions for the EU-28, detailing both the historical data and projections up to 2035. Since 1990, the sectors that have achieved the largest reductions have been energy related, although they still form a large proportion of the total GHG emissions. Projections indicate that the emission reductions from energy supply and consumption are set to continue, albeit at a reduced rate. The initial 20% GHG emission reductions are part of six legislative measures, collectively referred to as the “climate and energy package”. This emission reduction aim is part of a larger 20/20/20 objective, including a further two targets for 2020; to produce 20% of the EU’s energy from renewable sources and achieve a 20% improvement in energy efficiency. These, in turn, form part of a longer-term 2050 target – to reduce GHG emissions by 80-95% – with the EU policy focus on cost-effective, market-based mechanisms and the deployment of low-carbon technology [12].

The EU Emissions Trading System (ETS) is at the core of European climate policy, utilising market forces to drive emission reductions. Allocating a monetary value to GHG emissions – before instigating an emissions limit and the option to trade allowances – incentivises companies to reduce their emissions, while also allowing them to financially benefit from the sale of the superfluous allowances [13]. As a result, this cap-and trade system has prompted cost-effective emission reductions, currently accounting for nearly 2 billion tonnes of $CO_2$ emissions – a figure which has gradually decreased since the inception of the EU ETS [12]. In addition to utilising markets to drive emission reductions, the EU has also been a leader in the dissemination of technological innovation – demonstrated with their encapsulation of this in legislation, offering long-term stability to the business sector. The Renewable Energy Directive (Directive 2009/28/EC) outlines the EU’s intended policy for increasing the uptake and promotion of renewably sourced energy, specifically to help meet their 2020 targets. The renewable sources defined in the directive – wind, solar, hydropower, geothermal, tidal and wave power and biomass – represent opportunities for technology developments, helping phase out fossil fuels. Within the directive, Annex I details the individual renewable energy generation target for each member state; for the UK, the mandatory target is to achieve 15% gross final consumption of energy from renewable sources, by 2020 [14].

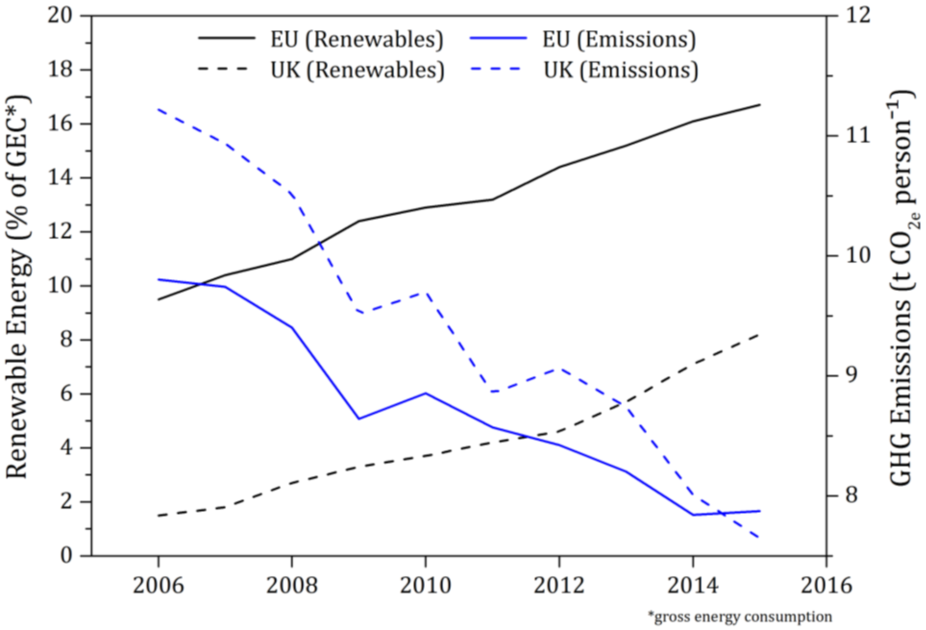


Figure 1.3 – **The share of the EU-28 and the UK's energy from renewable sources and their GHG emissions per capita [15]**

As highlighted by Figure 1.3, the EU-28's annual share of energy consumption attributed to renewable sources has continued to increase, reaching 16.7% in 2015. Consequently, the EU is set to meet its 20% renewables target by 2020. During this same period, their annual per capita GHG emissions decreased by ~20%, reducing to less than 8 tonnes of $CO_{2e}$ person$^{-1}$. The UK's reliance on renewables has increased considerably, growing from just 1.5% in 2006 to 8.2% in 2015. This trend continued in 2016, achieving 8.9% of gross energy consumption, with biomass proving to be the dominant renewable fuel source [16]. Since 2006 the UK's mean increase of renewables equates to 0.7% yr$^{-1}$, however to achieve the 15% target by 2020 this needs to double to 1.5% for the remaining four years. Although the UK's share of renewable energy is smaller than the majority of the remaining EU-28 nations, they have reduced their per capita emissions at a greater rate. Indeed, as shown in Figure 1.3, the UK eclipsed the per capita GHG emissions of the EU-28 in 2015, having continually reduced the gap over the previous decade.

The European Commission, as part of its Energy Union Framework Strategy, have announced plans for an updated renewable energy package, containing a new renewable energy directive (RED II). While the EU's current policies are predicted to achieve the 2020 renewable energy target, without additional policy mechanisms the Commission will fall short of its 2030 target; to achieve 27% of the gross energy consumption from renewable sources. In addition to an improved renewable energy policy framework, the new package will also contain regulations to Land Use, Land-Use Change and Forestry (LULUCF), which is set to include reinforced sustainability criteria for biomass – placing a legal requirement for proper carbon accounting of the resource [17].

#### 1.2.2.3. UK Climate Change Policy

The UK's commitments to combatting climate change has been enshrined in legislation, specifically the Climate Change Act 2008. This not only commits the UK to a long term GHG emissions reduction target, but it also defines the intended policy direction required to achieve it. Consequently, the UK's long-term reduction commitment is to reduce GHG emissions by at least 80% by 2050, compared to the 1990 baseline figures [18].

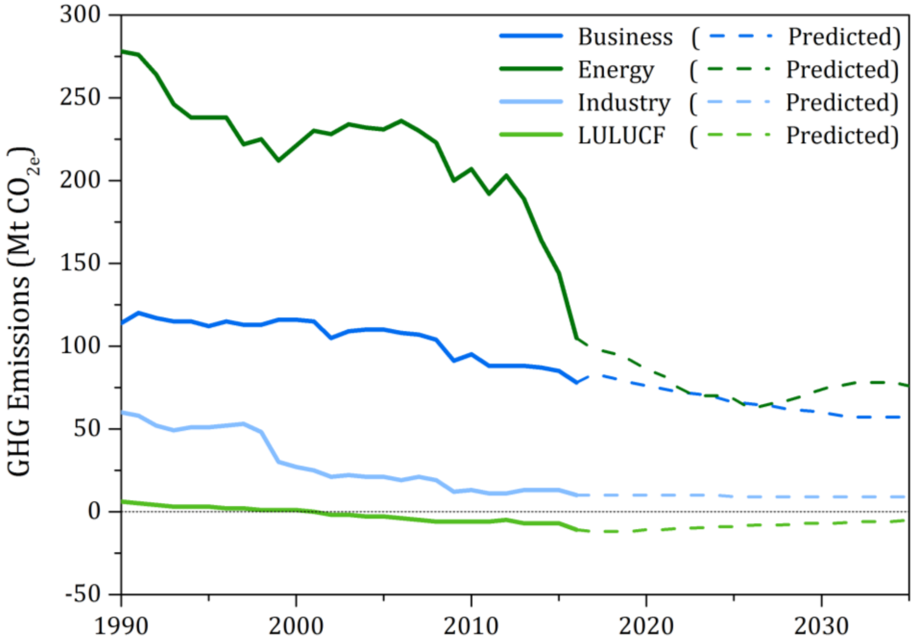


Figure 1.4 – **Historic GHG emissions from key UK sectors and predicted emissions considering the continuation of current climate change policies [19]**

The Act sets legally binding carbon budgets – each spanning a 5 year period – designed to keep the UK on track to meet its 2050 emission reduction targets. The 2nd budget period, 2013 to 2017, set a combined emission cap of 2,782 Mt

$CO_{2e}$, representing a reduction of 31% on the base year. This target is set to be met, with the release of the 2016 figures indicating a reduction of 42%. The targets and carbon caps for the remaining intermediate budget periods – taking the UK up to 2032 – can be found in Table 1.1 [19, 20]. Figure 1.4 shows the UK's progress in reducing the emissions in some of its key sectors, also detailing the predicted reductions, by 2035, if current policies were continued. Since the 1990 baseline year, the UKs emissions from its energy sector have reduced significantly, but are still responsible for the largest proportion of GHG emissions.

Table 1.1 – **Legally-binding UK carbon budgets and percentage reductions [20]**

| | **Intermediate Periods** | | |
|---|---|---|---|
| | **Period** | **Carbon Budget[1]** | **% Reduction[2]** |
| **1st** | *2008-12* | *3,018* | *25* |
| **2nd** | *2013-17* | *2,782* | *31* |
| **3rd** | *2018-22* | *2,544* | *37* |
| **4th** | *2023-27* | *1,950* | *51* |
| **5th** | *2028-32* | *1,725* | *57* |

*[1] Mt $CO_{2e}$ [2] compared to 1990 base year*

If the UK is to continue reducing its emissions, meeting the intermediate and long-term targets, then additional policies will be required. The government's long awaited *Clean Growth Strategy* – published in late 2017 – outlines the UK's key policies, required to further drive emission reductions over the next decade. In addition to promoting and accelerating 'clean growth', the strategy can be broken into six policy areas; 1) improving Business and Industry efficiency, 2) improving the housing sector, 3) aiding the uptake of low carbon transportation, 4) continuing the reduction of emissions from the energy sector, and 5) improving the nations natural resources [20]. There are a myriad of policies contained within these areas, however a key policy aim is to improve the energy efficiency of both the new and existing building stock – in both the commercial and residential sectors. This includes the continuation to existing schemes – such as the Energy Company Obligation (ECO) – and the promotion of innovative technological advancements. In the energy sector the use of coal for electricity production will be phased out by 2025, to be instead replaced with increases to offshore wind and nuclear power. The *Clean Growth Strategy* also contains the intention to increase forest cover within England – via a new network of forests and woodlands – with an additional commitment to increase the amount of UK-grown timber used within construction [20]. Figure 1.4 also indicates that the development of LULUCF can result in negative emissions, however new and coherent policy will be required to achieve and maintain this.

## 1.3. Biomass & Bioenergy

The term biomass refers to the organic materials sourced from either plant or animal origin. Plant-based biomass is produced via the process of photosynthesis; where the reaction between $CO_2$, water and sunlight form the necessary carbohydrate building blocks required for growth. Solar energy, a key driver of photosynthesis, is stored in the chemical bonds that exist within the structural components of biomass – energy which can be utilised at a later date [21, 22]. From early civilisation to the Industrial Revolution, biomass – predominantly in the form of wood – had been the main fuel utilised for heating and cooking. However, by 1850 the majority of Great Britain and Europe had replaced wood with fuels that contained a greater energy density, in particular coal [2, 22]. Today biomass plays an important role in global energy production, providing 10.2% of the annual global primary energy supply in 2008, equating to 50.3 EJ $yr^{-1}$. Of this figure, more than half can be attributed to developing nations, whose poorer populations utilise traditional methods – similar to those pre-industrialisation – for cooking, space heating and lighting [22, 23].

The role of biomass in energy generation – dubbed as bioenergy – has undergone a renewed interest in recent years; this has been driven by increases in fossil fuel prices, a desire to attain security of supply and, most prevalently, climate change. When used within efficient systems and sourced sustainably, bioenergy has a significant potential for GHG mitigation. Currently, the main biomass sources for electricity and heat generation are those from forestry, agricultural and municipal residues and a variety of wastes [22, 23].

### 1.3.1. Types of Biomass

Biomass can be obtained from a wide array of feedstocks, both from natural and man-made sources. Naturally produced biomass originates from either land- or water-based environments where it has grown, or alternatively, it can be produced from naturally occurring animal and human bodily functions. Waste streams of formerly natural products, which have undergone a level of human processing, can also be used as a source of biomass for bioenergy production [24].

Table 1.2 – **Sources and classification of biomass feedstocks [24]**

| **Biomass Group** | **Sub-Group** | **Examples** |
|---|---|---|
| **Wood/Woody[1]** | Hardwoods | Birch (*Betula* spp.) |
| | Softwoods | Scots pine (*Pinus sylvestris*) |
| **Herbaceous/ Agricultural** | Grasses | Sweet sorghum (*Sorghum bicolor* L.) |
| | Straws | Wheat straw (*Triticum aestivum* L.) |
| | Residues | Olive (*Olea europaea*) |
| **Aquatic** | - | Micro-algae (*Chlorella* spp.),<br>Macro-algae (*Fucus vesiculosus*) |
| **Animal-based** | - | Chicken litter |
| **Contaminated** | - | Waste woods, Sewage sludge |

[1] *can include stemwood, bark and residues*

Examples of the varied sources of feedstocks can be found in Table 1.2, highlighting how differing resources – both visually and from their fundamental characteristics – can still be classified under the same term of ‘biomass’.

### 1.3.2. Biomass & Climate Change

The versatility of biomass means that it continues to be a potential solution for an array of global- and national-level policy objectives – particularly those related to energy production and climate change mitigation. One of the key benefits is the role it can play in carbon sequestration; the process of accumulating atmospheric $CO_2$ in long-term carbon sinks [22, 25]. The Earth has a naturally occurring carbon cycle where, through the processes of photosynthesis and respiration, carbon is exchanged between the atmosphere and vegetation. The transfer of $CO_2$ into the living organisms and soil associated with terrestrial ecosystems – such as forests, woodlands and wetlands – means they represent an important constituent of stored carbon. From different tree species to grasses and plants, woody and herbaceous terrestrial biomass sources are dependent upon $CO_2$ for growth, storing the carbon as lignin or other polymeric carbon compounds. In addition to carbon storage, terrestrial sequestration has further environmental and economic benefits, making their increase – through schemes such as afforestation – a mitigation strategy with an almost complete consensus [25, 26].

Forest policy and its consequent impact on management decisions have the potential to affect sequestration, both negatively and positively. The carbon stored within forests and woodlands exist in different locations; it's found within the timber, the wood residues, the soil and the myriad of herbaceous and other woody species located on the forest floor. This diverse distribution exacerbates the challenges in understanding the impact of forest management measures on climate change mitigation [25-28]. The cessation of harvesting processes, and the other silvicultural measures practiced within the forestry industry, would normally prompt increases to the carbon stock – particularly over a shorter period. However, this will subsequently result in a decrease in the amount of carbon stored in harvested wood products, while there would also be major economic repercussions for the industries dependent upon the sales of extracted wood [28]. There is clearly a fine balance in the relationship that exists between climate change mitigation and biomass – particularly the industries that are reliant on it as a resource. It is important that the existing stocks of sequestered carbon are maintained and, where possible, increased, but this should not be harmful to the sectors that are actively working to maintain the balance.

#### 1.3.2.1. Global Biomass & Bioenergy Potential

The existing global terrestrial and oceanic biomass resource represents more than 800Gt of standing carbon, with ~90% of this located in the world's forests and woodlands. Considering the large quantities of existing biomass feedstocks – particularly from virgin sources – it's estimated that by 2050 the use of biomass for bioenergy could total 100-300 EJ $yr^{-1}$, representing somewhere between 2 and 6 times the amount of energy produced from biomass today [23, 26]. With the global forest cover estimated at ~4000 million ha, accounting for 30% of the Earth's land cover, wood biomass represents a significant resource that will likely form an important part of the future bioenergy supply. However, considering the importance of the existing forest resource as a carbon sink, the IPCC suggest that the additional wood biomass should be sourced from reforested degraded land; this alone could attribute as much as a third of the predicted bioenergy supply in 2050 [23, 26]. If biomass is to continue its prominent role in climate change mitigation and energy policy, then achieving a secure supply of resource is vital. A sustained increase in demand for woodfuel could, for example, place strains on the existing woodfuel supply chain as well as the markets for other forest products. Consequently, security of supply can be achieved – in principle – by either importing sustainably-sourced wood biomass from other nations, or by increasing – and best utilising – the current natural resources. As this demand increases, additional factors such as transportation and other environmental impacts require consideration [29-31].

The potential for biomass to replace fossil fuels in the short- to mid-term – helping reduce GHG emissions, while transitioning to a decarbonised energy system – is a key driver in their continued interest. However, the use of wood biomass in power and heat generation has caused contention, specifically around its carbon neutrality; that the $CO_2$ emissions released during the combustion of wood biomass are effectively absorbed through further forest growth [32]. The impact of differing forest management practices and the emissions produced throughout the supply chain – from the harvesting, extraction, comminution and transportation processes – are important factors when successfully quantifying the carbon neutrality of wood biomass. Considering the proposed inclusion of a robust sustainability criteria within RED II and the *Clean Growth Strategy*, this shows that carbon neutrality is very much under consideration.

## 1.4. UK Forest & Woodland Resource

Since the early 1980's there has been a significant reduction in the management of the UK's mature broadleaved stands – a result of post-war policies aimed at replacing broadleaved woodlands with conifer species to increase timber production. This was especially prevalent for privately owned woodlands where, less than 10 years ago, just 30% of the private forests in England had felling licences or participated in woodland grant schemes [33]. The continued lack of active management in broadleaved woodlands has been associated with a depressed timber market and, as a result, the structures of broadleaved forests have altered significantly – moving from coppice systems to high forest regimes with much larger rotations [33, 34].

### 1.4.1. UK Forest Policy

In 1992, the UN's 'Earth Summit' prompted a move towards sustainable forest management; maintaining the ecological, economic and social functions associated with forests and woodlands. As a result, sustainable forest management is now a fundamental principle within UK forestry today, with its objectives focused on the overlapping areas of sustainability; the environment, the economy and society [35]. In addition to focusing on afforestation and timber production, UK forestry – especially within the public sector – now includes aspects such as biodiversity, forest services and the people and communities that management decisions may impact upon. As detailed in Figure 1.5, these objectives converge around the core driver of mitigating climate change [35].

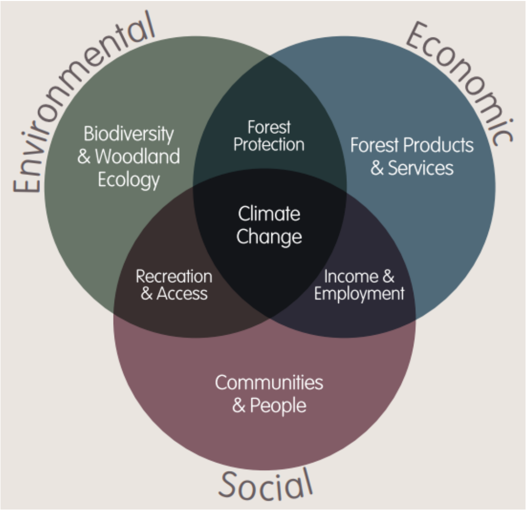


Figure 1.5 – **Sustainable forest management policy in the UK; environmental, economic and social benefits [35]**

The *Clean Growth Strategy* details the UK governments' intention to increase the coverage of woodlands and forests; this includes the creation of 130,000 ha of new woodland cover in England, proposing incentives for farmers to plant trees on marginal land. This forms part of a larger desire to better utilise the growth potential that exists in forestry, increasing security of supply by using home-grown wood [20]. When coupled with a coherent planting and restocking programme, the felling of trees forms part of a sustainable cycle. Therefore the intention to create and manage new woodlands and forests – combined with appropriate governmental support – could result in increased wood availability, particularly for use in bioenergy production.

### 1.4.2. Woodfuel for Energy

As of 2017, the growing stock of the UK's forests and woodlands totalled ~520 million green tonnes of standing timber, located across more than 3 million ha of forested area. The demand for UK-sourced woodfuel has continued to grow during the last decade, with the deliveries of home-grown wood to woodfuel industries increasing by 290% since 2007. Indeed, in 2017 the wood biomass used for woodfuel represented ~17% of the total removals – equating to 1.95 million green tonnes [36]. The utilisation of wood biomass continues to form a key part of renewable energy deployment in the UK; in 2016, domestic wood combustion accounted for half of the heat produced from renewable sources, with logs being the most commonly used fuel. Wood biomass has also become a significant constituent of renewable electricity generation. In the form of wood pellets, the UK imported 6.8 million tonnes in 2016, forming a key component of the 45 TWh of electricity generated from 'plant biomass' [16, 36].

## 1.5. Conclusions

The technological progression of mankind since the beginning of the Industrial Revolution is testament to our ability as a species to develop and innovate, however these benefits – of which there are undoubtedly many – have come at a cost. Our actions have prompted a significant increase in the concentration of atmospheric GHG's; this could severely impact the global climate, affecting those who are at greatest risk the most. Following the Paris Agreement, there is now a comprehensive consensus that universal action is required to reduce the potential impacts of climate change and avoid irreversible damage.

The proposed solutions for climate change mitigation are diverse, however it is clear that biomass will continue to form a key part of global policy, particularly in the short- to mid-term. This is especially prevalent for the UK, whose transition from fossil fuel dependence during the last decade has been driven through the increased utilisation of biomass for bioenergy, particularly imports of wood pellets. Forests represent a significant global resource – not just as a potential feedstock for energy generation, but also for their role in sequestering carbon. The balance between these two factors is important; if wood biomass is to continue as a prominent renewable fuel source then this should not be at the expense of the existing stored carbon. Therefore, increases in the amount of wood resource used in energy generation should correlate with defined, large scale tree planting programmes. With national-level support, the outcomes from afforestation and reforestation schemes would be 'win-win-win' scenarios; the forest industry would benefit, it would help establish supply security for bioenergy feedstocks, while also increasing sequestered carbon. The UK's recent stated desire to increase its national forest cover, highlights the importance of first understanding our existing resource – a key motivation for the work to be conducted in this thesis. This knowledge would not only help the decision making process in how best to utilise what we have, it could also help inform future approaches to planting and resource utilisation.

Consequently, the aim of this thesis is to increase the understanding of the UK's current forest resource, determining its potential to supplement the existing fuel sources for domestic heating. Although discussed further in the next chapter, an appreciation of the issues that surround the woodfuel market – in addition to the fundamental characterisation of UK wood samples, in the context of feedstocks for use as fuels – will not only increase our knowledge of the existing resource, but it should also provide valuable information for improving energy conversion technologies and how to best utilise the nations' forests for bioenergy.

## 1.6. References

[1]. Mantoux P. 1935. *The Industrial Revolution in the Eighteenth Century: An outline of the beginnings of the modern factory system in England*. 6th Ed. Jonathan Cape LTD, 30 Bedford Square, London

[2]. Wrigley E. A. 2013. Energy and the English Industrial Revolution. *Philosophical Transactions of the Royal Society A*, 371:20110568

[3]. Gaffney J. S. and Marley N. A. 2009. The impacts of combustion emissions on air quality and climate – from coal to biofuels and beyond. *Atmospheric Environment*, 43, pp23-36

[4]. Houghton J. 2005. Global warming. *Reports on Progress in Physics*, 68, pp1343-1403

[5]. Intergovernmental Panel on Climate Change. 2013. Summary for policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC [Stocker T. F., et al. (eds)]. Cambridge University Press, Cambridge, UK

[6]. Intergovernmental Panel on Climate Change. 2014. Summary for policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. [Field C. B., et al. (eds)]. Cambridge University Press, Cambridge, UK

[7]. UNFCCC. 1992. *United Nations Framework Convention on Climate Change, Article 2*. United Nations

[8]. UNFCCC. 1998. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. United Nations

[9]. Böhringer C. 2003. The Kyoto Protocol: a review and perspectives. *Oxford Review of Economic Policy*, 19(3), pp451-466

[10]. Schleussner C-F., Rogelj J., Schaeffer M., Lissner T., Licker R., Fischer E. M., Knutti R., Levermann A., Frieler K. and Hare W. 2016. Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*, 6, pp827-835

[11]. European Commission. 2017. *Report from the commission to the European parliament and the council. Two years after Paris – Progress towards meeting the EU's climate commitments*. Brussels, COM(2017) 646

[12]. Delbeke J. and Vis P. 2015. *EU Climate Policy explained*. Routledge, Taylor & Francis Group, London and New York

[13]. Zhang Y-J. and Wei Y-M. 2010. An overview of current research on EU ETS: Evidence from its operating mechanism and economic effect. *Applied Energy*, 87, pp1804-1814

[14]. European Commission. 2009. *Directive 2009/28/EC of the European Parliament and of the council on the promotion of the use of energy from renewable sources*. L140/16

[15]. Eurostat. 2018. Online: http://ec.europa.eu/eurostat/data/database

[16]. Department for Business, Energy and Industrial Strategy. 2017. *Digest of United Kingdom energy statistics (DUKES) 2017*. Victoria Street, London

[17]. European Commission. 2017. *Proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast).* Brussels, COM(2016) 767

[18]. *Climate Change Act* 2008, Ch. 27, ss.1-31

[19]. Department for Business, Energy and Industrial Strategy. 2018. *Updated energy and emissions projections 2017*. Victoria Street, London

[20]. Department for Business, Energy and Industrial Strategy. 2017. *The clean growth strategy – leading the way to a low carbon future*. Victoria Street, London

[21]. McKendry P. 2002. Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, 83, pp37-46

[22]. Bauen A., Berndes G., Junginger M., Londo M. and Vuille F. 2009. *Bioenergy – a sustainable and reliable energy source. A review of status and prospects*. International Energy Agency (IEA) Bioenergy

[23]. Chum H., Faaij A., Moreira J., Berndes G., Dhamija P., Dong H., Gabrielle B., Goss Eng A., Lucht W., Mapako M., Masera Cerutti O., McIntyre T., Minowa T. and Pingoud K. 2011. Bioenergy. In: *IPCC special report on renewable energy sources and climate change mitigation* [Edenhofer O., et al. (eds)], Cambridge University Press, Cambridge, UK

[24]. Vassilev S. V., Baxter D., Andersen L. K. and Vassileva C. G. 2010. An overview of the chemical composition of biomass. *Fuel*, 89, pp913-933

[25]. Lal R. 2008. Carbon sequestration. *Philosophical Transactions of the Royal Society B*, 363, pp815-830

[26]. Dhillon R. S. and von Wuehlisch G. 2013. Mitigation of global warming through renewable biomass. *Biomass and Bioenergy*, 48, pp75-89

[27]. Bonan G. B. 2008. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, 320(5882), pp1444-1449

[28]. Bösch M., Elsasser P., Rock J., Rüter S., Weimar H. and Dieter M. 2017. Costs and carbon sequestration potential of alternative forest management measures in Germany. *Forest Policy and Economics*, 78, pp88-97

[29]. Rauch P. 2017. Developing and evaluating strategies to overcome biomass supply risks. *Renewable Energy*, 103, pp561-569

[30]. Hansson J., Berndes G. and Börjesson P. 2006. The prospects for large-scale import of biomass and biofuels into Sweden – a review of critical issues. *Energy for Sustainable Development*, 10(1), pp82-94

[31]. Wolfsmayr U. J. and Rauch P. 2014. The primary forest fuel supply chain: A literature review. *Biomass and Bioenergy*, 60, pp203-221

[32]. Brack D. 2017. *Woody biomass for power and heat – Impacts on the global climate.* The Royal Institute of International Affairs, Chatham House, London

[33]. Hopkins J. J. and Kirby K. J. 2007. Ecological change in British broadleaved woodland since 1947. *IBIS*, 149(2), pp29-40

[34]. Amar A., Smith K. W., Butler S., Lindsell J. A., Hewson C. M., Fuller R. J. and Charman E. C. 2010. Recent patterns of change in vegetation structure and tree composition of British broadleaved woodland: Evidence from large-scale surveys. *Forestry*, 83(4), pp345-356

[35]. Forestry Commission. 2017. *The UK Forestry Standard – The governments' approach to sustainable forestry*. Forestry Commission, Edinburgh

[36]. Ward S. 2017. *Forestry Statistics 2017*. IFOS-Statistics, Forest Research, 231 Corstorphine Road, Edinburgh

# Chapter 2. Aims & objectives

*"All our wisdom is stored in the trees" – Santosh Kalwar*

Considering the UK's reliance on biomass for reducing $CO_2$ emissions – in the form of imported wood pellets – the recognition of afforestation as a potential mitigation approach, within the governments' *Clean Growth Strategy*, is certainly understandable. Indeed, expanding the nation's forest cover would result in increased carbon storage, while potentially creating additional wood supplies for use in bioenergy. However, before embarking upon any major tree planting project, it is important to first understand the established resource. Therefore, the research produced within this thesis will focus on the UK's existing forest feedstocks, determining their potential to supplement the current reliance on imported wood fuels for use in energy generation.

Forest research is truly diverse, incorporating a range of disciplines that – although inherently linked – differ considerably in their application. As a result, the aims of this research can be broken down into three distinct research areas; 1) to increase the knowledge of current forest feedstocks – both globally and within the UK, 2) to determine the potential of the UK's wood resource for use in established energy generation processes, and 3) to assess how the distribution and capacity of the UK's forests and woodlands, influences its accessibility and economic viability. To achieve these aims, the following objectives have been proposed;

## Knowledge of Forest Resource

I. To produce a conclusive review of the literature, giving details on the diverse disciplines of forestry; this will include the known fundamental differences of wood, the UK's existing forest resource, the silvicultural and harvesting practices employed in the forestry sector and their associated environmental impacts (Chapter 3).

II. To collate and analyse wood characterisation values from the literature, completing statistical analysis on the produced dataset. This will allow for the creation of global forest resource reference values for comparison with other work (Chapter 4).

III. To complete experimental analysis on UK-grown wood samples, producing a major characteristic dataset. This will include proximate, ultimate and lignocellulosic analysis. Additional statistical analysis will be completed, comparing the data to produced literature reference values (Chapter 4).

IV. To determine potential relationships between different tree sections and the elemental, chemical and structural data; this includes methods for illustrating correlation and varying levels of homogeneity (Chapter 4 & 5).

## Feedstock for Energy Generation

I. To determine the combustion characteristics, burning profiles and reaction rates for UK-grown wood – sourced from different species and different tree sections – quantifying the differences and similarities. This includes establishing the role of lignocellulosic compositions (Chapter 5).

II. To complete additional characterisation on a subset of the UK-grown wood samples, considering their macronutrient contents; this will comprise of nitrogen partitioning and establishing the potassium content (Chapter 5).

III. To explore and infer relationships between the determined combustion characteristics and the additional characterisation results; specifically the impact of potassium on the initial reactivity of wood (Chapter 5).

IV. To estimate the potential volumes of wood biomass – and its subsequent energy content – that could be sustainably sourced from the UK's forests and woodlands (Chapter 3 & 6).

## Assessing the Potential of the UK's Forests

I. To combine existing datasets of forest resource, published by different national administrations, mapping the distribution of the UK's hardwood and softwood feedstocks (Chapter 6).

II. To develop a framework for combining different geospatial data sources – specific to the UK – for use in a decision support system that could aid the uptake of small-scale energy generation systems, using UK-grown wood biomass (Chapter 6).

III. To establish the costs of accessing wood biomass in the UK – from standing timber to roadside sawlogs and woodchip – including the felling, extraction and comminution processes. This will combine different wood harvesting methods with the location of the UK's forest resource, considering the impacts of the existing road infrastructure and terrain (Chapter 3 & 6).

IV. To utilise data produced throughout the thesis – in combination with the developed framework – determining potential areas within the UK that could facilitate an increased uptake of local sources of wood, for use in energy generation (Chapter 6).

These stated aims and objectives will form the core of the research completed within this thesis, helping establish the potential of the UK's forests for use in sustainable energy generation. Although inherently linked with one another, each of the following chapters focuses on individual research areas; a brief overview of their content can be found below.

**Chapter 3** contains an in-depth literature review of wood science, the UK's current forest resource, different forest management practices and an array of issues and considerations associated with the discipline of forestry. The work contained within this chapter is utilised throughout the thesis, helping to inform the conducted research and analysis.

**Chapter 4** focuses on the extensive characterisation of wood biomass, collating large amounts of data from literature sources and experimentally produced methods. Critical statistical analysis has been conducted to produce conclusive fundamental reference values for an array of characteristics, both globally and from UK-sourced wood biomass.

**Chapter 5** builds upon the work completed in the previous chapter, using a refined subset of the UK-grown wood samples, focused on the stem, root and branch wood of birch and Sitka spruce. Their combustion characteristics have been determined, in addition to potential relationships between macronutrient content and the reactivity of the feedstocks.

**Chapter 6** utilises previously published literature to produce productivity and cost values for the different methods of felling and extracting timber from within forests, specific to the UK. Using geospatial data, these are applied to the UK's current forest resource, considering the impact of slopes and extraction distance on the costs of harvesting wood in the UK. Finally, this is combined with energy content values – produced in Chapter 4 – estimating how much additional woodfuel can be produced from UK forests, while identifying specific areas that can be utilised as local forest feedstocks.

**Chapter 7** addresses the defined research aims and objectives contained within this chapter, drawing conclusions from the combined work and proposing potential opportunities for expanding upon the results of this thesis.

# Chapter 3. Literature review

*"A person without knowledge of their past history, origin and culture is like a tree without roots" – Marcus Garvey*

## 3.1. Introduction

As outlined in the previous chapter, one of the main aims of this research is to better understand the UK's forest wood resource and how it could supplement current bioenergy production. Undoubtedly, the production and analysis of data will form a major component of this research, however it is important to first consider the work that has previously been completed. Just as a tree requires roots to grow, an appreciation of the existing literature will offer support and focus to the analysis of the data, produced throughout the thesis. This chapter will therefore consider an array of issues and attributes related to wood and the forest industry, helping to form the foundations of this research.

## 3.2. Chemistry of Wood Biomass

Plants are complicated and intricate organisms, characterised by properties such as their reliance on photosynthetic nutrition and the presence of polysaccharides – like cellulose – within their cell walls. This complexity, apparent between different plant types, makes the understanding of their functions and structure imperative [1]. The intricate chemistry of plants extends to tree species although, when considering their simplest categorisation, they can be separated into two defined taxonomical categories; angiosperms and gymnosperms. Of these, angiosperms represent the larger species group, containing a diverse number of hardwoods. These are most evident in the northern hemisphere, typified by deciduous broadleaved species and woodlands, located predominantly in colder climates. In contrast, gymnosperms contain a much smaller collection of species that are dominated by softwoods. Although smaller in species number, conifer trees hold global importance, both ecologically and economically, representing more than 39% of the world’s forests [1-5]. As a result of the visual differences existing between hardwood and softwood tree species – predominantly through their form and foliage – the identification of the two taxonomical groups is often uncomplicated. However, the distinctions between hardwood and softwood tree species also exists at basic chemical and compositional levels, highlighting the heterogeneous nature of wood [6].

### 3.2.1. Constituents of Wood

The major functions of wood are to transport water, store temporary reserves and to structurally support the continual growth of the tree. Although these roles are applicable to all trees, the composition of their produced wood is distinctly non-uniform. This variation is predominantly due to differences between species, however additional variability is evident within species; influenced by genetic factors or external conditions – such as weather – which affects the growth process [6-8]. Produced seasonally, the term wood refers to the secondary xylem, formed within the vascular cambium of the trunk. Derived from the procambium, the vascular cambium is a secondary meristem which originates from the apical meristem, found at the tip of the plant. In its most simple form, the woody tissue consists of heartwood and sapwood, while outside the vascular cambium are the inner and outer layers of bark [7, 8].

The anisotropic nature of wood prompts the physical properties of species and cell types to differ, specifically when considering the transverse, radial and tangential dimensions. This three-dimensional structure of wood cells is illustrated in Figure 3.1, specific to a typical hardwood species, highlighting its three main cell types; its vessels and fibres, which are visible in the vertical tangential and radial sections, and its horizontally situated ray parenchyma [8, 9]. Hardwoods rely on their vessels – enlarged cells with thin walls and large pore space, shown in Figure 3.1 – for fluid conduction throughout the wood, while its box-shaped parenchyma help transport materials laterally. Unlike the other two cell types, the fibres give structural support to the wood, accounting for 35-70% of the cellular arrangement – the consequent ray parenchyma content is reduced, ranging from 10-32%. The cellular types within softwoods differ; they consist predominantly of elongated tracheids, offering both structural support and a pathway for fluids. Tracheids resemble 85-95% of a softwood species' cells, with the remaining amount attributed to sugar-storing ray parenchyma. The discernible differences between cell structures prompts softwoods to be considered more homogenous than hardwoods [3, 4, 7-9].

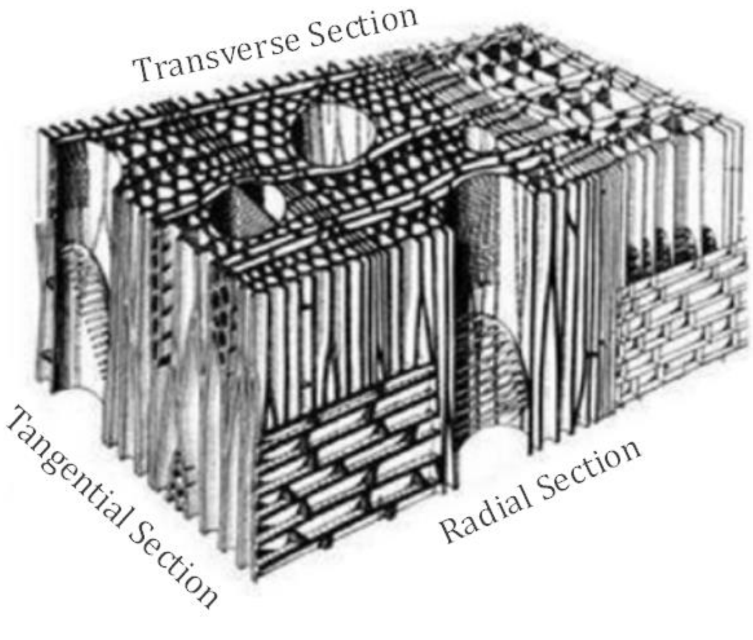


Figure 3.1 – **Three-dimensional association of different cell types; example of the transverse, radial and tangential planes in a hardwood species [7]**

#### 3.2.1.1. Wood Formation

The production of wood, and its consequent chemical and component structures, is a complex developmental process, incorporating a wide range of different subject areas. Occurring seasonally, wood formation involves five main steps; 1) cell division from the vascular cambium, 2) cell expansion, 3) secondary cell wall deposition, 4) cell death, and 5) heartwood formation [7-9]. Within the vascular cambium – which remains intact – the cells differentiate, changing shape to form the secondary cell wall. The expansion of these cells, occurring over a period of about 3 weeks, includes cell elongation and radial enlargement. Secondary wall formation results in the biosynthesis of cellulose, hemicellulose, lignin, cell wall proteins and minor soluble and insoluble compounds. Following lignification, the programmed cell death prompts the degradation of cellular content, leaving just the secondary walls. Once dysfunctional, the parenchyma cells – which act as temporary winter reserves – die and release phenolics, ultimately aiding in the formation of heartwood [7-9].

The heartwood is the most internal part of the trunk, taking on a much darker colour than the sapwood. This is a result of the released phenolics; these are a diverse group of aromatic substances, characterised by phenolic hydroxyl groups. Comparatively, the sapwood is lighter in appearance, located closer to the bark. Unlike the heartwood – which acts as mechanical support to the tree – the sapwood is still physiologically active, continuing to support processes such as liquid transport and resource storage. The heartwood characteristics and aesthetics of timber will often determine its final use – dark coloured wood is often more robust and durable, while the released phenolics can potentially increase the woods long-term resistance to pathogen attack [3, 7, 8].

The taxonomical categorisation of wood species – and the cellular variation that exists between hardwoods and softwoods – establish good foundations for differentiation, however the variability that exists in wood is much more complex. Considering the characterisation of wood, there are structural, physical and chemical differences evident, both between species and individual trees within a species [7]. The composition of wood can be separated simply into two component groups: structural, containing components with a high molecular weight, and non-structural, which have low molecular weights. This is presented in Figure 3.2, identifying the distinction between the principal structural components – lignin, cellulose and hemicellulose – from the non-structural compounds. Although species dependent, the structural components attribute for ~90% of the dry matter content of wood, with the remainder comprising of extractives and inorganic compounds [3, 4, 6].

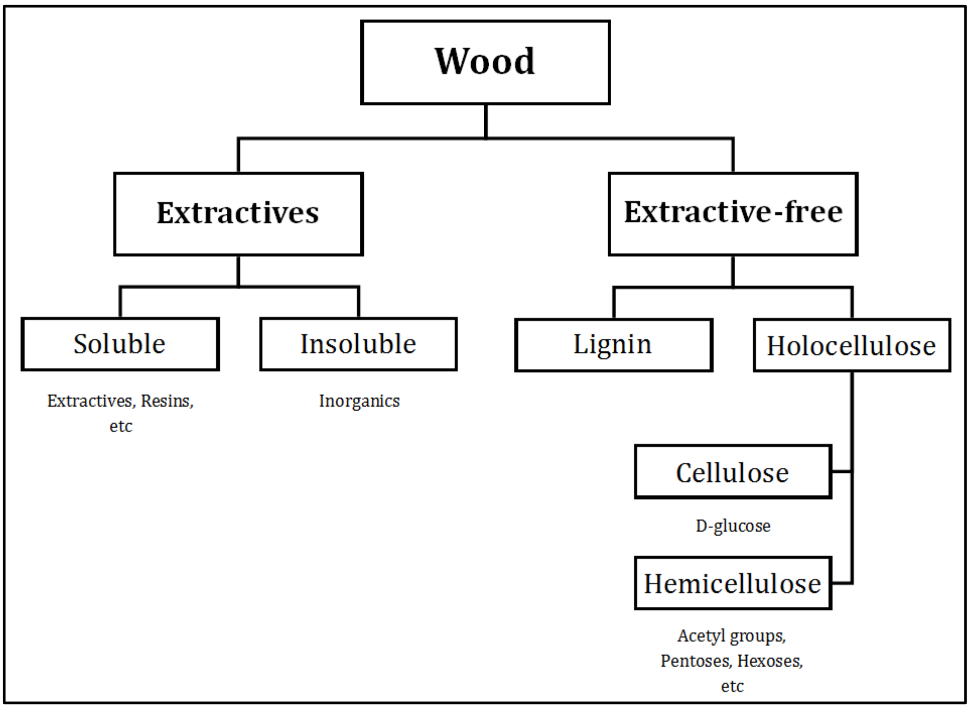


Figure 3.2 – **Outline of wood components; distinction between structural and non-structural [4, 6]**

Of the structural components, the polysaccharide constituents – cellulose and hemicellulose – are the most prominent which, when coupled with the lignin, form the cell walls and the basis of woods' physical structure [6].

### 3.2.1.2. Cellulose

Within the plant kingdom, cellulose is the main structural fibre, differing by its volume fraction between species. Forming the framework material of wood, the fibrous, tough and water-insoluble polymer exists within a rigid cell wall which, in addition to the cell membrane, encompasses the plant cell providing strength. Cellulose, a well-defined long-chained unbranched polysaccharide, is composed of $\beta$-D-glucopyranose units linked by (1→4) glycosidic bonds. The cellulose chains that exist in wood have a high degree of polymerization – calculated at around 10,000 glucopyranose units – aiding in its increased mechanical strength [1-4, 6, 9, 10]. The singular cellulose chains accumulate within the woods cell walls, collectively referred to as microfibrils, which in turn comprises between 40-50% of the total material. The differing lengths, widths, numbers of, and degree of crystallinity of the individual cellulose microfibril (CM) strands results in their heterogeneous classification. Although the cellulosic content of wood increases with age, differences are also apparent within the annual rings; the latewood, which is formed slowly during the winter, contains more CM's than earlywood, which is produced in the spring [3, 4, 7, 10]. Wood cell walls consist of four individual layers – a primary layer and three secondary layers – with the arrangement of the CM's differing between each of these; this is highlighted in Figure 3.3. The microfibril orientation clearly differs between the individual layers, distributed randomly in the primary wall while winding in differing helical patterns in the three secondary layers [9, 11].

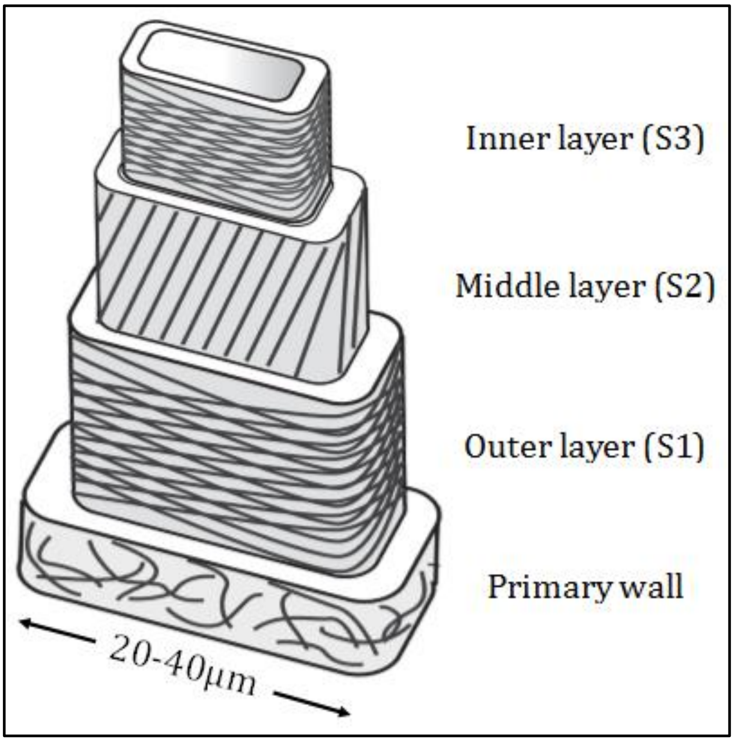


Figure 3.3 – **The distribution and orientation of cellulose microfibril (CM) within the cell wall of wood; primary wall, S1, S2 and S3 [9, 11]**

There are two forms of cellulose that exist within the individual CM's – types I$\alpha$ and I$\beta$ – however, unlike with other biomass species such as algae, it is difficult to distinguish between the two in wood. The two forms of cellulose contain the same atom skeleton as one another, differing by their hydrogen bonding patterns. The ratio of I$\alpha$ and I$\beta$ differ between species; increased contents of I$\alpha$ are associated with more primitive species, while I$\beta$ is found in greater concentration in softwoods [4, 10, 12].

### 3.2.1.3. Hemicellulose

Hemicellulose is an important component of both the primary and secondary walls, helping maintain the physical properties of the cell. Although the structural details of hemicellulose differ between species and individual cell types, their primary role is the same – to tether CM's, increasing the strength of the cell wall. Unlike cellulose, which is well-defined, hemicellulose is a complex mixture of heterogeneous soluble polysaccharides that account for ~25% of the dry weight of wood, and is more abundant in hardwood species [3, 4, 7, 13].

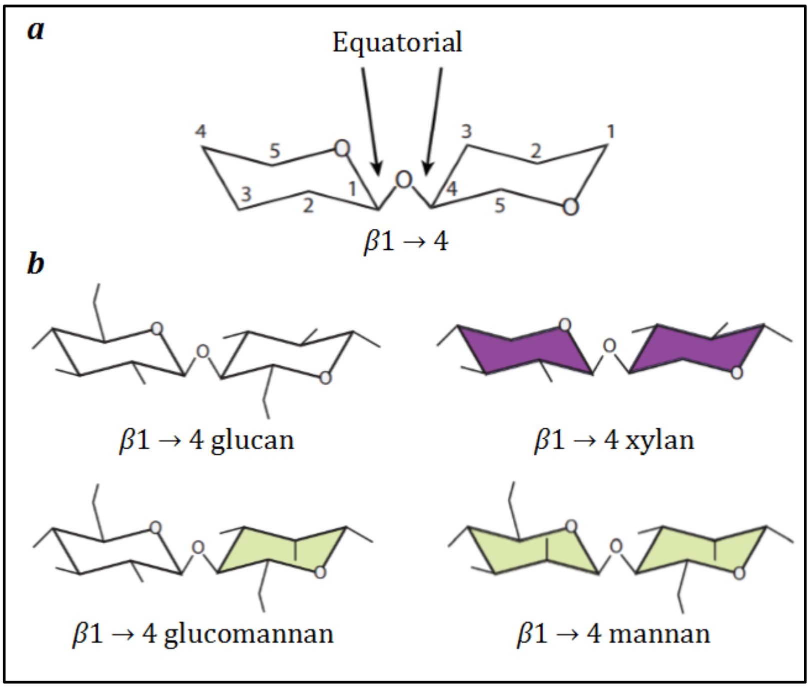


Figure 3.4 – **Definition and identification of hemicelluloses; a) characterised by a *β*-(1→4)-linked backbone with an equatorial configuration at C1 and C4, and b) examples of typical repeating disaccharides [13]**

This complexity has resulted in difficulties in defining the term hemicellulose – often grouped as the remaining non-cellulosic polysaccharides – however, they can be characterised by a *β*-(1→4)-linked backbone with an equatorial formation at C1 and C4 [13], as depicted in Figure 3.4. This also identifies some of the main disaccharides that are included within hemicellulose; other polysaccharides that are often grouped with these include galactans, arabinans and arabinogalactans, which are closely associated with pectin molecules. Establishing the structures of polysaccharides requires detailed information – relating to factors such as which individual sugars are present and the number of free hydroxyl groups – meaning that only the most important polysaccharide systems have been studied extensively [6, 7, 13]. Figure 3.5 details some of the common monosaccharides that are found within wood-based hemicellulose, combining to produce an array of different polysaccharide chains. A typical example is Galactoglucomannan, often associated with softwood species, which is located within the woods cell walls [13].

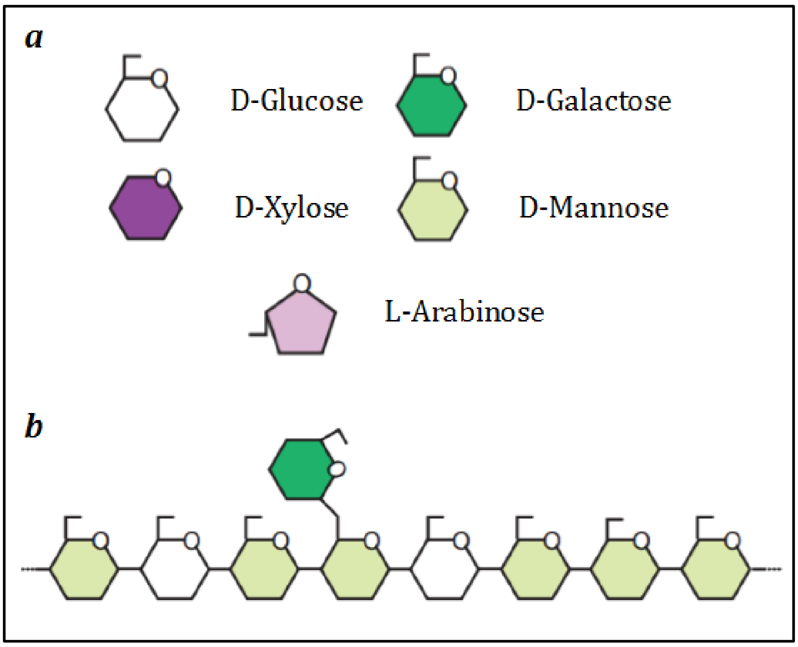


Figure 3.5 – **Schematic illustrations of hemicellulose; a) typical monosaccharides found in wood, and b) Galactoglucomannan, often found in softwoods [13]**

The hemicellulose content differs between hardwood and softwood species, not only in their combined total, but also the composition of specific polysaccharides. Indeed, the monosaccharide composition of softwoods is typified by a mixture of the five stated in Figure 3.5, with D-Glucose (61-65%) the most prominent and L-Arabinose (<3.5%) the least. In comparison, hardwood species contain a greater total volume of hemicellulose, with a large proportion of this dominated by glucose (55-73%) and xylose (20-39%) sugars [6]. Pectins – a group of polysaccharides that are rich in galacturonic acid units – have previously been grouped with hemicellulose, due to their close structural relationship. However, this is no longer the case as they do not share the linked backbone configuration, demonstrated in Figure 3.4 [9, 13, 14].

### 3.2.1.4. Lignin

The third major structural component within wood is lignin which, unlike the carbohydrate-based polysaccharides attributed to cellulose and hemicellulose, is a complex phenolic polymer that denotes the irreversible end product of plant metabolism. Representing between 18-38% of the total dry matter of wood, the lignin gives rigidity to the wood tissue, embedding the carbohydrate materials in the secondary cell wall. In addition to enhancing the cells physical properties, the lignin gives mechanical strength to the tree – allowing it to support the weight of its crown – while also providing a hydrophobic surface that allows for the water transportation required in photosynthesis. Finally, the chemical and physical properties of lignin act as a barrier to evasive pathogens and pests [6, 9, 15, 16].

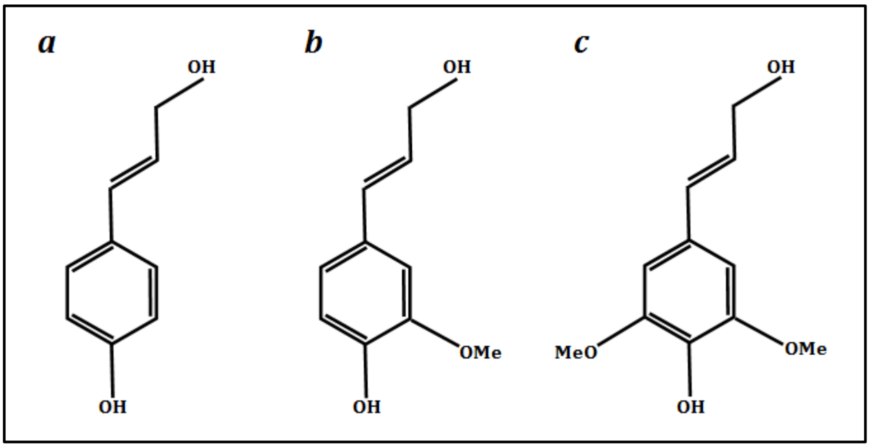


Figure 3.6 – **Hydroxycinnamyl alcohol monomers found within lignin; a) *ρ*-coumaryl, b) coniferyl, and c) sinapyl [16, 17]**

Lignins are derived principally from three different hydroxycinnamyl alcohol monomers, detailed in Figure 3.6; these are *ρ*-coumaryl, coniferyl and sinapyl. The composition and total lignin content – varying between species and cell types – is also influenced by other factors, such as the natural environment or other developmental cues [16, 17]. The variability of lignin is evident between softwood and hardwood species, dictated by the three alcohol monomers. Softwood lignin consists predominantly of guaiacyl (G) units, produced from the coniferyl monolignol, with a small amount of *ρ*-hydroxyphenyl (H) derived from the *ρ*-coumaryl. In comparison, hardwood species contain syringyl (S), formed from sinapyl alcohol, which alongside guaiacyl are the main constituents of its lignin; the ratio between the G and S units differ between individual hardwood species. Additionally, there are also trace amounts of H units contained within hardwood lignin [15-17].

The total lignin content of wood differs, not only between species – softwoods contain approximately 10% more lignin than hardwoods – but also in different aged wood tissue; older wood has an increased lignin content, when compared to that of new shoot growth. This is a result of the irreversible lignification of the secondary cell wall, occurring seasonally. Representing a substantial carbon sink, lignin has an energy content similar to coal – a result of the high bond energies contained in its aromatic monomers – which is ~30% larger than that of cellulosic carbohydrate [3, 15]. Effectively, wood with a greater lignin content will have an increased gross calorific value (GCV). This increase in energy content however comes at a cost, specifically on the volume of wood produced; a negative correlation exists between the lignin content and the accumulation of biomass, with an increase in lignin coinciding with reduced overall growth [15].

#### 3.2.1.5. Extractives & Inorganic Content

As discussed, the structural components of wood – accounting for more than 90% of the dry matter content – dominate the composition of both hardwood and softwood species. The remaining non-structural constituents represent a smaller proportion of the content, however the variability between and within species is sizeable, greatly impacting the homogeneity of wood. This variation is dictated by a broad spectrum of compounds; those that can be extracted by neutral solvents are referred to as the extractives, while the remaining matter consists chiefly of mineral constituents – requiring acidic extraction – denoted as the inorganic content [6, 18-21]. As illustrated in Figure 3.7, the extractive components of wood represent a diverse group; more commonly this will include a variety of saccharides, proteins, phenols and aromatics, while gums, tannins and flavonoids are less frequent. As with the structural elements of wood, the prevalence and mixture of the extractive contents found within wood are dictated by a number of factors, ranging from species choice and the differing tree sections, through to specific external environmental conditions. Indeed, the volume of extractive content can be controlled – to a certain degree – by changes in management practice; reducing the stocking density and rotation age within forest stands can reduce the extractive content of the trees. These differences are evident within individual tree specimens, with their bark typified by larger extractive contents than its wood [6, 18, 20]. As with lignin, the energy content of the combined extractives can be as much as twice that of the carbohydrate-based structural components – the increased lignin and extractive contents, found in softwood species, often results in them having larger gross calorific values [21].

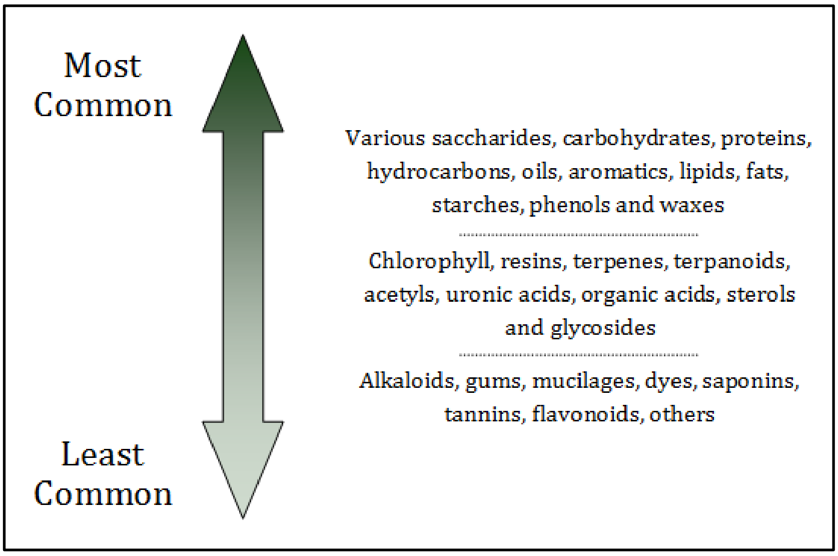


Figure 3.7 – **The extractive components of wood [6, 20]**

The inorganic materials contained within wood are predominantly mineral based, a number of which are important for plant growth; these are dominated by calcium (Ca), potassium (K) and magnesium (Mg) salts, however an array of other elements can also be found, including silicon (Si), phosphorous (P), sodium (Na), as well as other minor elements [6, 19-23]. As with the extractives and other structural components, the concentration of inorganics can differ greatly between species and the alternate tree sections. Most studies utilise the biomass ash – produced as part of the proximate analysis – to determine the feedstocks inorganic composition and total. Within the stem wood the ash content is often ~1% of the total, which is at the lower end when compared to other biomass feedstocks. Wood bark however contains a much larger ash content, ranging between 2.5-8.0% resulting in the sections of the tree with higher bark contents – the roots and the branches – having larger inorganic concentrations. The elemental constituents of ash, and their consequent concentrations, differ between species. As a result, hardwoods tend to contain more potassium and phosphorous than softwood species, but less calcium [6, 18, 21-23]. Although ash is almost exclusively formed from inorganic matter, it's not fully representative of the total content; the combustion process, utilised for producing ash, can result in the release of inorganic constituents during the gas phase [19, 20, 24].

The inorganic concentrations of wood are directly influenced by localised environmental conditions, in particular the soil; minerals are passively absorbed by the roots and transported throughout the tree via transpiration [6, 25]. Both potassium and calcium – obtained from the soil – are essential macronutrients, influencing the physiological roles that dictate the development and continued functioning of individual tree specimens. Potassium is crucial for processes such as osmoregulation and cell expansion, while calcium is important for cell wall synthesis and cell division. Consequently, potassium has been investigated as a potential fertiliser, demonstrating a positive influence on the above-ground net primary production of wood during field trials [25].

### 3.2.2. Fuel Characteristics

As discussed in Chapter 1, the Industrial Revolution coincided with a growing reliance on fossil fuels for energy generation, prompting the move away from wood as a fuel. However, the desire to reduce the emissions of manmade carbon dioxide ($CO_2$) – as an attempt to lessen the impacts of climate change – has been the key influence to again utilise biomass as a fuel. The exploitation of wood as a fuel – specifically during the combustion process – emits a similar volume of $CO_2$ as fossil fuels; although, the time it takes to recapture the carbon through forest growth pales into insignificance when compared to the millennia it takes to form coal, oil and gas [1, 26-30]. Though the replacement of fossil fuels with wood is relatively simple on a domestic scale, especially when compared to retrofitting a large-scale energy generation facility, a thorough understanding of the fuel properties of wood is important for ensuring its successful deployment.

#### 3.2.2.1. Moisture & Energy Content

One of the most significant properties of a fuel is its moisture content, which can directly limit the amount of energy that can be generated from its use. During the combustion process, energy is required to first evaporate the water, impacting its net calorific value; the greater the moisture content, the bigger the reduction in the produced energy. Accordingly, the water existing in wood can be separated into two categories; free moisture, which exists in the cell cavities and intercellular spaces, and the cell wall moisture that is found within the cells themselves [31, 32]. The moisture content of a fuel should range between 8-15%, however a newly felled tree often far exceeds this, containing approximately 50-200% moisture when compared to its dry matter weight. This large variation is potentially a result of several different parameters, including climatic conditions, the tree species and the season a tree is felled. The high moisture content, synonymous with newly felled forest wood, is one of the most important and controllable factors for increasing transport efficiency, reducing the consequent costs. As a result, when considering energy generation as the end use, there are two main processes for reducing the moisture content of wood: natural drying and mechanical drying [31-34].

Of these, the most cost effective method is natural drying, often referred to as seasoning. This process, beginning immediately following the felling of a tree, requires the delimbing of the felled timber before being stacked into piles; in addition to these stacks, the removal of bark may also help reduce the moisture content. Once drying begins, the loss of the free moisture occurs first – when removed, the resulting wood has reached its fibre saturation point. The removal of the free moisture has no structural impact on the wood, however the drying of the cell walls can cause the tissue to shrink, resulting in the development of potential defects. Natural drying is most effective during the spring and summer months, with some form of stack cover required during the wetter winter periods [31-34]. Although mechanical drying – most commonly by kiln – is a quicker, more regimented process than natural drying, this incorporates additional processing which increases the supply chain costs. The removal of moisture using a kiln is conducted at a wide array of temperatures, with low to moderate drying ranging between 21-82°C, and a more intense drying process occurring over 100°C [32, 34, 35].

Table 3.1 – **Published moisture and energy contents of a selection of wood species, taken from the literature**

| Species | Moisture (Wt.%) | GCV (MJ/kg)[d] | Ref. |
|---|---|---|---|
| Fir | *6.5* | *21.0* | *[27]* |
| Danish Pine | *8.0* | *21.2* | *[27]* |
| Willow | *60* | *20.0* | *[27]* |
| Poplar | *45* | *18.5* | *[27]* |
| Pine[a] | *4.0* | *20.2* | *[29]* |
| Willow[b] | *7.0* | *18.7* | *[29]* |
| Ash | - | *18.8* | *[30]* |
| Birch | - | *18.0* | *[30]* |
| Hazel | - | *18.8* | *[30]* |
| Willow[c] | - | *18.0* | *[30]* |

*[a]wood chips, [b]short rotation coppice, [c]billets, [d]on a dry basis*

The energy content is often reported on a dry basis, referred to as the gross calorific value (GCV); calculated at 0% moisture, the GCV is ideal for comparing fuels but is not useful for real world application. Unlike the GCV, which is the enthalpy of a fuels complete combustion with the moisture in a liquid state, the net calorific value (NCV) incorporates the moisture. Consequently, the NCV represents the amount of useful energy that can be achieved from the fuel, considering its moisture content [31, 36]. As with the other wood characteristic data, differences exist between the energy contents of alternate species; Table 3.1 details the published GCV's of different species, highlighting the increased fundamental energy contained within softwoods, when compared to hardwoods.

#### 3.2.2.2. Proximate & Ultimate Analysis

Although reasonably simple, two of the most important forms of fuel analysis are the proximate analysis – which determines the fixed carbon (FC), volatile matter (VM), ash content and moisture – and the ultimate analysis, establishing the main elemental composition [19, 31]. The proximate analysis of a fuel gives its basic constituents, with the greatest amount of variation occurring between the ash and moisture contents – two factors which have already been discussed within this chapter. The moisture component of wood is determined by the weight difference between the initial sample, as received, and the sample once it has been dried at 105°C. Alternatively, the ash content is calculated following the combustion of the sample at 550-600°C, with the weight of the residual inorganic matter taken as a percentage of the initial sample weight. In addition to giving basic, but important, information on a fuels characteristics, the moisture and ash data is often applied to other analytical data – adjusting these to either dry or dry ash-free values – which improves the comparison of chemical compositions between fuels [19].

This can be applied directly to the values of the ultimate analysis of a fuel, which are usually reported on a dry or dry ash-free basis. Focused on the principal elemental components of a fuel, the ultimate analysis establishes the carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulphur (S) that exist within the feedstock. Of these, the C, H and O are the most desirable elemental components contained within biomass, with others – such as the N and S – causing issues with pollutants, deposition and corrosion [19, 26-28, 37]. The standard method for attaining the C, H, N and S contents uses gas chromatography, quantitatively measuring the reaction products following combustion over 900°C; these are the produced $CO_2$, $H_2O$, $N_2$ and $SO_2$. The oxygen content is then normally determined by difference [21, 36]. The main elemental compositions of wood are similar between species; the contents for the C, H and O are usually around 50%, 6% and 44%, respectively. However, while the differences tend to be small, previously published elemental characterisation results indicate that softwood species are typified by larger carbon contents than hardwoods, which instead contain more oxygen [18, 30, 31]. Although nitrogen is the fourth most prevalent element in wood, its content is relatively small; N usually represents between 0.1-1% of the total content, which is low when compared to other biomass feedstocks. As a macronutrient, N stimulates productivity within the plant, helping to increase its growth. This is particularly evident for trees grown in soils containing large concentrations of available N, however this can often result in the accumulation of the nutrient within the wood tissue. As with the other stated characteristics of wood, heterogeneity is apparent within the nitrogen contents, both as a result of environmental conditions and between species [26, 31, 38-41]. Unlike coal and peat – which often contain large concentrations of sulphur – its existence within wood biomass is minimal, often falling well below the 0.05% limits of standard gas chromatography elemental analysers [19, 29, 31]. The results from both the proximate and ultimate analysis have important impacts on the combustion process, which will be considered in the next section.

### 3.2.3. Wood Biomass Combustion

Although combustion is still one of the most well established and important forms of energy generation, the desire to reduce $CO_2$ emissions has prompted a move away from fossil fuels. With wood as the main constituent, the combustion of alternative biomass fuels – which also includes straws, residues and wastes – has continued to grow. Indeed, the global energy consumption from renewable sources totalled 79 exajoules (EJ) in 2017, with wood combustion integral in achieving this [28, 29, 42, 43]. Incorporating a mix of consecutive homogenous and heterogeneous reactions, the combustion of biomass is a complex process that can be reduced into five main steps; drying, devolatilization, gasification, char combustion and gas-phase oxidation. These steps often overlap, dictated by factors such as particle size, temperature and combustion conditions. Indeed, within a continuously operated combustion system these complex reactions occur simultaneously within different sections of the furnace [26, 28].

The methods for utilising biomass in energy generation are diverse, containing a variety of different technologies that vary in size and suitability. Often adapted from existing solid fuel technologies, namely coal and coke, these range from small scale open fires and stoves (1-10kW) – suitable for domestic use – to larger industrial fluid bed (≤500MW) and co-firing (≤900MW) systems [29]. Fixed-bed systems are one of the simplest and most widely used combustion technologies, with combustion taking place in a single chamber that contains a fixed grate and primary and secondary air supplies. Although this process is employed within domestic stoves, larger fixed-bed combustors (≤5MW) utilise the same principles; the biomass fuel is fed into the chamber, decomposing to produce volatile gases and char [29, 42, 44]. Assuming the complete combustion of a simple biomass fuel, the following equation details the reaction of the fuel with oxygen ($O_2$), producing water ($H_2O$), carbon dioxide ($CO_2$) and heat;

$$C_xH_yO_z + O_2 \rightarrow H_2O + CO_2 + Heat \qquad (3.1)$$

Unlike the simple fuel detailed in Eq. 3.1, the composition of a typical biomass – such as wood – is much more complicated, containing a variety of additional elemental components. Their presence within a fuel can cause issues during combustion, not only forming airborne pollutants but also causing issues with fouling and corrosion of the combustion apparatus [26, 28-30, 42].

#### 3.2.3.1. Airborne Pollutants

In addition to producing $CO_2$ – as detailed in Eq. 3.1 – a number of airborne pollutants can also be formed following the combustion of biomass; this includes nitrogen and sulphur oxides, hydrogen chloride, volatile organic compounds (VOC), polyaromatic hydrocarbons (PAH) and additional organic and inorganic aerosol particulates. These pollutants are formed either as the product of the reactions that occur during combustion, as unburned species or as the emission of stable species [29, 42]. Nitrous oxide ($N_2O$) and $NO_x$ – a collective term for nitric oxide (NO) and nitrogen dioxide ($NO_2$) – are important products of the combustion reactions; a result of their impact on the ozone layer and air quality, respectively. Their production is dependent upon a number of operating conditions, however the combustion temperature is one of the most important; at lower temperatures the emissions of $N_2O$ increase, while increased $NO_x$ emissions are caused at higher temperatures. In addition, the fuel-bound nitrogen content of the fuel directly impacts the produced nitrogen oxides. Indeed, biomass species with lower nitrogen contents – such as virgin stem wood – will only produce small quantities of $N_2O$ and $NO_x$, when compared to other feedstocks [44-46].

Another key pollutant – which has become prevalent following the increased popularity of domestic stove use [44, 47] – is fine particulate matter (PM), often grouped into two main particle sizes; these are $PM_{10}$ and $PM_{2.5}$, which represent particles between 2.5-10 μm and ≤2.5 μm, respectively. The particulate matter produced during biomass combustion differs throughout the combustion cycle, as shown in Figure 3.8, which is also dependent on the fuel – a feedstock with a large volatile matter content will produce greater concentrations of smoke during the flaming stage. The main constituents of the produced PM are large polyaromatic hydrocarbons and oxygenated aromatic compounds. In addition to these, PM also contains pyrolytic PAH materials which have been derived from the residual unburned char particles, the aromatic compounds and other condensed products [29, 44].

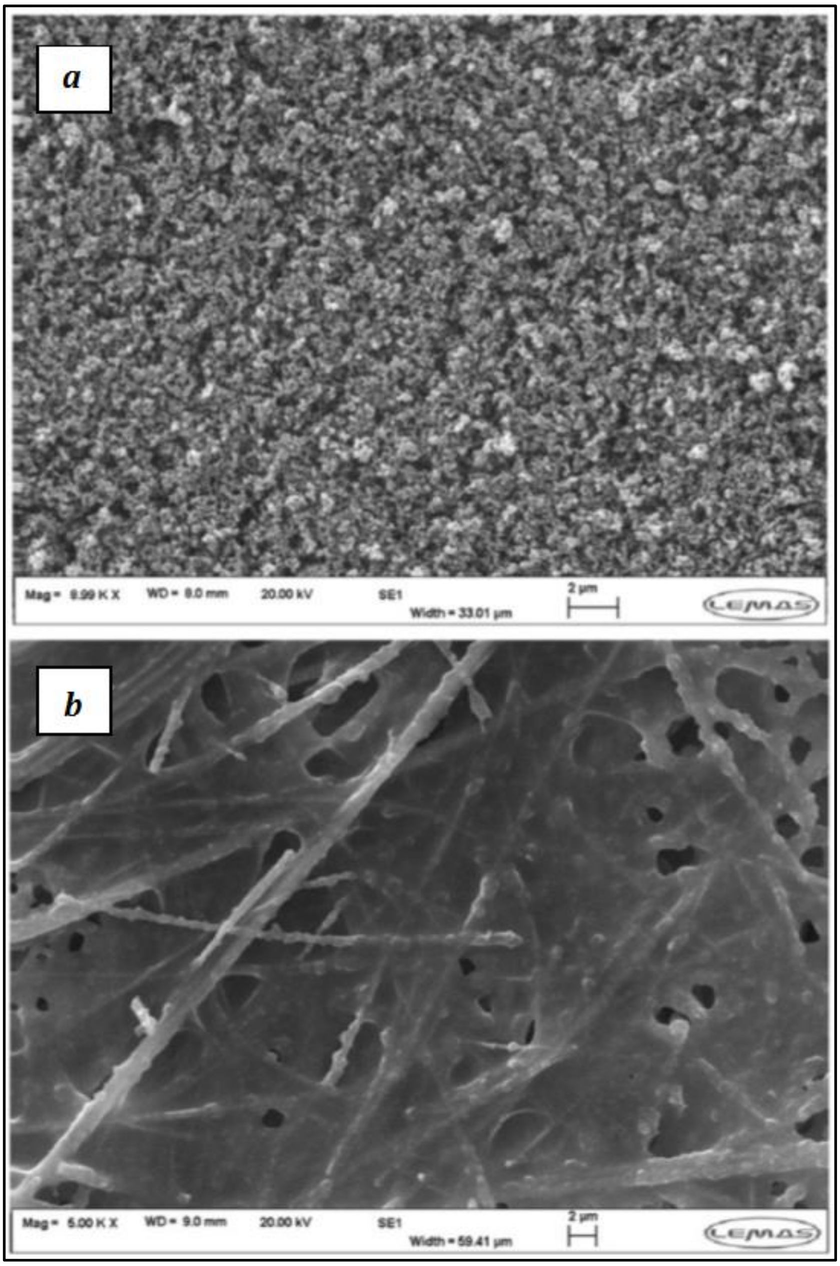


Figure 3.8 – **Physical differences of wood soot; SEM images of soot samples taken during a) flaming combustion, and b) smouldering combustion [47]**

Particulate matter can have major public health impacts, relating specifically to air quality; the existence of PM can cause issues with cardiovascular and respiratory systems, even after just short-term exposure. The composition and consequent health impacts of PM vary, differing not only geographically, but also seasonally. When considering the combustion of wood using a domestic stove, the inorganic composition of the fine particles found within PM is predominantly potassium chloride (KCl) and potassium sulphate ($K_2SO_4$); furthermore, the concentration of alkali salts differs between wood species [48-50].

#### 3.2.3.2. Fouling, Slagging & Corrosion

The advancement of large-scale biomass combustion has resulted in the occurrence of problems within the used appliances – particularly grate-fired boilers – which can experience major issues with fouling, slagging and corrosion that affects the equipment. Biomass combustion results in the partitioning of inorganic components – including potassium (K), calcium (Ca), sulphur (S) and chlorine (Cl) – which are either released into the vapour phase or retained in the ash. Those that are released can condense in the flue gases, before depositing within the combustion appliance. This can result in the fouling, slagging and corrosion, which can be costly and hinder the use of the combustion equipment [20, 24, 29, 51]. The release of inorganics into the vapour phase – and their consequent negative impacts – can be dictated by factors such as the type of biomass and the combustion temperature. Reducing the undesirable effects attributed to the inorganics that exist within biomass feedstocks, can be accomplished by either the addition of additives – mitigating their release – or by reducing their concentration before their use in the combustion process. This can be achieved by first washing the fuel, removing some of the minerals that are water soluble [24, 51, 52].

## 3.3. UK Forest Resource

Since the early 1980's there has been a significant reduction in the management of the UK's mature broadleaved stands – a result of post-war policies aimed at replacing broadleaved woodlands with conifer species to increase timber production. The reduced management is especially prevalent for privately owned woodlands where, less than 10 years ago, only 30% of the private forested areas in England had felling licences or participated in woodland grant schemes [53]. This continued lack of active management in private woodlands has been associated with a depressed timber market and, as a result, the structures of broadleaved forests have altered significantly – these have moved from coppice systems to high forest regimes with long rotations [53, 54].

Prior to the creation of the Forestry Commission, the UK had no collective state forest policy, instead relying on ad-hoc responses to particular issues if, and when, they arose. The focus of the UK's increase in forest cover following the 1st World War has been predominantly on softwood species, achieved through implemented afforestation programmes in upland areas; these were sites that were typified by low soil fertility, holding little agricultural use. Indeed, between 1950 and 1970 more than 90% of all new tree planting within the UK involved restocking with softwood species [55-58].

Table 3.2 – **Distribution of the UK's hardwood and softwood species between its constituent nations [60]**

| | **Species Forest Cover[a] (%)** | |
|---|---|---|
| | **Hardwoods** | **Softwoods** |
| **England** | *74* | *26* |
| **Wales** | *51* | *49* |
| **Scotland** | *26* | *74* |
| **Northern Ireland** | *41* | *59* |
| **UK** | *49* | *51* |

*[a] as of 31 March 2017*

### 3.3.1. Species Composition

The composition of the UK's forest and woodlands distribute relatively evenly between hardwood and softwood species, often referred to as broadleaves and conifers, respectively. This is evidenced in Table 3.2, which also outlines the variation in hardwood and softwood species cover that exists between the UK's constituent nations. England is dominated by broadleaved species, while Scottish forests are composed predominantly of softwoods. The UK's hardwood species include ash, birch, beech and oak species, while the softwood forest cover is comprised of firs, larches, pines and spruces [59, 60]. These will be covered in greater detail in the next two sections.

#### 3.3.1.1. Hardwoods

Hardwood tree species, or broadleaves as they are also referred to, are members of the angiosperm family and have historically been a major feature of the British landscape. Throughout history they have been utilised in a variety of ways, specifically as building materials, for fencing and as a fuel source. As a result, broadleaved species – many of which are native – form a major part of the UK's ancient and native woodlands. Key native species include oak (*Quercus* spp.), the common beech (*Fagus sylvatica*), ash (*Fraxinus excelsior*) and birch (*Betula* spp.), which differ greatly in their appearance, growth rates and timber quality [61-63]. Most of the broadleaves found in the UK are deciduous; their growth period occurs during the spring and summer, before dropping their leaves in the autumn to protect their shoot tips from the cold. The dropped leaves still contain important nutrients and minerals which, once decomposed, return into the soil system [61].

The Forestry Commission – in partnership with Natural Resources Wales and the Northern Ireland Forest Service – publish annual updates on the current state of the nation's forests and woodlands. These statistics detail the composition of the UK's forest resource, in addition to the current wood processing and timber market figures [60]. The existing species composition of the UK's broadleaved woodlands can be found in Figure 3.9. Oak species are the most dominant hardwood species in the UK, accounting for 28.4% of the standing volume of broadleaves – ash and beech are the next two most prevalent species, accounting for 16.5% and 12.2% respectively. The UK's broadleaved woodlands are dominated by five native species, as evidenced in Figure 3.9; these are oak, beech, ash, sycamore and birch, which account for 76.2% of the total volume. Figure 3.10 details the current volumes of standing hardwood species, specifying the differences in their ownership. Other than small amounts of oak, beech and birch, the majority of the UK's broadleaved woodlands are owned by the private sector.

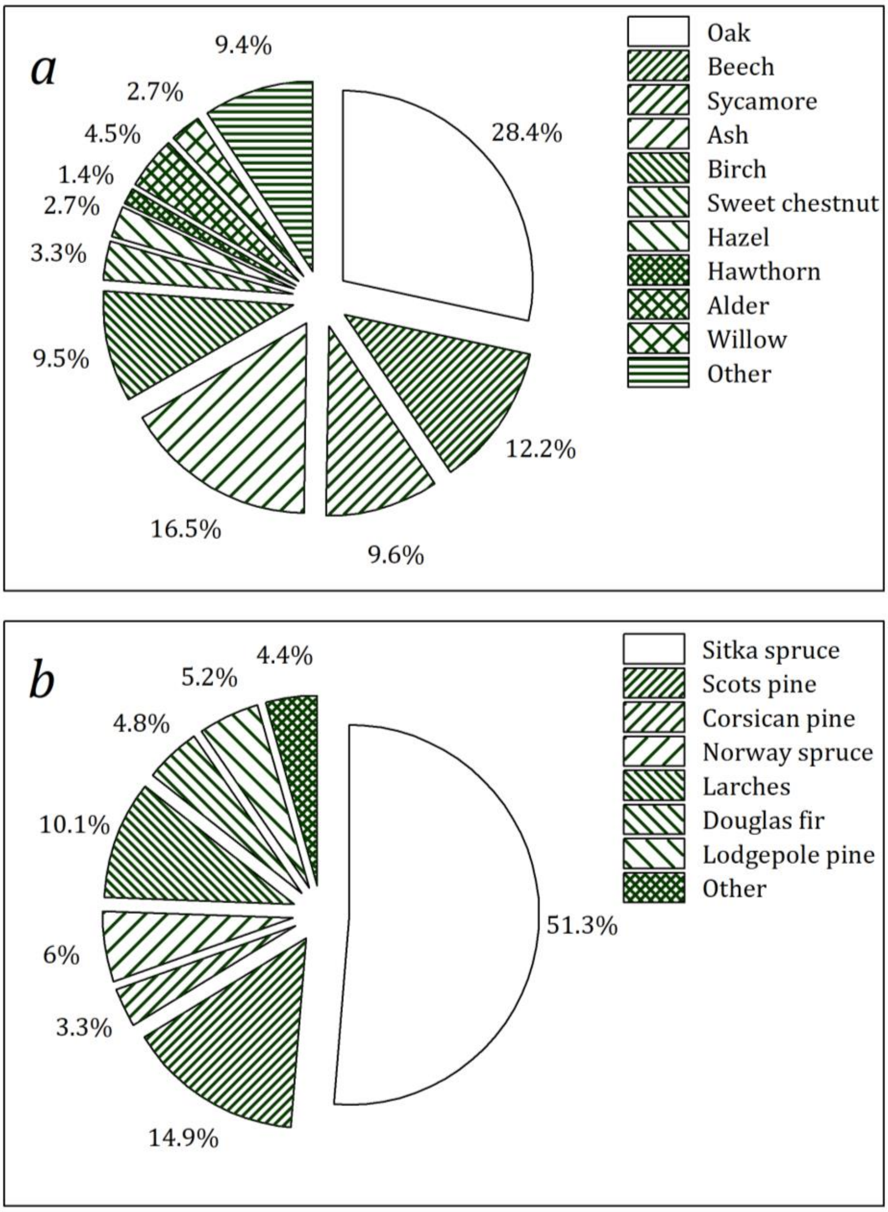


Figure 3.9 – **The species composition of the UK's forest and woodlands (Area), in 2017; a) broadleaved (hardwood), and b) conifer (softwood) species [60]**

The quality of British- and Irish-grown hardwoods can be extremely variable, a factor which prompts significant differences between the values achieved for low- and high-quality produced timber. The quality of the wood dictates its end use, with lower grade hardwoods more likely to be used as fuel instead of higher value products. Species such as pedunculate oak (*Quercus robur*) and sessile oak (*Quercus petraea*) are prone to experience poor form, knots, rot and other symptoms which are detrimental to their value. Ash trees are also susceptible to defects such as forking – occurring following poor management and neglect – and canker, which is caused by evasive bacteria or fungus and requires the removal of the affected specimen via thinning [64, 65]. The UK's broadleaved woodlands have experienced a considerable shift over the last century, resulting in clear visible changes to their structure. Wytham Woods – which is dominated by species such as sycamore (*Acer pseudoplatanus*), oak, birch and common beech – has chronicled clear changes to its wooded environment. The woods have experienced decreases in the canopy and understorey cover, while the remaining specimens have achieved large increases to their total basal area – evident for all the resident species – and increases to the mean diameter of the biggest trees [66]. The historical impacts are also species specific; within the canopy of the UK's mixed broadleaved woodlands, the existence of birch and ash specimens have increased in frequency. This has come at the expense of oak which, although still remaining as the dominant hardwood species, has seen its numbers significantly decrease. Although both oak and beech trees appear less often within a woodland, they will most often be the largest tree [54, 66].

#### 3.3.1.2. Softwoods

Softwoods, or alternatively conifers, are widely revered for their adaptability to extreme and stressful environments which, when coupled with their high growth rates, has resulted in their preference as a feedstock for the forest products industry. In total there are just three native softwood species found within the UK – Scots pine (*Pinus sylvestris* L.), yew (*Taxus baccata*) and juniper (*Juniperous communis).* However, of these, Scots pine is the only native species utilised for timber production. Scots pine is slower growing than other softwoods and is also sensitive to particular site conditions; this has resulted in the bulk of the UK's conifer stock composing of imported species from Europe and North America [57, 67, 68]. The main imported softwood species found in UK forestry are Sitka spruce (*Picea sitchensis* (Bong.) Carr.), lodgepole pine (*Pinus contorta* Douglas ex Loud.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Corsican pine (*Pinus nigra* var. *maritima* Ait. Melville) and several variations of larch (*Larix* spp.). Of these, Sitka spruce is the dominant commercial species utilised within the UK, accounting for more than half of the total volume of sawn timber produced. The UK's wet and mild climate are ideal conditions for Sitka spruce, promoting rapid growth. However, the produced wood is of poor quality – a result of its wide growth rings and low density – making it unsuitable for a lot of the more valuable traditional timber markets [69-71]. The quality of Sitka spruce timber is also dependent upon the size and frequency of knots contained within the wood. This directly impacts the timbers value, while also increasing the consequent harvesting costs; the greater the number of branches, the greater the processing time to remove them [72].

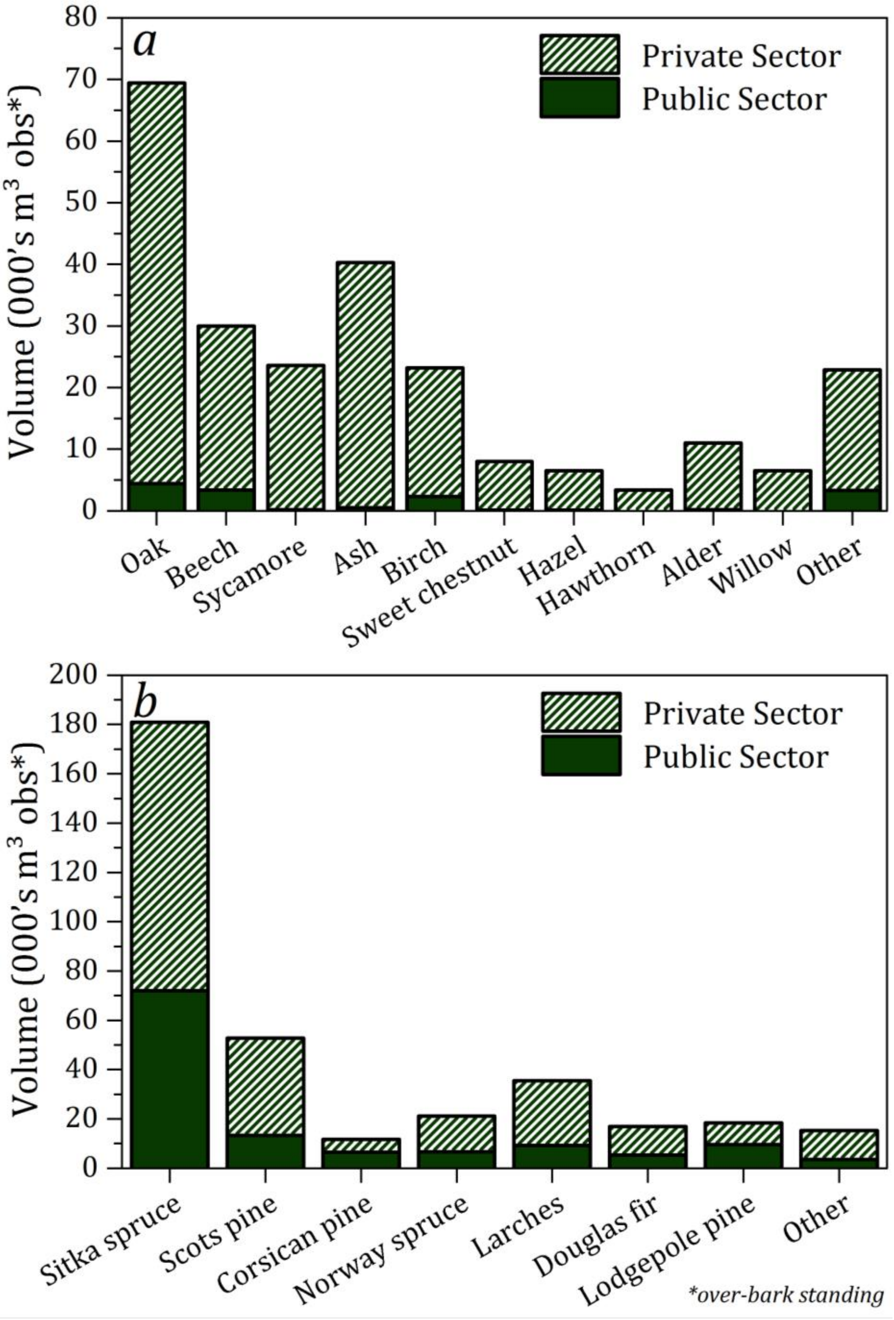


Figure 3.10 – **The standing volume and ownership of different UK species, in 2017; a) broadleaves (hardwoods), and b) conifers (softwoods) [60]**

Softwoods – a diverse and ancient member of the gymnosperm family – are often easily recognisable by their narrow needle or scale-like leaves, uniformed branch development and resinous fragrances. Their significant increase within the UK's forest cover, achieved following the 2nd World War, can be attributed to extensive planting regimes of conifer species in upland areas. These plantations are predominantly homogenous in nature, consisting of single species stands that are even-aged and uniformed in appearance – the planted seedlings have been cultivated in nurseries, specifically for improved growth. As a result, softwood plantations on strict 40-60 year rotations contain very little structural variety or biodiversity within their stands [69, 70, 73]. The dominance of Sitka spruce in the UK's conifer resource is evidenced in Figure 3.9 and 3.10; estimated at ~180 million $m^3$ of over-bark standing timber, it accounts for 51.3% of the conifer resource. In total, non-native species account for ~85% of the total softwood standing volume. Unlike the UK's broadleaved woodlands, the public sector owns a much larger proportion of the nation's conifer resource – extending across a more diverse number of species.

### 3.3.2. UK Forest Growing Stocks

The UK's forests and woodlands in 2017 account for an estimated 13% of the total land cover, a figure that has gradually increased since 1945. Details of the UK's growing stock can be found in Table 3.3; current calculations indicate there are ~520 million green tonnes (m.g.t) of wood resource, apportioned as 42% and 58% for hardwood and softwood species, respectively [60, 74, 75]. For 2016/17 the wood removals from the UK's forest resource totalled 11.32 m.g.t, with ~95% of the extracted wood sourced from softwood species. The reliance on softwood species for timber within the UK has remained constant during the last decade, maintained between 94-96%. During this period wood removals have steadily increased – for 2016/17 the total volume of wood removals was 23.4% larger than in 2007. The majority of the UK's softwood timber is sourced from Scottish forests, accounting for ~55% of 2017's removals [60]. It should be noted that the forecasted availability figures, found in Table 3.3, have been derived from Forest Research statistics publications [74, 75], using their stated growth model figures to estimate annual mean wood increment values.

Table 3.3 – **The UK's growing stock, removals and potential net growth of wood resource, 2017 [60, 74, 75]**

| | **Hardwood** | **Softwood** | **Total** |
|---|---|---|---|
| **Growing Stock** (million $m^3$) | *245.1* | *366.9* | *612* |
| **Growing Stock** (m.g.t)$^{ab}$ | *220.6* | *300.2* | *520.8* |
| **Privately Owned** (%) | *92* | *55* | *73* |
| **2017 Removals**$^{b}$ | *0.59* | *10.73* | *11.32* |
| **2017 Woodfuel Production**$^{b}$ | *0.40* | *1.55* | *1.95* |
| **Mean Forecasted Availability** ($yr^{-1}$)$^{bc}$ | *1.16* | *16.60* | *17.76* |
| **Potential Net Growth** ($yr^{-1}$)$^{b}$ | *0.56* | *5.87* | *6.44* |
| **Estimated Root Biomass**$^{b}$ | *0.13* | *2.15* | *2.28* |

$^{a}$*Calculated with FC conversion factors,* $^{b}$*million green tonnes,* $^{c}$*25-year forecasts*

Logging residues and other low quality timber – which is unsuitable for high value timber markets – can instead be utilised within the bioenergy industry. The increases in the UK's wood extraction correlates with a growing demand for UK-sourced woodfuel, resulting in an increase of 290% for deliveries to woodfuel production, since 2007 [60]. The sustainable potential of commercial forests can be calculated from the net increment of the forests growth and the current levels of felling experienced. In an established forest, when the net increment exceeds the current felling levels, the difference is considered its net growth – this represents a theoretically available resource for bioenergy, one which will not impact the current levels of sequestered carbon [76]. However, this approach requires a thorough understanding of the annual total wood growth; this is important, helping to avoid unintentional negative consequences such as deforestation.

The collated data in Table 3.3 indicates that there is potential to increase the volume of the UK's woodfuel production from local feedstocks, without impeding on other current timber industries or inducing deforestation. Increased wood extraction could however impact future wood growth – any additional tree that is removed for woodfuel can no longer grow. This must therefore be considered if the long-term sustainable management of the UK's wood resource is to be achieved. Therefore, the utilisation of forest residues – including branches and tree tops, which represent ~20% of the above-ground biomass of softwoods – avoids the need to fell additional trees, instead utilising the by-products of the forest felling industry. In addition to these residues, the stump also denotes a significant amount of the trees' entire biomass content; for softwood species the roots represent between 20-40% of the total, while for hardwoods this is slightly larger, estimated at 22-45%. As a result, the interest in removing and utilising tree stumps for fuel production – in addition to the harvesting residues – has grown, particularly in Scandinavia [77-80].

### 3.3.3. Impacts on Growth

Tree growth – as detailed in Section 3.2.1.1 – and the consequent effect on its form can be impacted by a number of external influences; the wood quality and its properties can be affected by site factors, the genetic quality of the tree, and perhaps most pertinently, the applied silvicultural practices. Forest management utilises silviculture to indirectly alter the growing environment within a forest stand, influencing the growth of the trees crown and roots. These are practices which are aimed at individual or groups of trees – such as thinning, initial spacing and pruning – or they can focus on improving the site [72, 81].

#### 3.3.3.1. Silvicultural Practices

One of the key impacts on wood quality is the rotation length of a forest stand – the allotted time from planting through to the final felling. As discussed in Section 3.2.1.1, the heartwood (hardwoods) or the mature wood (softwoods) – which both increase gradually with time – are vital components of a tree's mechanical strength. Longer rotation times therefore promote wood growth with better strength and dimensional stability, which are important attributes for high value timber markets [72]. The initial spacing, which is directly linked to the stocking density of a stand, affects the allocation of the resources required for growth; the available sunlight, moisture and nutrients. Trees with a greater allotted space will often achieve quicker diameter growth, while a reduced space will supress branch growth, encouraging the tree to grow straighter and taller. The growing stock within an area, often expressed as stems ha$^{-1}$ (hectare), usually decreases with time; a result of either competition-induced mortality, death as a result of pests or disease, windthrow, windsnap or intentional harvesting operations [72, 81, 82]. One of the most important operations, occurring during the rotation, is thinning. This is the removal of pre-identified trees which creates additional space within a stand, allowing the remaining trees to increase their mean size. In addition to the growth benefits of thinning, the process also provides an early source of revenue while maintaining canopy cover, helping to reduce soil erosion [72, 83].

#### 3.3.3.2. Site Conditions

The sustainable management of forest resources – maintaining the growth and form of the wood – requires a thorough understanding of the productivity of each individual site. Indeed, site-dependent variability of forest stands are often dictated by the topography and soil conditions, which can have either a positive or negative influence on wood growth. The influence of site quality on potential productivity of tree growth is often species dependant – certain species are more robust than others under specific conditions. By using the known site conditions, tree species and existing management regimes, the expected productivity and wood growth can be established from a yield class index; this gives a predicted annual increment value ($m^3$ $ha^{-1}$ $yr^{-1}$), specific to the site conditions [79, 81, 84].

The productivity of soil relies on several important functions; these include the aeration and porosity, nutrient content and biological capabilities, which relate to the existence of invertebrates and microbes within the soil [79, 84]. Site modifications – focused predominantly on soil improvements – utilise practices such as cultivation and fertilizer application to improve areas with poor growth conditions. The cultivation of land aerates the soil, improves the drainage while also reducing the weed numbers; as a result, cultivation, in combination with appropriate spacing, can prompt quick and vigorous initial wood growth. Alternatively, on sites that are nutrient deficient, fertilizers can be applied – these usually consist of nutrients such as nitrogen, potassium and phosphorus. The requirements for fertilizer vary at specific points during the different development stages of tree growth. During the early growth periods, large nutrient quantities are required, particularly for crown development. However, later in the trees life, growth nutrient cycling becomes dominate, reducing the need for nutrients from the soil. The application of additional nutrients can promote increased height and girth wood growth, however this can be at the detriment of timber density [72, 85, 86]. Although benefiting the growth process, fertilization can lead to issues with eutrophication; where excess nutrient availability, such as nitrogen, can prompt acidification of soils and freshwater systems [41, 78].

#### 3.3.3.3. Invasive Species

The existence of invasive species within an ecosystem can cause dramatic change, prompting a reduction in biodiversity, environmental degradation and a loss of native species. The term invasive can be applied to a variety of species, ranging from plants and insects through to larger mammals and birds. As a continuation of the site conditions, the establishment and growth of trees species within the UK's forested areas can also be affected by a number of invasive non-forest vegetation. These include rhododendron (*Rhododendron ponticum* (L)), heather (*Calluna vulgaris* (L)), and variations of both bracken (*Pteridium* spp.) and bramble (*Rubus* spp.) [79, 87]. Of these, rhododendron – a non-indigenous evergreen shrub – has been one of the most problematic for UK forestry. In addition to aggressively establishing itself, while supressing the regeneration of tree species, it is also difficult and costly to remove. The desire of forest managers to remove rhododendron was further increased following the discovery that the species could act as a host to the fungus (*Phytophthera ramorum*), responsible for sudden oak death in trees [88, 89].

Further to plant species, UK forestry has also been affected by other taxonomical species. In the last decade, evidence of the Asian longhorn beetle (*Anoplophora glabripennis*) has been found in Britain which, unlike other species of beetle, attacks healthy trees; preferring hardwood species, the beetle causes extensive damage which can result in tree mortality. Natural regeneration and tree growth within the UK are also impacted by bigger invasive species, such as deer, which are a particular problem in Scotland. In addition to their consumption of fallen acorns – before they establish – and browsing on advanced seedlings, deer also strip bark from trees, suppressing their growth and cause their death [90, 91].

#### 3.3.3.4. Pathogens & Fungi

The evolution of different tree species, and their geographical dispersion, can be directly linked to their relationship with invasive plants, pests and pathogens. Historically they have helped fashion the structure of the UK's forests, however their threat to biodiversity and tree growth have continued to increase. Trees are resilient, regularly coping with a number of biotic threats; however, the appearance of aggressive diseases and fungi can devastate the tree numbers within an area [92]. During the last decade the disease bleeding canker – caused by a pathogenic bacterium (*Pseudomonas syringae* pv. *aesculi*) – has dispersed across large sections of Britain, infecting a number of horse chestnuts (*Aesculus hippocastanum*). Consequently, the disease causes necrotic phloem and dieback of the wood which, if not dealt with, can lead to the trees death [93].

The existence of mycorrhizal fungi – and their symbiotic relationship with other plant species, particularly with root systems – benefits tree growth, aiding in the increased uptake of nutrients. Although helping to maintain the biodiversity and functionality of an ecosystem, evasive fungi species can be detrimental to tree growth and survival. The ascomycete fungus *Hymenoscyphus fraxineus*, also referred to as ash dieback or Chalara, has been attributed to the large losses of ash trees across Europe, including the UK. Chalara causes the infected trees to develop lesions and a reduction in their crowns, damaging the timber, which ultimately leads to the death of the tree [65, 94, 95]. Currently, the UK's ash trees account for ~40 million $m^3$ of standing timber, accounting for 16.5% of the nation's hardwood forests (Figure 3.9 and 3.10). Their demise would therefore represent the loss of a significant proportion of the UK's total forest cover, prompting Chalara to be the subject of current interest.

## 3.4. Harvesting & Extraction

The UK's forests provide a variety of goods and services that benefit society, the environment and local economies. These include recreational activities and the preservation of habitats and biodiversity, however their economic sustainability often depends upon productive and actively managed forests [86]. As discussed in Section 3.3.2, the wood removals from UK forests for 2016/17 totalled 11.32

m.g.t which, when considering forest cover totalling more than 3 million hectares (ha), equates to an annual removal rate of 1.22 t $ha^{-1}$ $yr^{-1}$ [60]. The conversion of standing timber – existing within a forest stand – to a useable natural resource, first requires the felling and then the extraction of the wood. The efficiency and productivity of this depends on a multitude of spatial factors, however the choice of harvesting technologies is one of the most important.

### 3.4.1. Felling Technologies

Within forest management, the more traditional methods of manual felling – using chainsaws – have gradually been replaced by more mechanised processes. Nevertheless, chainsaws are still considered an important harvesting tool, attaining acceptable levels of felling productivity that are not restricted by tree size or site conditions [96-98]. Although practiced across Europe, particularly on steeper sites, conventional chainsaw felling tends to result in uneven cuts and felling defects, impacting upon the timbers value. As a result, chainsaws are used predominantly in pre-commercial thinning, selective harvesting and salvage operations [96, 98]. During the felling process, the productivity of chainsaw use can be dictated by a number of factors. These include the size of the trees within a stand – both their diameter at breast height (DBH) and total height – and the distance between the harvested trees. Chainsaw productivity is generally impacted positively by increases in the size of the felled tree, while larger distances between harvestable trees reduces felling productivity. Across a series of chainsaw field trials – completed in both hardwood and softwood forests – the calculated mean productivity ranged between 9.41-33.63 $m^3$ $hr^{-1}$, felling trees with DBH's spanning 14.1-87.6cm [97-99].

The profitability and economic viability of forestry, particularly large-scale tree felling, is dependent upon reducing the costs of harvesting – this is especially prevalent when timber prices are low. One of the main options for reducing costs when increasing the scale of harvesting operation is by the mechanisation of forest processes; this focuses on the use of specific forest machines, such as harvesters, which increase felling productivity. This productivity is affected by factors including tree size and form, machine type and operator experience, the terrain conditions and even weather variations [100, 101]. Harvesters achieve their best felling productivities when utilised during clearcutting operations; where the harvesting regime results in the complete removal of seed-bearing or shelterwood trees. As a result, numerous single-grip harvester time studies have been conducted previously; their determined productivities range from 42.2-64.6 $m^3$ $hr^{-1}$, which includes both the felling and the processing of the timber [102, 103].

In comparison, shelterwood systems – in which trees are retained within a stand to shelter new growth – offer certain advantages over clearfelling; this includes an increased control over competing species, nutrient availability and ground water, while also reducing the costs of regeneration. The increased stand density results in a reduction for single-grip harvester productivity, ranging between 25.4-47.7 $m^3$ $hr^{-1}$. Again, this also includes the processing of the timber which involves the removal of brash and the cross-cutting of the stems into logs [102, 103]. The work elements associated with selective thinning – using a harvester – require more time to undertake, when compared to shelterwood or clearfelling operations. Of these elements, 'move and boom' – which refers to the harvesters movement between chosen trees, before extending its harvesting arm – is the most time-consuming aspect of mechanical harvesting. Selective thinning results in fewer trees being felled – when compared to other felling systems – increasing the travel time between trees, reducing the productivity. This ranges between 9.2-20.0 $m^3$ $hr^{-1}$ [100, 104]. A typical example of a single-grip harvester, operating within a forest stand, can be found in Figure 3.11.

An additional benefit to using a mechanised harvester for felling, instead of a chainsaw, is that the process includes the delimbing, cross-cutting and bunching of each harvested tree [100]. Although the literature indicates that chainsaws offer acceptable levels of felling productivity – in addition to their versatility for use on difficult sites or the removal of larger trees – their use requires the additional steps of branch removal and bucking.

Figure 3.11 – **Examples of forest machines, utilised in the felling and extraction processes; a) John Deere 1470G wheeled harvester, b) John Deere 1510G forwarder, and c) John Deere 948L grapple skidder [105]**

### 3.4.2. Extraction Technologies

The extraction of the felled timber represents one of the most important phases of the forest wood supply chain; this requires the accumulation of the felled wood products in one place. Historically, wood extraction was completed by a variety of animal species – ranging from oxen to horses and mules – however, the mechanisation of the process has now become prevalent, even from small-scale operations. The extraction process can be very expensive; this is often a result of large extraction distances, between the standing timber and the roadside, where it is stacked and stored before being sold. Once at the roadside, logging trucks transport the wood for further processing [106, 107].

Skidding, the simplest and most frequently used extraction method, involves the felled wood being dragged from the forest stand to the roadside. Due to its versatility, skidding can be completed by using animals or, more commonly, mechanised technologies. These range from tractors fitted with winches to purpose-built skidders, such as the example illustrated in Figure 3.11. The productivity of the skidding process is dictated by a number of factors, including the size and volume of each load, the winching distance and the site conditions, although the main influence is excessive skidding distance [106, 108-110]. Skidding operations are planned in advance – particularly the location and the planned routes of skid trails and temporary roads – ensuring that the ground disturbance from heavy machinery is minimised. This is vital, considering that the physicality of mechanised processes can cause ecological degradation to the soil and understory of a forest site [108]. The use of skidders for extraction has previously recorded productivities ranging between 14.5-22.4 $m^3$ $hr^{-1}$, across distances of 211-289m [108, 109, 111].

One of the main drawbacks of skidding is the potential damage that can be incurred from dragging the wood through the forest stand. This, coupled with an increased used of mechanised cut-to-length (CTL) systems, has resulted in a growing used of forwarders for wood extractions. As highlighted in Figure 3.11, instead of dragging the wood, forwarders pick the felled, delimbed and bucked logs off the ground, carrying the timber out of the forest in loads. This allows the forwarder to work in tandem with harvesters, collecting the processed wood with its attached hydraulic crane. A medium sized, purpose built forwarder can carry a payload of 10-12 tonnes, which is much greater than that of skidders [107, 112, 113]. As with skidding, the forwarding distance is vital, with increased extraction distances resulting in reduced productivity. Forwarding productivity is also dependent upon the chosen felling process; forwarder use after chainsaw felling, when compared to mechanised processes, can result in productivity reductions of nearly 50% [114]. Across extraction distances of 121-450m, previous field studies for forwarders recorded productivities between 9.0-17.2 $m^3$ $hr^{-1}$ [104, 113, 114].

Purpose built skidders and forwarders achieve high levels of productivity – an ideal attribute for commercial forestry – but, this can have environmental and ecological implications. Mechanised wood extraction can cause large amounts of damage to the soil substrate, particularly by compaction, shearing and rutting, which can be exacerbated by large, heavy machinery [115]. As a low-impact alternative, modified farm tractors have been used extensively in small-scale forestry, although these can also be susceptible to causing damage. The demand for sensitive extraction methods has resulted in the production of small, tracked 'mini' skidders and forwarders; their lower ground pressures reduce the environmental impact within forest stands [106, 116]. Although benefitting the ecological and environmental elements of a forest stand, the use of small-scale extraction methods is detrimental to productivity. Extracting timber across distances ranging from 103-736m, the achieved productivity is only 2.5-6.2 $m^3$ $hr^{-1}$ [106, 113, 117].

The decision of which felling and extraction technique to employ is often driven by site-specific terrain factors, such as slope gradient, which can prove to be a limiting feature for mechanised processes. This will be detailed in Section 3.5, however on sites that are too steep for mechanisation, the only effective extraction techniques are either gravity sliding – which is labour intensive – or cable yarding [116, 118, 119]. Cable yarding, or skyline extraction as it's often referred to, is used in mountainous regions, due to its suitability on steep sites. Although the process has a reduced impact on the forest stands environment, the process takes a considerable amount of time to plan and rig the cables before any wood extraction can take place. This subsequently affects the productivity of cable yarding, achieving between 7.0-10.7 $m^3$ $hr^{-1}$. These were achieved over a distance of 100-440m and slopes ranging from 17-38° [106, 120, 121].

### 3.4.3. Comminution & Transportation

The felling and extraction of wood – transferring the standing timber from within the forest stand to the roadside – are important components of the forest wood supply chain. Once successfully removed, the processing or comminution of the wood – in addition to its transportation – are also crucial for achieving the economic sustainability of forest wood as a natural resource. Although differing physically, the comminution and transportation processes are inherently linked; altering the bulk density – and therefore the energy content – of forest wood products, increases the transport efficiency [34].

#### 3.4.3.1. Forest Wood Processing

The initial processing of the felled tree includes its delimbing and cross-cutting, which removes the branches and reduces the stem length to produce roundwood logs. While the mechanisation of tree felling – utilising a single-grip harvester – incorporates this operation, chainsaw use requires additional processing; this is time-consuming, affecting the overall productivity and costs. When required for softwood species the delimbing operation is the most time-consuming while, alternatively, the cross-cutting is the most laborious procedure for the additional processing of hardwoods [122]. Within traditional timber markets, the produced roundwood logs are transported directly from the roadside to sawmills; for the bioenergy market the wood often requires further comminution, reducing its particle size [34].

One of the simplest forms is chipping, which produces wood chips that exhibit a large variation in shape and size. Wood chipping by the end user – at the combustion facility or terminal – will result in reduced chipping costs, however the increased bulk of transporting logs compounds the costs of handling and transportation. In addition to this, there are also potential issues with noise and dust emissions. Consequently, the chipping of wood at the roadside – directly into the truck – has increased in popularity, resulting in the development of a range of mobile chippers. Chipper productivity is dictated by working conditions and the intended physical properties of the produced woodchips; this includes the initial volume of the material to be chipped, the load size of the chipper, the employed chipper technology and the desired chip size and homogeneity of the final output [34, 123-125]. Using a lower powered disc chipper can result in a productivity of 20.6-27.7 $m^3$ $hr^{-1}$, while this increases for larger drum chippers, ranging between 66-270 $m^3$ $hr^{-1}$. This productivity diminishes with a reduction in the desired chip size, decreasing by as much as 23-54% when producing chips ≤35mm [124, 125]. In comparison to wood chipping, pellet production results in a refined, higher-value and higher-density product. Their production requires the drying and milling of the wood – resulting in a fine powder – which is then pressed into pellet dyes under high temperatures and pressures. Although this produces a highly desirable biomass fuel, its process is energy intensive, impacting its ability to reduce greenhouse gas (GHG) emissions. Representing 6.9 million tonnes of imported wood pellets in 2017, they are the dominant source of biomass fuel within the UK [126, 127].

#### 3.4.3.2. Wood Transportation

The distance of the forest feedstock from the processing facility location – such as a terminal or the end-use energy generator – is an important variable, greatly impacting the final cost of a product. Indeed, the transportation of wood often requires large quantities of energy, produced from fossil fuel sources, resulting in a costly process; the efficient use of wood biomass in bioenergy generation therefore necessitates a well-balanced transportation strategy [34, 125, 128]. Of the established biomass transportation techniques, road haulage continues to be the main mode for wood; a result of the dispersed nature of forest feedstocks, making the existing road infrastructure the most viable option for distances under 100km [34, 126, 129]. Although the flexibility of road haulage makes it the most preferable option over short distances, the more cost-effective method of land-based transportation is via rail, particularly for distances over 100km. The utilisation of electric trains, powered from renewable sources, can also reduce the GHG emissions associated with the transportation [34, 126].

Understanding the current processes of wood pellet transportation is especially relevant within the UK's bioenergy sector, with ~80% of the imported pellets sourced from the United States and Canada [60]. Although there are time constraints associated with shipping – a result of the typically large distances – its utilisation for transporting wood pellets is the most cost effective. In addition, the corresponding GHG emissions tend to be much smaller than alternative methods. This outcome is enhanced by ship size – the larger the cargo capacity, the more efficient the mode of transportation [34, 126, 129].

## 3.5. Impacts of Harvesting

Harvesting operations, be it the final felling of a forest stand or an intermediate thinning procedure, must take into account an array of outcomes and potential restrictions. Factors such as the geographical location, terrain accessibility, extraction distance and tree specification – including the volume and average tree size – should be taken into consideration. Indeed, larger tree sizes (DBH) or an increased volume of timber ($m^3$) dictate the chosen routes for felling and extraction; as these increase, the differences in productivity are magnified, ultimately affecting the final costs and viability of accessing the resource [107, 116]. Though the economic viability of the forest wood supply chain is important, the impacts of harvesting extend further than financial implications – there are an array of different environmental concerns which must also be considered.

### 3.5.1. Forest Terrain & Site Condition

As discussed in Section 3.4.2, the terrain and site conditions are limiting factors for mechanised processes, in particular the gradient of the slope. This is often the key determinant of machine stability and travel speed, consequently influencing which mechanised processes can be used safely. Mechanised felling can operate safely on slopes up to a maximum of 14° (25%), with manual chainsaw felling necessary on more severe gradients. This is also evident for extraction processes, such as forwarding, which are only effective on inclines up to 17° (30%), again with alternative methods required on steeper slopes [116, 118, 119]. In addition to the potential degradation of the forest floor on steep sites, the utilisation of mechanised harvesting operations can be detrimental to the environment and ecology within forest stands. This includes impacts to ecosystem services – such as soil fertility – biodiversity, water quality and even archaeologically important plots [116, 130]. An example of the physical damage caused by mechanised wood harvesting on a forest site is illustrated in Figure 3.12; the weight and resulting ground pressure associated with forest machinery can cause extensive damage and compaction of the soil.

Figure 3.12 – **An example of damage caused to a forest stand following mechanised harvesting processes**

#### 3.5.1.1. Environment

The majority of commercially harvested timber is felled and extracted using ground-based mechanised systems, however these can cause severe damage to the forest soil. This includes issues such as compaction, shearing and rutting, which occur when the soil's bearing capacity is exceeded by the ground pressure produced from the heavy mechanised equipment – this is further exacerbated on saturated ground. Subsequently, these issues can impair future tree growth, cause waterlogging on site and potentially mobilising heavy metals; as discussed throughout Section 3.2, this could have potential implications on the growth and end-use of the produced wood resource [115, 131]. Specific terrain features – particularly the grounds firmness, roughness and slope – can cause issues relating to soil erosion; harvesting operations that utilise large-scale machinery often depend upon the construction of forest access and extraction routes, especially on sensitive sites. Designed to reduce the impact on the site, the highest erosion rates will often occur on these temporary roads and extraction routes, which is further aggravated on steeper slopes. Modern silvicultural operations and site practices – aimed at improving the establishment and growth of planted trees – can result in substantial levels of soil disturbance, altering the soils properties and functions. The removal of trees from a sloped site can also aggravate the soil structure [79, 116, 132-134].

Nutrient availability within a forest ecosystem is dependent upon efficient nutrient recycling; a result of the successful decomposition and mineralisation of the nutrient rich leaf litter. As a result, the brash – which includes both branches and the foliage – represents a significant component of the nutrient sink within a forest stand. Indeed, their nutrient rich tissues can contain up to half of the available N, K, P, Mg and Ca, existing within the tree biomass [135]. The nutrients released following the decomposition of post-harvest brash and residues – which are used as important metrics for soil N availability – can contribute directly to new growth. Therefore their removal could have major implications on the future productivity and sustainability of the forest stand [136, 137]. This relationship extends to the practices of whole-tree harvesting and stump removal, which cause both positive and negative impacts on wood growth. The removal of the brash and stumps from a site – and the subsequently sustained soil disturbance – improves the survival rate and establishment of tree seedlings, however there are resulting environmental implications. In addition to the reduced nutrient content – exacerbated on sites typified by nutrient-poor, acidic soil – there is also an immediate reduction in the amount of sequestered carbon, which is discussed in Section 3.5.2. The removal of stumps has also been linked to a decrease in biodiversity, reducing the numbers of species dependent upon the dead wood left within a forest stand [79, 138, 139].

#### 3.5.1.2. Costs

The costs attributed to forest harvesting are important limiting factors, often prompting compromises between optimum performance and the price required to achieve this. Broken down, the total costings include capital costs, fixed and variable costs, labour availability, marketing strategy and the values of other comparative products [116]. Poor timber product prices – which can make wood felling and extraction economically fraught – occur as a culmination of unstable biomass markets, low delivered biomass prices and a limited number of facilities to deliver to. The wood bioenergy market is increasingly important to forest owners; however, in addition to the low product prices, there are additional obstacles. High operating costs, long transportation distances and inconsistent demand for fuelwood limit the potential utilisation of wood in energy generation, although the recent establishment of a UK bioenergy market has helped reduce issues with demand [77, 140]. Meeting and adhering to environmental concerns can also increase costs; reducing the size of timber loads during the extraction process can lessen the physical impacts on the environment, however this reduces the productivity and increases the financial costs [133].

Forest feedstocks that are situated in remote and isolated places often have large associated transportation costs, influencing the economic viability of the wood resource. As described in Section 3.4.3, the efficient utilisation of transport facilities and modes is a necessity, keeping the energy consumption and costs as low as possible. This also includes the closely linked comminution processes of forest wood – such as roadside chipping – which increases the bulk density, allowing for the optimal use of a vehicles payload [129, 141].

#### 3.5.1.3. Planting Policy

Finally, a significant limitation to utilising the UK's wood resource are national and local policy decisions that impact upon tree planting regimes. The majority of harvesting operations – and the consequent restocking of an area – requires regulatory approval. There are however certain environmental exceptions, such as the outbreak of diseases, which allow for the permanent removal of trees. If planting regimes are insufficient, then potential issues with deforestation could arise; deforestation occurs when tree felling rates outstrip the levels of replanting and regeneration of forests and woodlands [60, 142]. During the last 5 years, the restocking of the UK's felled woodland area has increased by ~30%, totalling 17,100 ha in 2017. In comparison, the planting of new forest areas in the UK has decreased by nearly 40%, determined as just 6,500 ha in 2017 [60]. Considering the UK's continued increase in softwood extractions for us in the bioenergy sector – as discussed in Section 3.3.2 – a lack of new tree planting within the UK could increase the risk of deforestation. This looks set to change, due to the UK governments' proposed *Clean Growth Strategy*, which proposes to create 130,000 ha of new woodland cover in England [143].

### 3.5.2. Carbon Sequestration

Forest ecosystems act as carbon sinks, sequestering atmospheric carbon (C) via photosynthesis, storing it within its trees, vegetation and other forest products; of these, the biomass C and soil C exist in a constant dynamic equilibrium with one another. Temperate and boreal vegetation, dominated by forests and tree species, are one of the main global sinks for carbon emissions, accounting for an estimated 1.3 (±0.9) petagrams (Pg) of C [40]. The successful sequestration of carbon within forests can be altered with intentional changes to the applied silvicultural measures; increasing the rotation length of a forest stand will often result in the sequestration of more C. In the short-term, terminating forest management practices can result in larger carbon stocks – contained within the living and dead biomass – however, this negatively affects the volume of sequestered carbon in harvested products [40, 144-146]. Determining the capabilities of a forest to sequester atmospheric C – both in its biomass and soil – continues to be of great interest, driven specifically by their potential for mitigating the negative influences of climate change. These strategies, in addition to improved forest management, include the promotion of afforestation and reforestation projects, the restoration and protection of secondary forests and, most importantly, reducing deforestation [147]. As shown previously – in Figure 1.2 and 1.4 – the GHG emission data for Land Use, Land-Use Change and Forestry (LULUCF) identify that these strategies have been successful in increasing the amount of sequestered carbon.

#### 3.5.2.1. Tree Mortality

Carbon sequestration in older trees occurs at a reduced rate, when compared to younger forests. Therefore the active management of forest stands – through thinning operations in forests affected by high tree mortality – can have GHG benefits. When a tree dies and is left to decompose, some of the previously stored carbon is released back into the atmosphere; the removal of a tree before its death, particularly for use within traditional timber markets, can help maximise the carbon storage associated with forests [146-148]. The rate of biomass accumulation – and the consequent sequestration of carbon – in trees tends to peak early within the rotation, with the declining rate a result of canopy closure within the forest stand. Causes of tree mortality are difficult to verify, arising from endogenous factors and a number of differing external pressures and stresses. Inherent biological features, such as the trees age or its genetic potential, can be exacerbated by external influences including environmental stresses – like droughts – or the establishment of invasive species and pathogens, as previously described [40, 149, 150].

Another important cause of tree mortality, particularly due to the release of carbon back into the atmosphere, is fire; although influenced by uncontrollable factors, such as the climate or weather, there are management decisions which can reduce the impact of fire on forests. An established forest fire requires fuel, therefore most control measures focus on reducing the potential sources which could spread the fire. The active management of forests and the creation of fuelbreaks – which are strategically located strips of barren ground or non-flammable vegetation, between forest stands – are employed to slow the spread of fire. Alternatively, the use of deliberate burning under controlled conditions is used to remove the potential for larger, more devastating fires [151-153]. During severe forest fires, the single largest loss of stored carbon is from fire-related mortality of trees, which can be significant; in the Canadian boreal forests, the annual loss of carbon is estimated at between 10-30% of the average net primary production. The long-term impact of forest fires on the soil carbon is dictated by both the distribution of the carbon within the soil profile, and also the duration and temperature of the fire [40, 145, 151].

#### 3.5.2.2. Forest Soils

The forests located in the northern hemisphere – especially those at mid to high latitudes – have been in a constant state of change, resulting in the accumulation of large quantities of carbon over the last 10,000 years. As a result, the soil carbon stock differs between forest types; the soil found in boreal forests, typified by softwood species, contains around 85% of the C within its ecosystem, while this is reduced in hardwood-dominated temperate forests, estimated at 60% [40, 145]. Further to the differences in forest types, there are also a number of anthropogenic and natural factors which dictate the volume of C stored within soil. Influences from natural occurrences include climatic factors – such as precipitation, wind and the temperature – and biological destructive events, often related to invasive insect and disease establishment. In comparison, the bulk of the anthropogenic factors relate directly to the harvesting management practices, covered extensively in Section 3.4 [145].

The sequestered soil carbon can be categorised into two main forms; labile – which regularly fluctuates in carbon content, a result of its short-term nature – and stable, which is much more long-term. Disturbances to these can prompt an increase in heterotrophic respiration, leading to losses in sequestered carbon. As discussed previously in this chapter, the roots and stump – left following the felling process, as illustrated in Figure 3.13 – represent 20-45% of the total volume of the tree, depending upon the species and the chosen felling process [79, 80]. The majority of this is located below ground, resulting in a reduced decomposition rate of the remaining biomass, with large amounts of the carbon retained within the soil. This is important when considering the increased interest in utilising stumps as a feedstock for bioenergy, particularly observable across Scandinavia. The method of stump removal is primitive, using unrefined physical processes that are detrimental to the forest stand and its carbon stock. As a result, the immediate influence of stump harvesting on the stored carbon is not only contained to the removal of the increased volume of biomass, but in its severe disturbance to the soil. The accepted view, albeit one containing a degree of uncertainty, is that stump removal has a negative impact on the carbon stored within soil. However, recent field studies have indicated that soil disturbance doesn't increase the release of carbon back into the atmosphere [79, 139].

Figure 3.13 – **Example of a tree stump left in a forest stand, following mechanised harvesting [139]**

#### 3.5.2.3. Life Cycle Assessment

Historically, the UK's forests and woodlands have functioned as an important natural resource, producing timber for a number of different markets. Although the UK's forest cover is inferior to other European countries – representing ~2% of the total forested area in Europe – it still constitutes a significant feedstock for biomass resource. During the last decade, the bioenergy sector has established itself as a key component of the UK's renewable energy strategy, which has prompted a notable increase in home-grown woodfuel production; evidenced by the increased deliveries of UK grown wood to energy producers, as discussed in Section 3.3.2 [60]. In addition to their potential as a fuel source, a nation's forests could also help form GHG mitigation strategies; a result of their capability to capture and store atmospheric $CO_2$, alleviating the impact of carbon intensive sources. Biomass production is however limited by the availability of land and the existing resource, while the need to fulfil sustainability criteria also restricts access to particular feedstocks [60, 144, 154, 155]. The effective use of a nation's forest resource, for reducing GHG emissions, must balance against the carbon implications of their management and the different processes associated with producing bioenergy from wood sources.

An important tool for quantifying the costs and benefits associated with forest feedstocks and silvicultural practices are life cycle assessments (LCA's), which evaluate the carbon implications that occur throughout the entire life cycle of the resource. Assessing a process and its potential future outcomes can be difficult, resulting in differing levels of uncertainty which should be considered; for GHG emissions these range from uncertainties with the specific data and subject knowledge, through to other external natural factors. Within a forest system, the uncertainty stems predominantly from the sequestered carbon – for both the biomass and soil – the local climate and, as discussed extensively, the specific management decisions [144, 155, 156].

The utilisation of biomass in energy generation processes releases $CO_2$, however as a fuel source it is often deemed 'carbon neutral'; unlike the emission of $CO_2$ from fossil fuels, which are produced over millennia, the atmospheric carbon released from biomass feedstocks can be captured again, through additional plant growth [144]. The assumption of carbon neutrality for wood biomass is however flawed – there are a range of emissions associated with the different processes of forest harvesting, each containing their own levels of uncertainty. Numerous LCA's have been completed previously, covering different aspects of the bioenergy sector and forest procedures, however their methods often differ and lack the continuity required for proper comparison. Indeed, within the forestry sector there is yet to be a defined – and commonly accepted – approach for conducting an LCA, particularly lacking clarity on the system boundaries, functional units and management assumptions [144, 157-160]. For example, uncertainties corresponding to the selected felling and extraction technologies used during forest harvesting – particularly the achieved productivities, as discussed previously in this chapter – can have a considerable impact on the 'neutrality', affecting the influence of forests in mitigation strategies [157, 159].

## 3.6. Conclusions

The number of differing disciplines and inherent complexities, associated with forestry and forest research, have been highlighted within this literature review. This is pertinent when considering the utilisation of wood biomass for energy generation, particularly with the specific aim of reducing the impacts of climate change. Increasing the volumes of extracted wood used in bioenergy would cause additional consequences – such as the potential reduction in produced timber products or changes to the carbon balance within the forest stand itself – which could affect the sustainability of the process. The UK is typified by a variety of native and non-native hardwood and softwood tree species, distributed across four constituent nations, within forested areas that contain unique individual site conditions. This variability in the UK's forest feedstocks – evident both between- and within- species – will directly impact its suitability as a fuel, thus its detailed characterisation would be undoubtedly beneficial.

The heterogeneous nature of biomass resource clearly extends to its analysis using LCA methods – this is especially apparent within forestry. Indeed, for truly effective LCA's to be completed, that are specific to the forest sector, then clarity on the numerous existing uncertainties is first required; the assumptions of harvesting process productivity require an understanding of the individual site conditions that directly affect it, while the assumptions of carbon sequestered within wood biomass first require the detailed understanding of the resource. Although the work completed within this thesis will not include a life cycle analysis of the UK's forest resource for use in bioenergy, it will help inform on a number of the uncertainties that surround the feedstocks utilisation. As a result, the in-depth analysis of; 1) the UK's current wood feedstock characteristics, 2) their fundamental combustion, and 3) the impact of terrain and infrastructure on the different harvesting processes, will give both a detailed insight into the UK's current forest resource, while also proving a potentially useful aid for any future LCA's.

## 3.7. References

[1]. Spellman F. R. 2011. *Forest-based biomass energy – concepts and applications*. CRC Press, Taylor & Francis Group

[2]. Sjöström E. 1981. *Wood chemistry – fundamentals and applications*. Academic Press Inc. New York

[3]. Savidge R. A., Barnett J. R. and Napier R. 2000. *Cell and molecular biology of wood formation*. CRC Press, Taylor & Francis Group

[4]. Hon D. N-S. and Shiraishi N. 2001. *Wood and cellulosic chemistry*, 2nd Edition. Marcel Dekker, Inc. New York

[5]. Wang X-Q. and Ran J-H. 2014. Evolution and biogeography of gymnosperms. *Molecular Phylogenetics and Evolution*, 75, pp24-40

[6]. Browning B. L. 1963. *The chemistry of wood*. Interscience Publishers, John Wiley & Sons, Inc. New York

[7]. Plomion C., Leprovost G. and Stokes A. 2001. Wood formation in trees. *Plant Physiology*, 127, pp1513-1523

[8]. Déjardin A., Laurans F., Arnaud D., Breton C., Pilate G. and Leplé J-C. 2010. Wood formation in Angiosperms. *Comptes Rendus Biologies*, 333, pp325-334

[9]. Gibson L. J. 2012. The hierarchical structure and mechanics of plant materials. *Journal of the Royal Society Interface*, 9, pp2749-2766

[10]. O'Sullivan A. C. 1997. Cellulose: the structure slowly unravels. *Cellulose*, 4(3), pp173-207

[11]. Barnett J. R. and Bonham V. A. 2004. Cellulose microfibril angle in the cell wall of wood fibres. *Biological Reviews*, 79, pp461-472

[12]. Fernandes A. N., Thomas L. H., Altaner C. M., Callow P., Trevor Forsyth V., Apperley D. C., Kennedy C. J. and Jarvis M. C. 2011. Nanostructure of cellulose microfibrils in spruce wood. *Proceedings of the National Academy of Sciences of the USA*, 108(47), pp1195-1203

[13]. Scheller H. V. and Ulvskov P. 2010. Hemicelluloses. *Annual Review of Plant Biology*, 61, pp263-289

[14]. Ridley B. L., O'Neill M. A. and Mohnen D. 2001. Pectin: structure, biosynthesis, and oligogalacturonide-related signalling. *Phytochemistry*, 57, pp929-967

[15]. Novaes E., Kirst M., Chiang V., Winter-Sederoff H. and Sederoff R. 2010. Lignin and biomass: a negative correlation for wood formation and lignin content in trees. *Plant Physiology*, 154, pp555-561

[16]. Rogers L. A. and Campbell M. M. 2004. The genetic control of lignin deposition during plant growth and development. *New Phytologist*, 164, pp17-30

[17]. Boerjan W., Ralph J. and Baucher M. 2003. Lignin biosynthesis. *Annual Review of Plant Biology*, 54, pp519-546

[18]. Senelwa K. and Sims R. E. H. 1999. Fuel characteristics of short rotation forest biomass. *Biomass and Bioenergy*, 17, pp127-140

[19]. Vassilev S. V., Baxter D., Andersen L. K. and Vassileva C. G. 2010. An overview of the chemical composition of biomass. *Fuel*, 89, pp913-933

[20]. Vassilev S. V., Baxter D., Andersen L. K., Vassileva C. G. and Morgan T. J. 2012. An overview of the organic and inorganic phase composition of biomass. *Fuel*, 94, pp1-33

[21]. Molino A., Nanna F. and Villone A. 2014. Characterisation of biomasses in the southern Italy regions for their use in the thermal processes. *Applied Energy*, 131, pp180-188

[22]. van Loo S. and Koppejan J. 2008. *The handbook of biomass combustion and co-firing*. Earthscan Ltd, Dunstan House, London

[23]. Pitman R. M. 2006. Wood ash use in forestry – a review of the environmental impacts. *Forestry*, 79(5), pp563-588

[24]. Deng L., Ye J., Jin X., Zhu T. and Che D. 2017. Release and transformation of potassium during combustion of biomass. *Energy Procedia*, 142, pp401-406

[25]. Fromm J. 2010. Wood formation of trees in relation to potassium and calcium nutrition. *Tree Physiology*, 30, pp1140-1147

[26]. Jenkins B. M., Baxter L. L., Miles Jr. T. R. and Miles T. R. 1998. Combustion properties of biomass. *Fuel Processing Technology*, 54, pp17-46

[27]. McKendry P. 2002. Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, 83, pp37-46

[28]. Nussbaumer T. 2003. Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. *Energy and Fuels*, 17, pp1510-1521

[29]. Williams A., Jones J. M., Ma L. and Pourkashanian M. 2012. Pollutants from the combustion of solid biomass fuels. *Progress in Energy and Combustion Science*, 38, pp113-137

[30]. Phillips D., Mitchell E. J. S., Lea-Langton A. R., Parmar K. R., Jones J. M. and Williams A. 2016. The use of conservation biomass feedstocks as potential bioenergy resources in the United Kingdom. *Bioresource Technology*, 212, pp271-279

[31]. Speight J. G. 2011. *The biofuels handbook*. RSC Energy Series No.5, Royal Society of Chemistry, Thomas Graham House, Cambridge

[32]. Stillwell S. T. C. 1930. The seasoning of timber. Forestry: *An International Journal of Forest Research*, 4(1), pp34-39

[33]. Rémond R. and Perré P. P. 2007. The effect of temperature and moisture content on the mechanical behaviour of wood: a comprehensive model applied to drying and bending. *European Journal of Mechanics A/Solids*, 26, pp558-572

[34]. Wolfsmayr U. J. and Rauch P. 2014. The primary forest fuel supply chain: a literature review. *Biomass and Bioenergy*, 60, pp203-221

[35]. Oltean L., Teischinger A. and Hansmann C. 2011. Influence of low and moderate temperature kiln drying schedules on specific mechanical properties of Norway spruce wood. European *Journal of Wood and Wood Products*, 69(3), pp451-457

[36]. Friedl A., Padouvas E., Rotter H. and Varmuza K. 2005. Prediction of heating values of biomass fuel from elemental composition. *Analytica Chimica Acta*, 544, pp191-198

[37]. Gusiatin Z. M. and Pawlowski A. 2016. Biomass for fuels – classification and composition. In: Bulkowska K. ed. *Biomass for Biofuels*. CRC Press, Taylor & Francis Group, pp15-36

[38]. Rennenberg H., Dannenmann M., Gessler A., Kreuzweiser J., Simon J. and Papen H. 2009. Nitrogen balance in forest soils: nutritional limitation of plants under climate change stresses. *Plant Biology*, 11, pp4-23

[39]. Millard P. and Grelet G-A. 2010. Nitrogen storage and remobilization by trees: ecophysiological relevance in a changing world. *Tree Physiology*, 30, pp1083-1095

[40]. Hyvönen R., Ågren G. I., Linder S., Persson T., Cotrufo M. F., Ekblad A., Freeman M., Grelle A., Janssens I. A., Jarvis P. G., Kellomäki S., Lindroth A., Loustau D., Lundmark T., Norby R. J., Oren R., Pilegaard K., Ryan M. G., Sigurdsson B. D., Strömgren M., van Oijen M. and Wallin G. 2007. The likely impact of elevated $CO_2$, nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. *New Phytologist*, 173, pp463-480

[41]. Jones L., Provins A., Holland M., Mills G., Hayes F., Emmett B., Hall J., Sheppard L., Smith R., Sutton M., Hicks K., Ashmore M., Haines-Young R. and Harper-Simmonds L. 2014. A review and application of the evidence for nitrogen impacts on ecosystem services. *Ecosystem Services*, 7, pp76-88

[42]. Zhang L., Xu C. and Champagne P. 2010. Overview of recent advances in thermos-chemical conversion of biomass. *Energy Conversion and Management*, 51, pp969-982

[43]. EIA. 2017. *International Energy Outlook – delivered energy consumption by end-use sector and fuel*. US Energy Information Administration, Washington

[44]. Mitchell E. J. S., Lea-Langton A. R., Jones J. M., Williams A., Layden P. and Johnson R. 2016. The impact of fuel properties on the emissions from the combustion of biomass and other solid fuels in a fixed bed domestic stove. *Fuel Processing Technology*, 142, pp115-123

[45]. Hayhurst A. N. and Lawrence A. D. 1992. Emissions of nitrous oxide from combustion sources. *Progress in Energy and Combustion Science*, 18(6), pp529-552

[46]. Johnsson J. E. 1994. Formation and reduction of nitrogen oxides in fluidized-bed combustion. *Fuel*, 73(9), pp1398-1415

[47]. Atiku F. A., Mitchell E. J. S., Lea-Langton A. R., Jones J. M., Williams A. and Bartle K. D. 2016. The impact of fuel properties on the composition of soot produced by the combustion of residential solid fuels in a domestic stove. *Fuel Processing Technology*, 151, pp117-125

[48]. Bell M. I. 2012. *Assessment of the health impacts of particulate matter characteristics*. Health Effects Institute, Research Report 161, Boston, Massachusetts

[49]. Cheng Z., Jiang J., Fajardo O., Wang S. and Hao J. 2013. Characteristics and health impacts of particulate matter pollution in China (2001-2011). *Atmospheric Environment*, 65, pp186-194

[50]. Nyström R., Lindgren R., Avagyan R., Westerholm R., Lundstedt S. and Boman C. 2017. Influence of wood species and burning conditions on particle emission characteristics in a residential wood stove. *Energy and Fuels*, 31, pp5514-5524

[51]. Clery D. S., Mason P. E., Rayner C. M. and Jones J. M. 2018. The effects of an additive on the release of potassium in biomass combustion. *Fuel*, 214, pp647-655

[52]. Gudka B., Jones J. M., Lea-Langton A. R., Williams A. and Saddawi A. 2016. A review of the mitigation of deposition and emission problems during biomass combustion through washing pre-treatment. *Journal of the Energy Institute*, 89, pp159-171

[53]. Hopkins J. J. and Kirby K. J. 2007. Ecological change in British broadleaved woodland since 1947. *IBIS*, 149(2), pp29-40

[54]. Amar A., Smith K. W., Butler S., Lindsell J. A., Hewson C. M., Fuller R. J. and Charman E. C. 2010. Recent patterns of change in vegetation structure and tree composition of British broadleaved woodland: Evidence from large-scale surveys. *Forestry*, 83(4), pp345-356

[55]. Forestry Commission. 2017. *The UK Forestry Standard – the governments' approach to sustainable forestry*. Forestry Commission, Edinburgh

[56]. Aldhous J. R. 1997. British forestry: 70 years of achievement. *Forestry*, 70(4), pp283-291

[57]. Malcolm D. C. 1997. The silviculture of conifers in Great Britain. *Forestry*, 70(4), pp293-307

[58]. Adam M. 1999. Nutrient fluctuations in Sitka spruce (*Picea sitchensis*) plantations: the implications for future forest management practice. *Forestry*, 72(3), pp249-271

[59]. DEFRA. 2012. *Independent panel on forestry: final report*. Department for Environment, Food and Rural Affairs, London

[60]. Ward S. 2017. *Forest Statistics 2017*. IFOS-Statistics, Forest Research, 231 Corstorphine Road, Edinburgh

[61]. Edlin H. L. and Mitchell A. F. 1985. *Broadleaves*. Forestry Commission Booklet no.20, 2nd ed. HMSO, London

[62]. Evans J. 1997. Silviculture of hardwoods in Great Britain. *Forestry*, 70(4), pp309-314

[63]. Forestry Commission. 2010. *Managing ancient and native woodland in England*. Forestry Commission England Practice Guide, Bristol

[64]. Savill P. S., Fennessy J. and Samuel C. J. A. 2005. Approaches in Great Britain and Ireland to the genetic improvement of broadleaved trees. *Forestry*, 78(2), pp163-173

[65]. Dobrowolska D., Hein S., Oosterbaan A., Wagner S., Clark J. and Skovsgaard J. P. 2011. A review of European ash (*Fraxinus excelsior* L.): implications for silviculture. *Forestry*, 84(2), pp133-148

[66]. Kirby K. J., Bazely D. R., Goldberg E. A., Hall J. E., Isted R., Perry S. C. and Thomas R. C. 2004. Changes in the tree and shrub layer of Wytham woods (southern England) 1974-2012: local and national trends compared. *Forestry*, 87, pp663-673

[67]. Mitchell A. F. and Edlin H. L. 1985. *Conifers*. Forestry Commission Booklet no.15, 3rd ed. HMSO, London

[68]. Lorenz W. W., Ayyampalayam S., Bordeaux J. M., Howe G. T., Jermstad K. D., Neale D. B., Rogers D. L. and Dean J. F. D. 2012. Conifer DBMagic: a database housing multiple de novo transcriptome assemblies for 12 diverse conifer species. *Tree Genetics and Genomes*, 8(6), pp1477-1485

[69]. Mason W. L. 2007. Silviculture of Scottish forests at a time of change. *Journal of Sustainable Forestry*, 24(1), pp41-57

[70]. Macdonald E., Gardiner B. and Mason W. 2010. The effects of transformation of even-aged stands to continuous cover forestry on conifer log quality and wood properties in the UK. *Forestry*, 83(1), pp1-16

[71]. Gardiner B., Leban J-M., Auty D. and Simpson H. 2011. Models for predicting wood density of British-grown Sitka spruce. *Forestry*, 84(2), pp119-132

[72]. Macdonald E. and Hubert J. 2002. A review of the effects of silviculture on timber quality of Sitka spruce. *Forestry*, 75(2), pp107-138

[73]. Mason W. L. 2007. Changes in the management of British forests between 1945 and 2000 and possible future trends. *IBIS*, 149(2), pp41-52

[74]. Brewer A. 2014. *50-year forecast of hardwood timber availability*. NFI Statistical Analysis Report, Forestry Commission, 231 Corstorphine Road, Edinburgh

[75]. Brewer A. 2016. *25-year forecast of softwood timber availability (2016).* NFI Interim Report, Forestry Commission, 231 Corstorphine Road, Edinburgh

[76]. Sikkema R., Faaij A. P. C., Ranta T., Heinimo J., Gerasimov Y. Y., Karjalainen T. and Nabuurs G. J. 2014. Mobilization of biomass for energy in boreal forests in Finland and Russia under present sustainable forest management certification and new sustainability requirements for solid biofuels. *Biomass and Bioenergy*, 71, pp23-36

[77]. Barrett S. M., Boulding M. C., Aust W. M. and Munsell J. F. 2014. Characteristics of logging businesses that harvest biomass for energy production. *Forest Products Journal*, 64(7/8), pp265-272

[78]. Daystar J. Gonzalez R., Reeb C., Venditti R. A., Treasure T., Abt R. and Kelley S. 2014. Economics, environmental impacts, and supply chain analysis of cellulosic biomass for biofuels in the southern US: pine, eucalyptus, unmanaged hardwoods, forest residues, switchgrass, and sweet sorghum. *BioResources*, 9(1), pp393-444

[79]. Walmsley J. D. and Godbold D. L. 2010. Stump harvesting for bioenergy – a review of the environmental impacts. *Forestry*, 83(1), pp17-38

[80]. Mokany K., Raison R. J. and Prokushkin A. S. 2006. Critical analysis of root:shoot ratios in terrestrial biomes. *Global Change Biology*, 12(1), pp84-96

[81]. Forest Commission. 2016. *Forest yield – a handbook on forest growth and yield tables for British Forestry*. Forestry Commission, 231 Corstorphine Road, Edinburgh

[82]. O'Hara K. L. and Gersonde R. F. 2004. Stocking control concepts in uneven-aged silviculture. *Forestry*, 77(2), pp131-143

[83]. Kerr G. and Haufe J. 2011. *Thinning practice – a silvicultural guide v1.0*. Forestry Commission, 231 Corstorphine Road, Edinburgh

[84]. Skovsgaard J. P. and Vanclay J. K. 2013. Forest site productivity: a review of spatial and temporal variability in natural site conditions. *Forestry*, 86, pp305-315

[85]. Miller H. G. 1981. Forest fertilization: some guiding concepts. *Forestry*, 54(2), pp157-167

[86]. Fox T. R. 2000. Sustained productivity in intensively managed forest plantations. *Forest Ecology and Management*, 138, pp187-202

[87]. Jose S., Singh H. P., Batish D. R. and Kohli R. K. 2013. *Invasive plant ecology*. CRC Press, Taylor & Francis Group

[88]. Edwards C. 2006. *Managing and controlling invasive rhododendron*. Forestry Commission Practice Guide, 231 Corstorphine Road, Edinburgh

[89]. Maclean J. E., Mitchell R. J., Burslem D. F., Genney D., Hall J. and Pakeman R. J. 2017. The epiphytic bryophyte community of Atlantic oak woodlands shows clear signs of recovery following the removal of invasive *Rhododendren ponticum*. *Biological Conservation*, 212, pp96-104

[90]. Straw N. A., Fielding N. J., Tilbury C., Williams D. T. and Inward D. 2015. Host plant selection and resource utilisation by Asian longhorn beetle *Anoplophora glabripennis* (Coleoptera: Carambycidae) in southern England. *Forestry*, 88, pp84-95

[91]. Miller G. W., Brose P. H. and Gottschalk K. W. 2017. Advanced oak seedling development as influenced by shelterwood treatments, competition control, deer fencing, and prescribed fire. *Journal of Forestry*, 115(3), pp179-189

[92]. Woodcock P., Cottrell J. E., Buggs R. J. A. and Quine C. P. 2018. Mitigating pest and pathogen impacts using resistant trees: a framework and overview to inform development and deployment in Europe and North America. *Forestry*, 91, pp1-16

[93]. Green S., Laue B., Steele H. and Nowell R. 2014. *Horse chestnut bleeding canker*. Forestry Commission Research Note, FCRN017

[94]. van der Heijden M. G. A., Klironomos J. N., Ursic M., Moutoglis P., Streitwolf-Engel R., Boller T., Wiemken A. and Sanders I. R. 1998. Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. *Nature*, 396, pp69-72

[95]. Landolt J., Gross A., Holdenrieder O. and Pautasso M. 2016. Ash dieback due to *Hymenoscyphus fraxineus*: what can be learnt from evolutionary ecology? *Plant Pathology*, 65, pp1056-1070

[96]. Han H-S. and Renzie C. 2005. Effect of ground slope, stump diameter, and species on stump height for feller-buncher and chainsaw felling. *Journal of Forest Engineering*, 16(2), pp81-88

[97]. Mederski P. S. 2006. A comparison of harvesting productivity and costs in thinning operations with and without midfield. *Forest Ecology and Management*, 224, pp286-296

[98]. Behjou F. K., Majnounian B., Dvořák J., Namiranian M., Saeed A. and Feghhi J. 2009. Productivity and cost of manual felling with a chainsaw in Caspian forests. *Journal of Forest Science*, 55, pp96-100

[99]. Wang J., Long C., McNeel J. and Baumgras J. 2004. Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. *Forest Products Journal*, 54(12), pp45-51

[100]. Nakagawa M., Hamatsu J., Saitou T. and Ishida H. 2007. Effect of tree size on productivity and time required for work elements in selective thinning by a harvester. *International Journal of Forest Engineering*, 18(2), pp24-28

[101]. Eliasson L. and Lageson H. 1999. Simulation study of a single-grip harvester in thinning from below and thinning from above. *Scandinavian Journal of Forest Research*, 14(6), pp589-595

[102]. Eliasson L., Bengtsson J., Cedergren J. and Lageson H. 1999. Comparison of single-grip harvester productivity in clear- and shelterwood cutting. *Journal of Forest Engineering*, 10(1), pp43-48

[103]. Hånell B., Nordfjell T. and Eliasson L. 2000. Productivity and costs in shelterwood harvesting. *Scandinavian Journal of Forest Research*, 15(5), pp561-569

[104]. Puttock D., Spinelli R. and Hartsough B. R. 2005. Operational trails of cut-to-length harvesting of poplar in a mixed wood stand. *International Journal of Forest Engineering*, 16(1), pp39-49

[105]. John Deere. 2018. *Products, machines and equipment*. Online: https://www.deere.com

[106]. Melemez K., Tunay M. and Emir T. 2014. A comparison of productivity in five small-scale harvesting systems. *Small-scale Forestry*, 13(1), pp35-45

[107]. Bredström D., Jönsson P. and Rönnqvist M. 2010. Annual planning of harvesting resources in the forest industry. *International Transactions in Operational Research*, 17(2), pp155-177

[108]. Holmes T. P., Blate G. M., Zweede J. C., Pereira Jr. R., Barreto P., Boltz F. and Bauch R. 2002. Financial and ecological indicators of reduced impact logging performance in the eastern Amazon. *Forest Ecology and Management*, 163, pp93-110

[109]. Ghaffariyan M. R., Naghdi R., Ghajar I. and Nikooy M. 2013. Time prediction models and cost evaluation of cut-to-length (CTL) harvesting method in a mountainous forest. *Small-scale Forestry*, 12(2), pp181-192

[110]. Borz S. A., Dinulică F., Bîrda M., Ignea G., Ciobanu V. D. and Popa B. 2013. Time consumption and productivity of skidding Silver fir (*Abies alba* Mill.) round wood in reduced accessibility conditions: a case study in windthrow salvage logging form Romanian Carpathians. *Annals of Forest Research*, 56(2), pp363-375

[111]. Behjou F. K., Majnounian B., Namiranian M. and Dvořák J. 2008. Time study and skidding capacity of the wheeled skidder Timberjack 450C in Caspian forests. *Journal of Forest Science*, 54(4), pp183-188

[112]. Spinelli R., Owende P. M. O., Ward S. M. and Tornero M. 2004. Comparison of short-wood forwarding systems used in Iberia. *Silva Fennica*, 38(1), pp85-94

[113]. Laitila J., Asikainen A. and Nuutinen Y. 2007. Forwarding of whole trees after manual and mechanised felling bunching in pre-commercial thinning. *International Journal of Forest Engineering*, 18(2), pp29-39

[114]. Laitila J. 2008. Harvesting technology and the cost of fuel chips from early thinnings. *Silva Fennica*, 42(2), pp267-283

[115]. Pierzchała M., Talbot B. Astrup R. 2016. Measuring wheel ruts with close-rage photogrammetry. *Forestry*, 89, pp383-391

[116]. Hall A. 2005. *Small-scale systems for harvesting woodfuel products*. FC Technical Note, FCTN009, Forest Research, Dumfries

[117]. Gallis C. 2004. Comparative cost estimation for forwarding small-sized beech wood with horses and mini-skidder in northern Greece. *Forest Products Journal*, 54(11), pp84-90

[118]. Davis C. J. and Reisinger T. W. 1990. Evaluating terrain for harvesting equipment selection. *Journal of Forest Engineering*, 2(1), pp9-16

[119]. Spinelli R., Magagnotti N. and Lombardini C. 2010. Performance, capability and costs of small-scale cable yarding technology. *Small-scale Forestry*, 9(1), pp123-135

[120]. Stampfer K., Visser R. and Kanzian C. 2006. Cable corridor installation times for European yarders. *International Journal of Forest Engineering*, 17(2), pp71-77

[121]. Ghaffariyan M. R., Stampfer K. and Sessions J. 2009. Production equations for tower yarders in Austria. *International Journal of Forest Engineering*, 20(1), pp17-21

[122]. Gałęzia T. 2014. Analysis of the duration of basic logging operations performed using a chainsaw. *Leśne Prace Badawcze*, 75(1), pp25-30

[123]. Röser D., Mola-Yudego B., Prinz R., Emer B. and Sikanen L. 2012. Chipping operations and efficiency in different operational environments. *Silva Fennica*, 46(2), pp275-286

[124]. Eliasson L., von Hofsten H., Johannesson T., Spinelli R. and Thierfelder T. 2015. Effects of sieve size on chipper productivity, fuel consumption and chip size distribution for open drum chippers. *Croatian Journal of Forest Engineering*, 36(1), pp11-17

[125]. Yoshida M., Berg S., Sakurai R. and Sakai H. 2016. Evaluation of chipping productivity with five different mobile chippers at different forest sites by a stochastic model. *Croatian Journal of Forest Engineering*, 37(2), pp309-318

[126]. Thornley P. and Adams P. 2018. *Greenhouse gas balances of bioenergy systems*. Academic Press, Elsevier Inc.

[127]. Forestry Commission. 2018. *UK wood production and trade: 2017 provisional figures*. IFOS-Statistics, Forest Research, 231 Corstorphine Road, Edinburgh

[128]. Polagye B. L., Hodgson K. T. and Malte P. C. 2007. An economic analysis of bio-energy options using thinnings from overstocked forests. *Biomass and Bioenergy*, 31, pp105-125

[129]. Hamelinck C. N., Suurs R. A. A. and Faaij A. P. C. 2005. International bioenergy transport costs and energy balance. *Biomass and Bioenergy*, 29, pp114-134

[130]. Dunker P. S., Raulund-Rasmussen K., Gundersen P., Katzensteiner K., De Jong J., Ravn H. P., Smith M., Eckmüllner O. and Spiecker H. 2012. How forest management affects ecosystem services, including timber production and economic return: synergies and trade-offs. *Ecology and Society*, 17(4), pp1-17

[131]. Wood M. J., Carling P. A. and Moffat A. J. 2003. Reduced ground disturbances during mechanised forest harvesting on sensitive forest soils in the UK. *Forestry*, 76(3), pp345-361

[132]. Barrett S. M., Aust W. M., Boulding M. C., Lakel W. A. and Munsell J. F. 2016. Estimated erosion, ground cover, and best management practices audit details for postharvest evaluations of biomass and conventional clearcut harvests. *Journal of Forestry*, 114(1), pp9-16

[133]. Saunders C. J. and Ireland D. 2005. *Extraction route trials on sensitive sites*. Forestry Commission Technical Note, 010, 231 Corstorphine Road, Edinburgh

[134]. Williamson J. R. and Neilsen W. A. 2000. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. *Canadian Journal of Forest Research*, 30(8), pp1196-1205

[135]. Prescott C. E. 2002. The influence of the forest canopy on nutrient cycling. *Tree Physiology*, 22, pp1193-1200

[136]. Jerabkova L., Prescott C. E. and Kishchuk B. E. 2006. Nitrogen availability in soil and forest floor of contrasting types of Boreal mixedwood forests. *Canadian Journal of Forest Research*, 36, pp112-122

[137]. Weatherall A., Proe M. F., Craig J., Cameron A. D., McKay H. M. and Midwood A. J. 2006. Tracing N, K, Mg and Ca released from decomposing biomass to new tree growth. Part I: a model system stimulating harvest residue decomposition on conventionally harvested clearfell sites. *Biomass and Bioenergy*, 30, pp1053-1059

[138]. Moffat A. Nisbet T. and Nicoll B. 2011. *Environmental effects of stump and root harvesting*. Forestry Commission Research Note, 009, Farnham

[139]. Persson T., Egnell G. and Lithell C. 2017. *Stump harvesting – impact on climate and environment*. IEA Bioenergy, Task43, TR2017:02

[140]. Dirkswager A. L., Kilgore M. A., Becker D. R., Blinn C. and Ek A. 2011. Logging business practices and perspectives on harvesting forest residues for energy: a Minnesota case study. *Northern Journal of Applied Forestry*, 28(1), pp41-46

[141]. Möller B. and Nielsen P. S. 2007. Analysing transport costs of Danish forest wood chip resources by means of continuous cost surfaces. *Biomass and Bioenergy*, 31, pp291-298

[142]. Levy P. E. and Milne R. 2004. Estimation of deforestation rates in Great Britain. *Forestry*, 77(1), pp9-16

[143]. Department for Business, Energy and Industrial Strategy. 2017. *The clean growth strategy – leading the way to a low carbon future*. BEIS, Victoria Street, London

[144]. McKechnie J., Colombo S., Chen J., Mabee W. and Maclean H. L. 2011. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science and Technology*, 45, pp789-795

[145]. Lal R, 2005. Forest soils and carbon sequestration. *Forest Ecology and Management*, 220, pp242-258

[146]. Bösch M., Elsasser P., Rock J., Rüter S., Weimar H. and Dieter M. 2017. Costs and carbon sequestration potential of alternative forest management measures in Germany. *Forest Policy and Economics*, 78, pp88-97

[147]. Intergovernmental Panel on Climate Change. 2014. Agriculture, forestry and other land use (AFOLU). In: *Climate Change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the IPCC* [Edenhofer O., *et al*. (eds.)]. Cambridge University Press, Cambridge, UK

[148]. Zanchi G., Pena N. and Bird N. 2012. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, 4, pp761-772

[149]. Acker S. A., Halpern C. B., Harmon M. E. and Dyrness C. T. 2002. Trends in bole biomass accumulation, net primary production and tree mortality in Pseudotsuga menziesii of contrasting age. *Tree Physiology*, 22, pp213-217

[150]. Güneralp B. and Gertner G. 2007. Feedback loop dominance analysis of two tree mortality models: relationship between structure and behaviour. *Tree Physiology*, 27, pp269-280

[151]. Carlson C. H., Dobrowski S. Z. and Safford H. D. 2012. Variation in tree mortality and regeneration affect forest carbon recovery following fuel treatments and wildfire in the Lake Tahoe Basin, California, USA. *Carbon Balance and Management*, 7(7), pp1-17

[152]. Agee J. K., Bahro B., Finney M. A., Omi P. N., Sapsis D. B., Skinner C. N., van Wagtendonk J. W. and Weatherspoon C. P. 2000. The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management*, 127, pp55-66

[153]. Whitlock C. 2004. Forests, fires and climate. Nature, 432, pp28-29

[154]. Pilli R., Grassi G., Kurz W., Fiorese G. and Cescatti A. 2017. The European forest sector: past and future carbon budget and fluxes under different management scenarios. *Biogeosciences*, 14, pp2387-2405

[155]. Thornley P., Gilbert P., Shackley S. and Hammond J. 2015. Maximising the greenhouse gas reductions from biomass: The role of life cycle assessment. *Biomass and Bioenergy*, 81, pp35-43

[156]. Röder M. and Thornley P. 2016. Bioenergy as climate change mitigation option within a 2°C target – uncertainties and temporal challenges of bioenergy systems. *Energy, Sustainability and Society*, 6(6), pp1-7

[157]. Klein D., Wolf C., Schulz C. and Weber-Blaschke G. 2015. 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for

the LCA of forest production. *International Journal of Life Cycle Assessment*, 20, pp556-575

[158]. Ruiz D., San Miguel G., Corona B. and López F. R. 2018. LCA of a multifunctional bioenergy chain based on pellet production. *Fuel*, 215, pp601-611

[159]. Abbas D. and Handler R. M. 2018. Life-cycle assessment of forest harvesting and transportation operations in Tennessee. *Journal of Cleaner Production*, 176, pp512-520

[160]. Ter-Mikaelian M. T., Colombo S. J. and Chen J. 2015. The burning question: does forest bioenergy reduce carbon emission? A review of common misconceptions about forest carbon accounting. *Journal of Forestry*, 113(1), pp57-68

# Chapter 4. Characterisation of the UK's forest wood resource

*"We have nothing to fear and a great deal to learn from trees" – Marcel Proust*

## 4.1. Introduction

Forest research incorporates a wide array of scientific disciplines that span a number of topics; from the role of forests as a key global resource, to their management and the consequent issues that can arise. This variation is not just specific to the different forms of forest research, it can also be found throughout the world's existing wood feedstocks. Be it the species type, the distribution or the sheer volume of a nation's standing wood resource, the world's forests differ from country to country.

Table 4.1 – **Global Forests; Current resource and recent changes, 1990-2015 [1]**

| | Global Forest Cover | |
|---|---|---|
| | **2015$^1$** | **% Change$^2$** |
| **Boreal** | *1,225* | *+ 0.5* |
| **Temperate** | *685* | *+ 10.8* |
| **Tropical** | *1,770* | *- 9.9* |
| **Sub-tropical** | *320* | *- 1.5* |

*$^1$ Forested area (M ha), $^2$ between 1990-2015*

The global forest cover in 2015 was estimated to be 3,999 million hectares (M ha), representing ~31% of the world's total land area [1]. Table 4.1 depicts the current distribution of global forests between the four main forest domains –

boreal, temperate, tropical and sub-tropical – as well as the changes that have occurred over the last 25 years. Tropical forests account for the largest forested area but have suffered a sustained decrease in forest cover, while alternatively temperate forests have flourished in recent years [1]. As discussed in the previous chapter, the UK's forest resource – located in both boreal and temperate biomes – has increased in coverage since the 2nd World War. By 2016 this had reached an estimated total area of 3.16 M ha, representing ~13% land coverage. This growth in the UK's forest resource, driven predominantly by an influx of introduced, non-native softwood species, has increased the availability of potentially useable wood resource.

Wood biomass contains a variety of components which can differ between species; this can range from the basic chemical composition of individual trees, to the more complex carbohydrate and aromatic polymer contents [2]. For the UK's forests to be properly exploited, either for timber production or as a potential source of bioenergy, the fundamental characteristics of its wood resource must first be fully understood. This chapter will therefore characterise the UK's existing forest wood resource, quantify its suitability for use as a fuel while offering a point of context in how it compares to other sources of wood – we do indeed still have a great deal to learn from trees.

## 4.2. Methodology

Global forests represent a significant amount of wood resource; a factor which has prompted a large number of published studies to characterise a variety of softwood and hardwood species from around the world. With more than 30% of the earth's land mass covered by forests, the sustained interest in the properties and potential uses of wood – intensified by the significant role of biomass in energy generation – is understandable. For the UK's existing wood resource to be properly understood, it is important to consider the existing published data on wood characterisation – this will, importantly, allow for the evaluation and validation of any completed experimental work. This chapter will subsequently focus on two main tasks; 1) to collate and analyse existing published data, qualifying the fundamental areas of wood chemical analysis and, 2) to extensively characterise a variety of wood biomass samples sourced from different species and sites across the UK, using fundamental experimental and analytical methods. The data attained from the literature and the completed experimental work will then be analysed using statistical analysis techniques, forming detailed conclusions and comparisons of the UK's wood resource.

Table 4.2 – **Reviewed sample data; types and published sources**

| | | **Data Types** | | | |
|---|---|---|---|---|---|
| **Reference** | **Samples** | **Proximate** | **Ultimate** | **Lignocellulosic** | **GCV** |
| [37][a] | *6* | | + | + | + |
| [38] | *2* | + | + | + | + |
| [39] | *1* | + | + | | + |
| [40][a] | *1* | + | + | | + |
| [41] | *1* | + | + | + | + |
| [42][a] | *1* | + | + | | + |
| [43][a] | *2* | + | + | + | + |
| [44] | *4* | + | + | + | + |
| [45] | *4* | | | + | + |
| [46] | *5* | | | + | + |
| [47][a] | *3* | | + | + | + |
| [48][a] | *3* | | + | | + |
| [49] | *1* | + | + | + | + |
| [50] | *2* | + | | + | + |
| [51][a] | *1* | + | + | | + |
| [52][a] | *1* | + | + | | + |
| [53][a] | *1* | + | + | | + |
| [54] | *1* | + | + | + | + |
| [55] | *1* | + | + | + | + |
| [56] | *1* | + | + | + | + |
| [57] | *1* | + | + | | + |
| [22] | *5* | + | + | | + |
| [58] | *5* | + | + | | + |
| [59] | *2* | | | + | |
| [60] | *2* | + | + | | + |
| [61] | *3* | + | + | + | + |
| [62][a] | *2* | + | + | + | + |
| [63][a] | *2* | + | + | | + |
| [64] | *2* | + | + | | + |
| [65]<br>[66] | *12* | + | + | + | + |
| [67][a] | *1* | + | + | | + |
| [68][a] | *2* | + | + | | + |
| [69] | *2* | + | + | | + |
| [70] | *1* | + | + | | + |
| [71] | *2* | | | + | |

[a] *Gross Calorific Value (GCV) calculated using Friedl et al (2005) – see Section 4.2.3.5*

### 4.2.1. Literature Review Analysis

There are, in one form or another, an extensive number of published, peer-reviewed studies investigating wood resource. Although the research interests and end-use of the biomass samples often differ between projects, the initial data produced during the wood's compositional analysis is often comparable.

#### 4.2.1.1. Fuel Properties & Sample Choice

Compositional wood data extracted from 36 published journal articles has been considered in this section, resulting in a total of 86 separate stem wood samples being assembled for analysis. Table 4.2 details these samples, the publications they were taken from and the specific data that was extracted. This includes fundamental characteristics that dictate a resource's potential use as a fuel; particularly proximate, ultimate and lignocellulosic data, as well as the Gross Calorific Value (GCV). These fundamental characteristics are covered in greater detail in Section 4.2.3.

The 86 samples identified from the literature represent a wide array of species from different global locations, therefore to enable an affective comparison they have been classified into two broad groups; hardwoods (48 samples) and softwoods (38 samples). As the data has been obtained from different published sources, the format of the reported data tends to differ between publications. To ensure that each individual sample is comparable with one another, the data has first been standardised; proximates have been reported on a dry basis (db), ultimate data has been reported both dry and dry ash free (daf), where required, and the lignocellulosic data has been adjusted on a db and extractive free (EF).

### 4.2.2. Statistical Analysis

Although it is possible to identify and express the relationships and differences between datasets visually, it is important that these visual representations are supported quantifiably. The mathematical discipline of statistics allows for the analysis and interpretation of data, resulting in a quantified explanation of the results, especially when considering levels of uncertainty. Statistical analysis can be divided into two categories – descriptive and inferential – both of which are utilised within this research. Descriptive statistics offer basic, yet fundamental, numerical summaries, presenting an overall impression of the data in a sensible way. Inferential statistics are used in an attempt to infer conclusions that extend beyond the considered datasets [3, 4]. Put simply, descriptive statistics describe what we initially see from the data, whereas inferential statistics conject how this can be expanded upon. Although simple, the forms of statistics used within this chapter are powerful, giving an excellent foundation to compare important fuel parameters; both collated from the literature and produced experimentally.

#### 4.2.2.1. Descriptive Statistics

When considering large sets of data, the use of descriptive forms of statistics allow for the simplification into something more manageable. Although simple, they can offer a powerful form of analysis, both when considering a singular variable of a dataset – referred to as univariate – or multivariate, which examines more than one variable. Descriptive analysis can itself be separated into two general areas; 1) as a measure of central tendency, including the mean, median and mode, or 2) as a measure of variability, which includes the variance and the standard deviation [4]. As shown in Eq. 4.1, the sample standard deviation (σ) – an expression of how a sample set differs from its calculated mean value – is given as the square root of the calculated variance;

$$\sigma = \sqrt{\frac{\sum(\mathrm{X}-\bar{\mathrm{X}})^2}{(n-1)}} \tag{4.1}$$

where:

| | |
|---|---|
| X | is an individual value |
| $\bar{\mathrm{X}}$ | is the mean value |
| $n$ | is the total number of values |

In addition to giving comparable values for the central tendency and variability of a dataset, these can be combined to give a standardised dispersion measure, referred to as relative standard deviation ($RSD$).

$$RSD = \frac{\sigma}{\bar{\mathrm{X}}} \tag{4.2}$$

Given as the ratio between the standard deviation and the mean, the calculated $RSD$ shows how the variability of a population relates to its arithmetic central point. In effect, the smaller the $RSD$ – often given as a percentage – the greater the confidence that a calculated mean is representative of a population.

One of the most basic, yet robust, methods for measuring scale and variability is the interquartile range ($IQR$); a trimmed estimator which is calculated as the difference between the 75th and 25th percentiles, or the upper ($Q_3$) and lower ($Q_1$) quartiles as they are also referred to. In addition to their use for representing the spread of data, both numerically and visually, the $IQR$ can also be used to identify the outliers within a specific dataset. The outliers are observed data points which fall above $Q_3$+1.5*$IQR$ and below $Q_1$-1.5*$IQR$.

$$IQR = Q_3 - Q_1 \tag{4.3}$$

#### 4.2.2.2. Inferential Statistics

As outlined above, inferential statistics are used to produce more generalised conclusions that can be applied to a larger population, than that considered within the initial dataset [3]. The inferential statistical analysis of population characteristics can be separated into two further categories; 1) estimates of magnitude, and 2) tests of hypotheses. Estimation-based statistics utilise a combination of factors, such as confidence intervals and meta-analysis, to analyse and interpret data. Hypothesis testing is used to compare data sets with one another, proposing a hypothesis ($H_1$) for a particular statistical relationship, which is then compared to a null hypothesis ($H_0$) that represents no relationship [5]. The inferential statistics undertaken within this research focus on two separate types of hypothesis testing; independent $t$-test and analysis of variance (ANOVA). Although they are conceptually similar to one another – both being used to determine significant differences within sets of data – they differ in their application.

The independent $t$-test – a parametric test, drawing assumptions from the defining properties of a dataset – is designed to determine any statistically significant evidence that the means of two independent groups differ [3]. The hypotheses of a $t$-test can be described as;

$$H_0 : \mu_1 = \mu_2 \tag{4.4}$$

$$H_1 : \mu_1 \neq \mu_2 \tag{4.5}$$

where:

| | |
|---|---|
| $\mu_1$ | is the population mean of group 1 |
| $\mu_2$ | is the population mean of group 2 |

As shown by Eq. 4.4 and 4.5, the independent $t$-test is designed purely for the comparison of means between two independent groups – so in this chapter for example, between hardwoods and softwoods. For an equal variance, where both populations are assumed to have identical population variances, the following equations are used to conduct the independent $t$-test;

$$t_{test} = \frac{\bar{X}_1 - \bar{X}_2}{\sigma_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{4.6}$$

and;

$$\sigma_p = \sqrt{\frac{(n_1 - 1)\sigma_1^2 + (n_2 - 1)\sigma_2^2}{n_1 + n_2 - 2}} \tag{4.7}$$

where:

| | |
|---|---|
| $\bar{X}_{1,2}$ | is the mean of the 1st and 2nd samples |
| $n_{1,2}$ | is the sample size of the 1st and 2nd samples |
| $\sigma_{1,2}$ | is the standard deviation of the 1st and 2nd samples |
| $\sigma_p$ | is the pooled standard deviation |

In addition to producing a value for $t$, the $t$-test also identifies the degrees of freedom ($df$); a figure which depicts the number of independent pieces of information used when conducting the hypothesis test, minus the number of parameters used during the estimation. Together these give a probability value ($p$-value), ranging between 0 and 1, which is used to determine the statistical significance of the results. The smaller the value, the greater the association with

$H_1$ resulting in the rejection of the null hypotheses, $H_0$. A significance level of $\leq 0.05$ has been chosen, indicating that when the $p$-value falls below this, it can be assumed that a statistically significant difference between the means exist. Additionally, to establish if the variance of a population is equal or unequal, a test for equality of variance is conducted alongside the independent $t$-test. In this case, the Levene's test has been applied in conjunction with the $t$-test to produce a value, given as $F$, and its corresponding $p$-value. Again the significance level used is $\leq 0.05$.

In cases where more than two populations exist, an alternative analysis to the independent $t$-test is necessary. Analysis of variance (ANOVA) is an alternate hypothesis test, used for comparing the means of three or more different groups of data. As a result, the hypotheses of a one-way ANOVA test differ, instead expressed as;

$$H_0 : \mu_1 = \mu_2 = \mu_3 = \ \ldots = \mu_n \tag{4.8}$$

$$H_1 : \mu_i \ are\ not\ all\ equal \tag{4.9}$$

where;

| | |
|---|---|
| $\mu_{1,2,3}$ | is the population means of groups 1, 2 and 3, respectively |
| $n$ | is the number of independent comparison groups |
| $\mu_i$ | is the population mean of the $i^{th}$ group ($i$=1, 2, 3, …, $n$) |

ANOVA testing is a widely used process, applying a range of inferential statistical procedures that are designed to compare the mean differences across numerous conditions. In its simplest form the ANOVA hypothesis test considers the variability between groups – which includes the variability related to the independent variables and/or random factors – against the random factor variability found within the groups themselves [6]. The ANOVA test is conducted using inbuilt tool within the utilised software, based on the following equation;

$$F = \frac{MSR}{MSE} \tag{4.10}$$

where:

| | |
|---|---|
| $MSR$ | is the regression mean square |
| $MSE$ | is the mean square error |

The results from the above ANOVA equation, given as the $F$-ratio, provide an estimation for the relationship of between-group and within-group variability. The independent variables – contained within the calculated values for MSR and MSE – correspond to the different categories of groups, such as the variety of hardwood and softwood species or specific tree sections – like the stump, roots or branches. The larger the $F$-ratio, the stronger the argument for rejecting $H_0$, accepting there are statistically significant differences between their means. Unlike the significance level of the $t$-test, the statistical significance of the ANOVA test is accepted when the $F$-ratio's corresponding $p$-value is less than 0.001 ($p < 0.001$).

In addition to establishing the existence of significant statistical differences between all of the groups combined, it is possible to complete additional post-hoc analysis which identifies specific differences between each group, when compared against one another. There are several different procedures for conducting these multiple comparisons, however as some of the sample sizes used in this research are unequal, Tukey's HSD (honest significant difference) test has been utilised. This test – based upon a studentized range distribution – has been selected as it compares the mean of each independent variable against the mean of every other independent variable. As with the $t$-test, to be deemed statistically significant, the $p$-value's produced following the Tukey's HSD test must achieve a significance level of ≤0.05.

#### 4.2.2.3. Regression Analysis

Regression, in the context of statistical analysis, considers the relationship between a single dependent variable ($y$) and one or more independent variables ($x$); specifically, how the value of y can change with a variation in one of the quantitative $x$ values [7]. As a form of inferential statistics, regression analysis is used to explore the nature of the relationship between the dependent and independent variables and infer causality.

The simplest and most widely used form of regression are simple linear models, which can be used to predict values for the dependent variable by utilising the independent variables. Figure 4.1 shows a straight line summary of a given bivariate plot, highlighting the relationship between the two continuous variables. Although the line passes through only two of the points, it shows clearly that the data has a positive correlation – as the independent variable increases, so does the dependent variable.

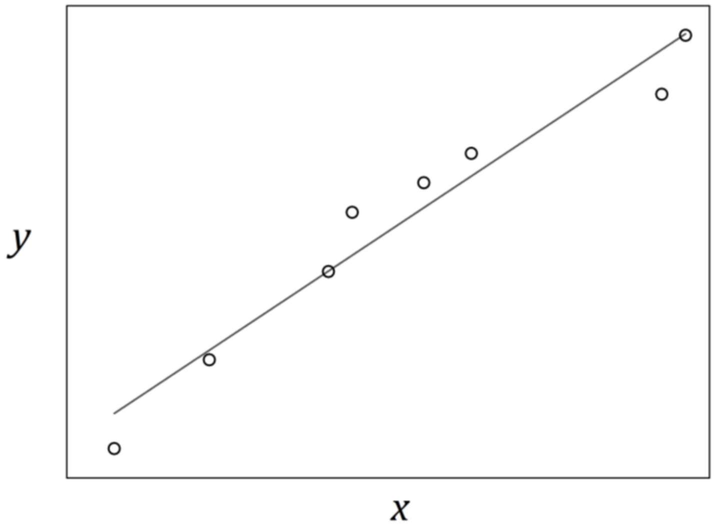


Figure 4.1 – **Example of Simple Linear Regression between two variables**

The relationship of a bivariate dataset containing numerous data points $(x_i, y_i)$, such as that shown in Figure 4.1, can be approximately described in the form of a simple linear function, as shown in Eq. 4.11;

$$y_i = \alpha + (x_i)\beta + \varepsilon_i \tag{4.11}$$

where:

| | |
|---|---|
| $\alpha$ | is the $y$-intercept |
| $x_i$ | is the independent variables of the $i^{th}$ group ($i$=1, 2, …, $n$) |
| $\beta$ | is a vector of unknown parameters |
| $\varepsilon_i$ | is an experimental error term related to the deviation |

The desired output of using a linear regression model is to identify values for $\alpha$ and $\beta$, producing a line that best fits the points within a dataset. This is achieved using ordinary least squares (OLS) – an approach which sums the squared distances between the regression line and each data point – establishing the line that results in the smallest sum, via minimisation. Once this line has been established it is important to calculate the coefficient of determination, denoted as $R^2$, which is a measure of how well the regression model fits the data. This is also calculated using the squared distances of the data points and can be defined generally as;

$$R^2 \equiv 1 - \frac{SS_{res}}{SS_{tot}} \tag{4.12}$$

where:

| | |
|---|---|
| $SS_{res}$ | is the residual sum of squares |
| $SS_{tot}$ | is the total sum of squares |

This '*goodness of fit*' is given as a value between 1 and 0, with a value of 1 indicating that the regression model fits perfectly. It should be noted that the value for $R^2$ depicts the level of correlation between data points; it is not a definitive indication that changes to the independent variable cause the dependent variable to change. For cases where more independent variables are included within the regression, an adjusted $R^2$ approach can be used ($\bar{R}^2$) which incorporates the degrees of freedom (*df*);

$$\bar{R}^2 = 1 - \frac{SS_{res}/df_e}{SS_{tot}/df_t} \tag{4.13}$$

where:

| | |
|---|---|
| $df_e$ | is the *df* of the population error variance |
| $df_t$ | is the *df* of the dependent variables population variance |

Linear regression is ideal for depicting a visible relationship between two variables. However, in cases where the data is grouped – with no clear linear relationship – other methods should be pursued. These non-linear methods of regression analysis include quadratic, exponential and logarithmic functions, each with different applications, dependent upon the original data set. Fitting circles and other geometrical shapes to data – either by use of algebraic or geometric methods – can offer alternative forms of regression which best fit the observed data [8]. These are often highly complicated with many different methods and algorithms for fitting the curves. To simplify this, in cases where bivariate data is clustered together, the following equations have been developed to display and compare individual data sets with one another;

$$f = (x - x_c)^2 + (y - y_c)^2 - r^2 \tag{4.14}$$

and:

$$r = \sqrt{\left(\frac{\sum_{i=1}^{n} |x_i - x_c|}{n}\right)^2 + \left(\frac{\sum_{i=1}^{n} |y_i - y_c|}{n}\right)^2} \tag{4.15}$$

where:

| | |
|---|---|
| $x_i$ | is the independent variables of the $i^{th}$ group ($i$=1, 2, …, $n$) |
| $x_c$ | is the mean of a specific independent variable |
| $y_i$ | is the dependent variables of the $i^{th}$ group ($i$=1, 2, …, $n$) |
| $y_c$ | is the mean of a specific dependent variable |
| $r$ | is the calculated radius |

In essence, using Eq. 4.14 and 4.15 produces a circular line which represents the dispersion of the data from the mean, in relation to both the $x$ and $y$ variables. The circle's centre $(x_c, y_c)$ are the mean points of the $x$ and $y$ data sets, respectively, while the calculated radius value is the mean distance between the individual points and the centre point of the circle. As a result, the greater the spread of the original data points from the calculated mean values, the larger the radius and, ultimately, the larger the circle. A smaller circle would therefore indicate that the data points are clustered closer together.

#### 4.2.2.4. Standard Error & Confidence Bands

In any type of statistical analysis there will always be a level of uncertainty and error that should be appropriately reported. One of the most important is the standard error, shown in Eq. 4.16, which is the standard deviation of a statistic's sampling distribution, usually relating to the mean;

$$SE_{\overline{X}} = \frac{\sigma}{\sqrt{n}} \tag{4.16}$$

where:

| | |
|---|---|
| $SE_{\overline{X}}$ | is the standard error of the mean |
| $\sigma$ | is the sample standard deviation |
| $n$ | is the number of observations in the sample |

The $SE_{\bar{X}}$ incorporates the number of samples included within the analysis, inferring how far the sample's calculated mean is likely to be from the population mean. As a result, a larger number of observations will reduce the size of the standard error. This also plays an important role in the production of confidence bands; used to display the uncertainty of lines and curves, produced during regression analysis. Confidence intervals – closely associated to confidence bands – depict the uncertainty related to individual points. Upper $(CI_3)$ and lower $(CI_1)$ 95% confidence intervals, reflecting significance levels of 0.05, can be calculated using the following equations;

$$CI_3 = \bar{X} + (1.96 \times SE_{\bar{X}}) \qquad (4.17)$$

$$CI_1 = \bar{X} - (1.96 \times SE_{\bar{X}}) \qquad (4.18)$$

Pointwise confidence bands, when estimated for a function $f(x)$ instead of the mean, are produced from individual confidence intervals calculated for separate $x$ values. These are combined to produce upper and lower 95% confidence bands.

#### 4.2.2.5. Statistical Software

The previous sections have discussed the basic principles and theory behind statistical applications, however in practice there is a wide variety of statistical software available. These packages are designed specifically to undertake the discussed analysis. Of the software available, this research has used IBM SPSS statistics *v21*. Although originally designed for use in social sciences, the versatility and wide range of statistical analysis packages available in SPSS make it suitable for use in other branches of science and engineering [3]. In addition, the visual representation of data – coupled with additional data analysis – has been completed using OriginPro 9; a software package that is specifically used for scientific graphing. It's also important to note that, while the collated datasets utilised within this chapter are larger than anything produced previously, they still represent just a small sample of what is an extensive natural resource – any established relationships and values should not automatically be assumed as definitive.

### 4.2.3. Experimental & Analytical Characterisation

The heterogeneous nature of biomass – consisting of a complex mix of organic and inorganic material – makes the initial identification and characterisation of the chemical composition one of the most important steps for its utilisation. Wood biomass is of no difference; its fundamental composition directly impacts the quality, properties and end-use applications as a fuel, as well as any consequent environmental issues [9]. In addition to the statistical analysis of data from the literature, fundamental characterisation of wood biomass has been undertaken, using different analytical methods.

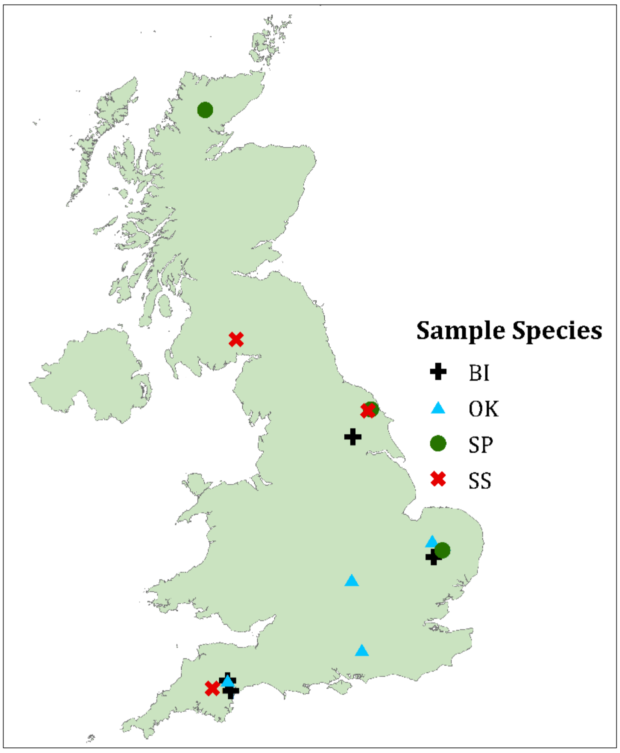


Figure 4.2 – **Geographical locations of samples used in experimental work**

#### 4.2.3.1. UK Wood Samples & Sample Preparation

The characterisation experimental work considered a total of 145 wood samples, sourced from 14 sites located across the British Isles. The location of these samples is depicted in Figure 4.2, with the associated site data found in Table 4.3. There are 12 sites situated in England; located in the Northeast of the country and in regions in both the Southeast and Southwest. In addition to these, there are two sites in Scotland; one in the North and one in the South.

These samples, which were part of a larger collaborative investigation into wood fuel, are typical of the UK's diverse feedstock, representing four key species that account for a significant amount of forest cover. Although the samples are by no means definitive, they have been sourced from a number of sites – typified by different conditions – resulting in a unique dataset, giving a valuable insight into vital fuel parameters required for establishing a resource's suitability.

Table 4.3 – **Site data for experimental samples**

| Site Name | Species | Longitude & Latitude | Altitude (m) | Planting Year | Soil |
|---|---|---|---|---|---|
| Frith End, Bordon | OK | *51.153716, -0.86180801* | *85* | *1935* | *Gley* |
| Haldon, Exeter | BI | *50.61937, -3.5435727* | *220* | *1953* | *Podzol* |
| Whitestone, Exeter | BI | *50.75155, -3.6117105* | *110* | *1950* | *Brown Earth* |
| Whitestone, Exeter | OK | *50.75155, -3.6117105* | *110* | *1950* | *Brown Earth* |
| Wordwell, Suffolk | BI | *52.335002, 0.6873772* | *50* | *1952* | *Brown Earth* |
| Wheldrake, York | BI | *53.919369, -0.98743347* | *15* | *1960* | *Podzol* |
| Didlington, Thetford | OK | *52.544361, 0.66777721* | *65* | *1927* | *Brown Earth* |
| Hazelborough, Brackley | OK | *52.064470, -1.0532434* | *150* | *1930* | *Acidic Loam* |
| Thetford Forest Park | SP | *52.415999, 0.8757002* | *40* | *1991* | *Sandy Breckland* |
| Wykeham, Scarborough | SP | *54.269404, -0.57621976* | *205* | *1980* | *Acidic Loam* |
| Dalby Forest, Scarborough | SS | *54.251828, -0.64694118* | *195* | *1974* | *Iron pan* |
| Dartmoor National Park | SS | *50.643443, -3.9205897* | *475* | *1950* | *Acidic Peat* |
| Ae Village, Dumfries | SS | *55.173172, -3.5935832* | *155* | *1970* | *Peaty Gley* |
| Lairg, Highlands | SP | *58.133985, -4.4795303* | *175* | *1959* | *Peat* |

*OK=Oak, BI=Birch, SP=Scots pine, SS=Sitka spruce*

The samples consist of two native hardwood species, oak (*Quercus robur*) and silver birch (*Betula pendula*), and two softwood species, the native Scots pine (*Pinus sylvestris*) and the non-native Sitka spruce (*Picea sitchensis*). As shown by the planting year of the stands in Table 4.3, the samples were taken from mature trees that were close to final felling, ensuring that they were representative of the wood material likely to be utilised in the woodfuel market. In addition to the species variation, the sample set also includes wood from different sections of the tree; namely the stem, the roots and the branches. The stem wood has been taken from the halfway point of the tree's stem, with the samples consisting of a mixture of mature and juvenile wood. The root samples were taken from the primary root, located >30cm below the ground level, while the branch wood was sourced from the middle third of the tree's crown.

The tree documentation, felling, sample removal and initial processing of the wood was undertaken by Forest Research. The stem wood was removed as a disk using a chainsaw for the initial cross-cutting, before being re-cut to remove any potential contamination. Once removed from the ground, the root wood was chipped; to be consistent with this type of material, there is likely to be contamination in the wood chip as a result of the residual soil. The branch wood was also chipped on removal. All the samples were placed in individual, air-tight containers and labelled before being transported for cold storage. The second phase of processing was undertaken by the *Institute of Biological, Environmental and Rural Sciences* (IBERS) at Aberystwyth University. This involved oven drying the individual wood samples at 103°C before being chipped, using a cutting mill, reducing the particle size to ~1mm. These were then stored in labelled vials, each containing around 2-3g of the wood samples.

Before any analytical experiments were undertaken, the coarsely chipped samples required further processing, in line with EN 14780 [10]. This was to ensure that each sample was consistent with the next and that they were an appropriate size for analysis. The samples were individually milled using a *Retsch CryoMill* (see Appendix A). The cryomill utilises liquid nitrogen, in an integrated cooling system, cooling the milling vessel before and during the milling process. Once at temperature, the entirety of each sample was placed in the grinding jar before undergoing two, two-minute grinding cycles. The milled samples were then passed through a 90 μm sieve to ensure homogeneity of particle size, between the different wood samples. This produced finely milled 'wood flour' samples, which were used in the following proximate, ultimate and low nitrogen analysis.

#### 4.2.3.2. Proximate Analysis

The proximate analysis of a fuel determines its basic composition, separating into four basic constituents; moisture, volatile matter (VM), fixed carbon (FC) and ash. Identifying these components gives an initial understanding of a sample's viability to be utilised as a fuel [9].

The moisture content of a given sample, which can differ greatly between biomass species, refers to the amount of water contained within the material [11]. The standard method for determining the moisture content of a solid biofuel, given in EN 14774-3, entails the sample being oven dried at 105°C for an extended period, before being weighed [12]. The moisture content of the sample is calculated from the following equation;

$$MC = 1 - \left(\frac{m_d}{m_w}\right) \tag{4.19}$$

where:

$MC$ is the mass fraction of moisture of the sample

$m_d$ is the mass of the dried sample

$m_w$ is the initial mass of the sample

The VM component of biomass – released during the devolotilisation phase – can vary between samples, usually consisting of light hydrocarbons, hydrogen, carbon monoxide, carbon dioxide and tars [13]. The standard method for determining the VM content of a solid biofuel is given in EN 15148 [14]. The previously dried sample is heated in a furnace at 900°C for 7 minutes – out of contact with ambient air – until the devolatilisation process has completed, before then being weighed. The VM content of the sample can therefore be calculated from the following equation;

$$VM_{db} = \frac{m_d - m_{vm}}{m_d} \quad (4.20)$$

where:

$VM_{db}$ is the mass fraction of volatile matter on a dry basis

$m_{vm}$ is the mass of the sample following devolatilisation

Once the devolatilisation phase has finished, the remaining constituents of the sample are the FC and the ash. The standard method for determining the ash content of a solid biofuel is given in EN 14775 [15]. The devolatilised sample is heated in a furnace with a suitable air flow, first at 250°C for an hour, and then at 550°C for a further two hours. The remaining inorganic residual is weighed, giving the mass of the samples ash. The ash content of the sample can be calculated using Eq. 4.21;

$$ash_{db} = \frac{m_{ash}}{m_d} \quad (4.21)$$

where:

$ash_{db}$ is the mass fraction of ash on a dry basis

$m_{ash}$ is the mass of the samples ash

Consequently, the FC content of the sample can be derived using the following equation;

$$FC_{db} = 1 - VM_{db} - ash_{db} \quad (4.22)$$

where:

$FC_{db}$ is the mass fraction of fixed carbon on a dry basis

The standard procedures, as described above, require ~1g of sample for each analysis. Considering the relatively small amount of available sample (2-3g), it would be a misuse undertaking the proximate analysis via conventional methods; it would not allow for any further fundamental analysis. Therefore the proximate data will be produced using thermogravimetric analysis (TGA), which requires significantly less sample per run. TGA is a characterisation method which utilises a precision balance and a furnace to measure the changes in weight of a given sample, as a function of increasing temperature over time [16]. Although it is accepted that the proximate values determined by TGA can differ from standard procedures, it is still considered a suitable method for producing a comparative set of proximate data for biomass samples [17]; this is a result of the high precision balance and temperature controls associated with TGA.

The analysis was undertaken using a *TA Instruments* TGA Q5000 thermo-gravimetric analyser (see Appendix A). The proximate analysis of each sample used ~10mg of finely milled wood flour – sieved to ≤ 90 μm as described in Section 4.2.3.1 – which was spread evenly, in a thin layer, on a platinum sample pan. The TGA instrument was programmed to simulate the method for proximate analysis, in line with the standard procedures described above. In a nitrogen atmosphere the sample, held within the instrument's furnace, was heated at 10°C min$^{-1}$ up to 105°C and kept isothermal for 15 minutes. The temperature was then increased at 10°C min$^{-1}$ up to 900°C and held for 15 minutes, before reducing quickly to 40°C. The nitrogen atmosphere was then replaced with air and the temperature held at 40°C for 5 minutes. The temperature was then finally increased at 10°C min$^{-1}$ up to 550°C and held for 10 minutes. This was completed in duplicate for each wood sample.

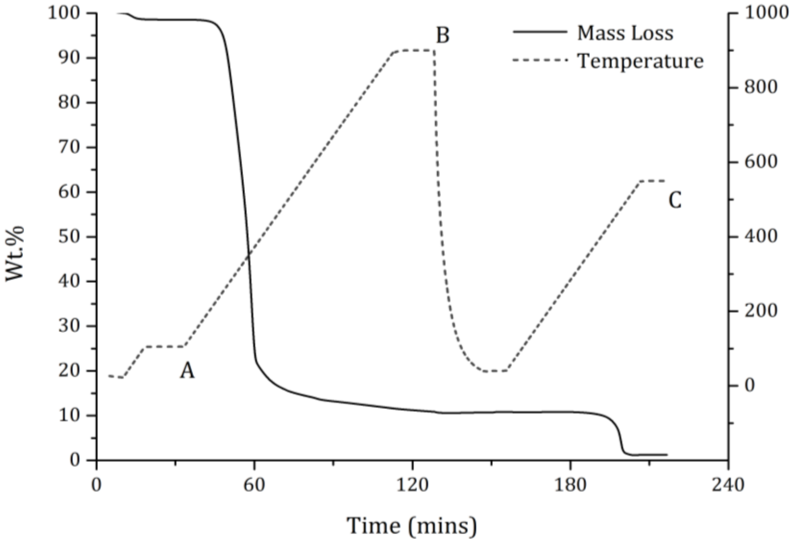


Figure 4.3 – **Temperature profile and mass loss curve for proximate analysis, using TGA methodology**

The simulated temperature profile – and the mass loss curve associated with the process – can be found in Figure 4.3. The initial mass value of a sample ($m_w$) is taken once the balance has settled, before any temperature increases occur. As shown in Figure 4.3 the mass value of the dried sample ($m_d$) is taken at point A, the mass of the sample following devolatilisation ($m_{vm}$) is taken at point B and the mass of the samples ash ($m_{ash}$) is taken at point C. The moisture value of each sample is calculated using Eq. 4.19, while the volatile matter, fixed carbon and ash contents are determined on a dry basis using Eq. 4.20, 4.22 and 4.21, respectively.

#### 4.2.3.3. Ultimate Analysis

Originally designed for the characterisation of coal, the ultimate analysis of biomass determines the content of individual elements – namely carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulphur (S) – existing within the feedstock. Of these, the key elemental constituents of biomass are C, H and O which make up >97% of the feedstocks total content, on a dry ash free (daf) basis [18]. Although the N and S content of biomass is relatively small, their existence in fuels can result in the formation of nitrogen oxides and sulphur dioxide during combustion – atmospheric pollutants which can cause an array of detrimental impacts [19].

The standard procedure for determining the C, H, N and S content of a solid biofuel can be found in EN 15104 [20]. Using an automated organic elemental CHNS analyser, a known mass of a sample is combusted in an oxygen atmosphere, at 900°C. The resulting gaseous products – $CO_2$, $H_2O$, oxides of nitrogen and oxides of sulphur – are passed through a gas-chromatography column, where they are separated from one another. At the end of the column the changes to the gases thermal conductivity is detected, giving the relative volume fraction of the elemental contents. This allows for the absolute masses of C, H, N and S within a sample to be calculated. Using the previously calculated moisture content (see Section 4.2.3.2.), the following equations can be used to establish the principle elemental composition on a dry basis.

$$C, N, S_{db} = C, N, S_{ad} \times \left(\frac{1}{1-MC}\right) \tag{4.23}$$

where:

$MC$ is the mass fraction of moisture of the sample

$C, N, S_{db}$ is the mass fraction of carbon, nitrogen & sulphur on a dry basis

$C, N, S_{ad}$ is the determined carbon, nitrogen & sulphur content

$$H_{db} = \left(H_{ad} - \frac{MC}{8.937}\right) \times \frac{1}{1-MC} \qquad (4.24)$$

where:

$H_{db}$ is the mass fraction of hydrogen on a dry basis

$H_{ad}$ is the determined hydrogen content

Following the determination of C, H, N and S, while also accounting for the mass of ash in the sample, the oxygen content was determined by difference;

$$O_{db} = 100 - (C_{db} + N_{db} + S_{db} + H_{db} + ash_{db}) \qquad (4.25)$$

where:

$O_{db}$ is the mass fraction of oxygen on a dry basis

$ash_{db}$ is the mass fraction of ash on a dry basis

The ultimate analysis in this research was undertaken using a *CE Instruments* Flash EA1112 elemental analyser (see Appendix A), in line with the described standard procedure. Before analysing the wood samples, the analyser must first be calibrated using appropriate calibration substances. Table 4.4 details the principle elemental contents of the standards utilised within the calibration process.

Table 4.4 – **Principle elemental contents of calibration standards**

| | **Elemental Constituents (%)** | | | |
|---|---|---|---|---|
| | **C** | **H** | **N** | **S** |
| **Atropine** | *70.56* | *8.01* | *4.84* | *0* |
| **BBOT** | *72.36* | *6.11* | *6.84* | *7.44* |
| **Oatmeal** | *41.59* | *5.85* | *1.90* | *0.16* |
| **Olive Stone** | *47.50* | *6.30* | *0.20* | *0* |

Each calibration standard had ~2.5mg placed in a small pressed tin capsule, having the precise weight logged before being folding to remove any air. The same process is applied to the cryomilled wood samples, with ~2.5mg placed in the tin capsules before being weighed and folded. In addition to the calibration substances and the samples, it is important to include laboratory control samples during the analysis, to ensure the continued performance of the instrument. The procedure in EN 15104 insists that the control should have a similar C, H and N content to the samples undergoing analysis, therefore the Olive Stone standard was used. The calibration standards were loaded into the instrument's auto sampler, followed by the wood samples. After every 10 wood samples a control sample was run to ensure the validity of the wood sample results. In total, each wood sample was analysed in triplicate.

#### 4.2.3.4. Low Nitrogen Analysis

A common trait with biomass fuels, in particular wood, is the low nitrogen content – a factor highlighted throughout the literature. The nitrogen content of wood biomass reportedly ranges from <0.1-0.6%, which is often less than that of sources such as grasses, straws and other biomass residues [9, 19, 21, 22]. With the nitrogen content of wood falling way below 1%, any differences in the reported values, as a result of instrument performance, are exacerbated and can result in high errors. In addition, the nitrogen detection limits of the Flash EA1112 elemental analyser is ~500ppm, which means that woods with a nitrogen content below this limit are not registered. Therefore, to ensure that the correct nitrogen contents are reported in this research, additional low nitrogen analysis has been undertaken using an *Analytik Jena* Multi 5000 elemental analyser (see Appendix A) – an instrument with superior detection limits, specifically designed for samples with low contents of principle elements.

A sample with a known mass is placed in an individual sample boat, positioned on the instruments auto sampler. The sample is then fed into a furnace, heated to 1050°C, where it is first pyrolysed in an argon atmosphere and then combusted in an oxygen atmosphere. Following the combustion, the reaction between NO and $O_3$ produces $NO_2$ in a temporarily excited state, which in turn emits a visible light [23], as shown by the following equation;

$$NO + O_3 \rightarrow NO_2^* \rightarrow NO_2 + hv(NIR) \qquad (4.26)$$

The light is directly proportional to the chemiluminescent species, allowing for the sample's elemental N to be detected with the instrument's chemiluminesence detector.

The low nitrogen analysis of the 145 wood samples considered in this chapter was conducted in duplicate, using between 2-3mg of sample per run. Each sample was weighed, with the correct weight logged on the instrument's software. The instrument was calibrated to 0.5% N and then, in a similar fashion to the elemental analyser, a control sample of olive stone was used after every 10 runs to ensure acceptable instrument performance.

#### 4.2.3.5. Calorific Values

The energy content of a fuel, referred to as its calorific value, is a vital parameter when considering its potential end use, especially within thermal systems [24, 25]. In academic literature the energy content is often reported as a gross value, however in real world applications the net value is the most important figure. The gross calorific value (GCV), or higher heating value as it is also called, is reported on a dry basis and refers to the enthalpy of a fuels complete combustion with the moisture in a liquid state. This considers both the fuel's original moisture content and any additional moisture produced from the oxidation of its hydrogen content. In comparison, the net calorific value (NCV), or lower heating value, includes the moisture as a gaseous product [24-26]. In effect the NCV reflects how a fuel's moisture can impede the amount of useful energy that is ultimately produced.

The standard experimental procedure for calculating the calorific values, detailed in EN 14918, utilises adiabatic bomb calorimetry. This procedure requires a bomb calorimeter, within which a weighed portion of the sample is combusted in high-pressure oxygen. The observed temperature changes, before and after, allow for the calculation of the specific energy required to increase the temperature [26]. The value produced as a result of this procedure is the GCV at constant volume ($GCV_{cv}$), which can then be calculated on a dry basis, using the following equation;

$$GCV_{db} = GCV_{cv} \times (\frac{1}{1-MC}) \quad (4.27)$$

Once the GCV has been calculated, again using equations derived from EN 14918, the net calorific values of a fuel can be calculated, both on a dry basis and with moisture content, respectively.

$$NCV_{db} = GCV_{db} - 2.122\, H_{db} - 0.008\,(O_{db} + N_{db}) \quad (4.28)$$

where:

| | |
|---|---|
| $NCV_{db}$ | is the net calorific value on a dry basis |
| $GCV_{db}$ | is the gross calorific value on a dry basis |
| $H, O, N_{db}$ | is the mass fraction of hydrogen, oxygen and nitrogen |

$$NCV_{wb} = NCV_{db} \times (1 - MC) - 2443 \times MC \quad (4.29)$$

where:

| | |
|---|---|
| $NCV_{wb}$ | is the net calorific value, including the moisture |

Bomb calorimetry of solid biofuels, which requires the production of a pellet for analysis, is a long-served and widely used technique, utilised in the characterisation of both hardwood and softwood species [26-28]. In keeping with standard procedures, the pellet produced for use in bomb calorimetry should have a mass of ~1g which, if completed in duplicate, would require significantly more sample than is at the disposal for this research. Considering the other analysis to be undertaken, the size of the sample set and the time-consuming nature of the process, an alternative method for calculating the energy content for each individual wood sample is necessary.

The use of empirical formulae to calculate the GCV from basic analysis data has been extensively investigated, using the determined proximate, ultimate or lignocellulosic values of a sample to estimate its energy content [24, 25]. The following linear empirical equation, produced by Friedl *et al* (2005), utilises elemental composition data to predict the GCV of plant-based biomass samples, on a dry basis;

$$GCV = \frac{3.55C^2 - 232C - 2230H + 51.2C \times H + 131N + 20600}{1000} \quad (4.30)$$

where:

$GCV$ is the gross calorific value in MJ/kg (db)
$C, H, N$ is the mass fraction of carbon, hydrogen and nitrogen (db)

Friedl *et al* (2005) reported a strong correlation ($R^2$=0.935) between predicted GCV values, using their equation and experimental values [24]. This method of estimating the energy content of biomass has previously been widely utilised, with their produced wood GCV values (18.5-19.6 MJ/kg) representative of the resource. The GCV of this chapters samples will therefore be estimated using Eq. 4.30 and their corresponding proximate and ultimate experimental data.

### 4.2.3.6. Lignocellulosic Analysis

The proximate and ultimate analysis of fuels are both fundamental analytical processes for characterising solid biomass fuels, allowing for the comparison of basic compositions and principle elemental contents between samples. Another key form of characterisation, particularly prevalent for biomass fuels, relates to the biochemical composition of a sample. Lignocellulosic analysis considers the organic and inorganic constituents of biomass, which can be separated into two basic groups; 1) structural components, which are the lignin, cellulose and hemicellulose, and 2) non-structural components, such as the extractives and inorganic compounds. The lignocellulosic data, used in combustion analysis, differs between biomass sources, such as hardwood and softwood species [29].

The process for determining the lignin, cellulose and hemicellulose contents within biomass utilises a series of digestion and filtration techniques; established methods, stemming from agricultural and animal husbandry research [30]. As a result, standard procedures exist to determine a sample's acid detergent fibre (ADF), acid detergent lignin (ADL), neutral detergent fibre (NDF) and acid-insoluble lignin, which is referred to as 'Klason' lignin [31-33]. The NDF method, utilising a gravimetric process, is used to determine the total fibre in a feedstock. ADF utilises an acid detergent, leaving the least digestible components of a biomass; namely the lignin, cellulose and acid-insoluble ash. The results of the ADF and NDF methods are then used in combination to establish the hemicellulose content of the sample, as shown by the following equation;

$$He_{db} = NDF_{ad} - ADF_{ad} \times (\frac{1}{1-MC}) \qquad (4.31)$$

where:

| | |
|---|---|
| $He_{db}$ | is the mass fraction of hemicellulose on a dry basis |
| $NDF_{ad}$ | is the determined NDF content |
| $ADF_{ad}$ | is the determined ADF content |

The ADL procedure utilises the previously produced ADF solution, which is treated with 72% sulphuric acid ($H_2SO_4$) to dissolve the cellulose and produce a crude lignin content. As shown in Eq. 4.32, the mass values from both the initial ADF solution and the consequent ADL method can be used to determine the cellulose content;

$$Ce_{db} = ADF_{ad} - ADL_{ad} \times (\frac{1}{1-MC}) \qquad (4.32)$$

where:

| | |
|---|---|
| $Ce_{db}$ | is the mass fraction of cellulose on a dry basis |
| $ADL_{ad}$ | is the determined ADL content |

The process for determining the total lignin, referred to as 'Klason' lignin, requires a separate acid digestion that digests the wood sample in 72% $H_2SO_4$, without undergoing any previous digestions.

$$Li_{db} = KL_{ad} \times (\frac{1}{1-MC}) \qquad (4.33)$$

where:

| | |
|---|---|
| $Li_{db}$ | is the mass fraction of total lignin on a dry basis |
| $KL_{ad}$ | is the determined Klason lignin content |

The described methods, in line with standard procedures, determine the mass% of the wood samples structural components, on a dry basis. Finally, the extractive content ($Ext_{db}$) has been determined by difference using the following equation;

$$Ext_{db} = 100 - (Li_{db} + He_{db} + Ce_{db} + ash_{db}) \qquad (4.34)$$

The lignocellulosic analysis on the 145 wood samples considered within this research was completed externally, keeping to the above standard procedures, by the *Institute of Biological, Environmental and Rural Sciences* (IBERS), Aberystwyth University.

### 4.2.4. Calculating Experimental Error

All of the experimental work contained within this chapter has been performed in duplicate, as a minimum, with the reported values for each sample given as the calculated mean. Completing each experimental procedure multiple times increases the confidence in the stated values, while allowing for the calculation of errors related to the utilised analysis methods. The margin of uncertainty associated with a measurement can be expressed as absolute error, which is equivalent to the standard deviation. As a result the relative standard deviation (RSD) – calculated using Eq. 4.2 – is also referred to as the relative error, usually given as a percentage.

Experimental methods of analysis often involve different procedures which each have their own attributed error. Therefore, when combining experimental values – such as adjusting elemental data on a dry basis – it requires the propagation of errors. When the propagation requires the addition of error values, this is achieved by using the following equation;

$$E = \sqrt{\sum_{i=1}^{n} e_i^2} \tag{4.35}$$

where:

| | |
|---|---|
| $E$ | is the total relative experimental error |
| $e_i$ | is the individual error of the $i^{th}$ group ($i$=1, 2, …, $n$) |

For cases where the multiplication of error is required, the errors must first be converted to percent relative errors before using Equation 4.36;

$$\%E = \sqrt{\sum_{i=1}^{n} \%e_i^2} \tag{4.36}$$

where:

| | |
|---|---|
| $\%E$ | is the total percent relative experimental error |
| $\%e_i$ | is the individual percent error of the $i^{th}$ group ($i$=1, 2, …, $n$) |

## 4.3. Results

The following results section can be broken down into three focused areas; 1) a comparison of the data collated from the literature, in the context of hardwoods and softwoods, 2) how this compares with the experimental data – again in the context of hardwoods and softwoods – and 3) how the experimental data differs between individual species and the different tree sections.

### 4.3.1. Statistical Analysis of Literature

Data acquired from a total of 86 samples – collated from 36 published journals – has been evaluated in this section. As a result, the mean values and additional descriptive statistical data has been calculated for an array of analytical wood characteristics, which can be found in Table 4.5. In addition to the descriptive statistics, Table 4.6 contains the results of the hypothesis testing undertaken on the results of Table 4.5; this includes the Levene's test for variance and the independent $t$-test, undertaken between the defined hardwood and softwood groups. The results of the Levene's test show that there are no significant differences in the variation of the hardwood and softwood variables considered in this section.

The calculated proximate data indicates that hardwood species have a larger volatile matter (VM) content than softwood species. As a result, their fixed carbon (FC) content is reduced while their ash mass is also lower. From the 31 hardwood samples considered, the mean values of the VM and FC contents were calculated as 83.97% and 14.99%, respectively. In comparison, the calculated means of the VM and FC softwood sample contents were 82.53% and 16.26%. The results of the independent samples $t$-tests, given in Table 4.6, indicate that although there are differences in the mean values for the hardwood and softwood proximate data, none of these are shown to be statistically significant.

Although the calculated VM and FC means do not differ significantly, the spread of the data within the interquartile range (IQR), which ignores extreme values,

Table 4.5 – **Characterisation of hardwood and softwood resource; descriptive statistics, based on existing published literature**

| | **Hardwood** | | | | | **Softwood** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n | Mean | Std. Dev. | RSD (%) | IQR | n | Mean | Std. Dev. | RSD (%) | IQR |
| **VM (Wt.% db)** | *31* | *83.97* | *5.59* | *6.7* | *8.40* | *30* | *82.53* | *5.80* | *7.0* | *3.36* |
| **FC (Wt.% db)** | *31* | *14.99* | *5.33* | *35.5* | *7.65* | *30* | *16.26* | *5.60* | *34.4* | *3.67* |
| **Ash (Wt.% db)** | *31* | *1.07* | *0.91* | *85.6* | *0.90* | *30* | *1.19* | *1.17* | *98.7* | *1.44* |
| **FC:VM Ratio** | *31* | *0.18* | *0.08* | *42.2* | *0.02* | *30* | *0.20* | *0.09* | *43.9* | *0.03* |
| **N (Wt.% db)** | *38* | *0.27* | *0.19* | *70.5* | *0.15* | *33* | *0.21* | *0.22* | *104.5* | *0.13* |
| **Atomic H:C Ratio** | *38* | *1.48* | *0.15* | *10.1* | *0.10* | *33* | *1.48* | *0.12* | *8.3* | *0.12* |
| **Atomic O:C Ratio** | *38* | *0.70* | *0.07* | *9.7* | *0.06* | *33* | *0.66* | *0.06* | *8.6* | *0.06* |
| **GCV (MJ/kg db)** | *46* | *19.14* | *1.02* | *5.3* | *0.53* | *36* | *19.85* | *0.85* | *4.3* | *0.74* |
| **L:H Ratio** | *35* | *0.35* | *0.10* | *28.8* | *0.16* | *19* | *0.43* | *0.11* | *24.7* | *0.14* |

Table 4.6 – **Characterisation of hardwood and softwood resource; Levene's Test and Independent *t*-test analysis (literature)**

| | **Levene's Test** | | ***t*-test** | | |
|---|---|---|---|---|---|
| | F | Sig. | *t* | *df* | Sig. (2-tailed) |
| **VM (Wt.% db)** | *0.238* | *0.628* | *0.985* | *59* | *0.328* |
| **FC (Wt.% db)** | *0.155* | *0.695* | *-0.910* | *59* | *0.367* |
| **Ash (Wt.% db)** | *1.599* | *0.211* | *-0.443* | *59* | *0.659* |
| **FC:VM Ratio** | *0.000* | *0.984* | *-0.915* | *59* | *0.364* |
| **N (Wt.% db)** | *0.001* | *0.971* | *1.205* | *69* | *0.232* |
| **Atomic H:C Ratio** | *0.508* | *0.478* | *0.030* | *69* | *0.976* |
| **Atomic O:C Ratio** | *0.745* | *0.391* | *2.749* | *69* | *0.008* |
| **GCV (MJ/kg db)** | *0.091* | *0.764* | *-3.354* | *80* | *0.001* |
| **L:H Ratio** | *0.015* | *0.903* | *-2.743* | *52* | *0.008* |

shows that differences exist between the hardwood and softwood species. The IQR for the hardwood samples VM and FC contents, calculated at 8.40 and 7.65 respectively, are more than twice the size of those for the softwoods (3.36 and 3.67); this indicates that the hardwood data has a larger spread than the softwood species. This is visualised in Figure 4.4, which plots the collated FC values against their corresponding VM contents. The hardwood data points show a relatively even distribution while, for the softwoods, there is a more defined grouping around the mean values.

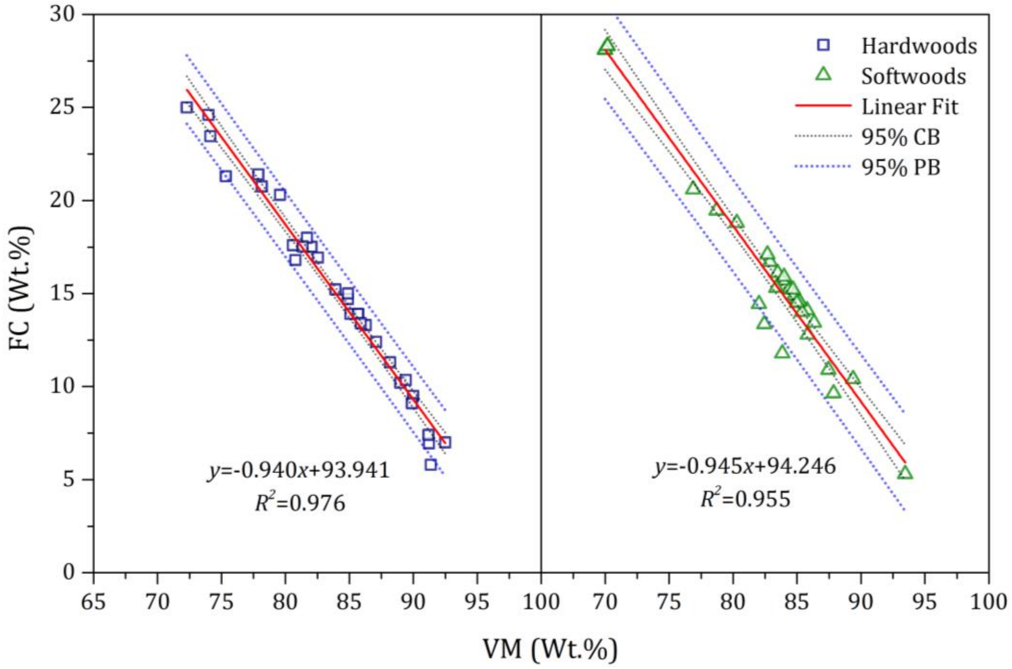


Figure 4.4 – **Linear relationship between VM and FC (on a dry basis); comparison between hardwood and softwood resource, based on published literature**

In addition to the distribution of hardwood and softwood data points, Figure 4.4 also displays the linear relationship between the two dominant proximate variables. Naturally, there is a strong negative correlation between the VM and FC contents for both the hardwood and softwood data; as the VM content increases, the FC content decreases. It's important to note that the FC contents – on a dry basis – are derived from the determined VM and ash contents, adjusted for moisture; the FC is therefore inherently linked to the other proximate values. The hardwood and softwood $R^2$ values are calculated as 0.976 and 0.955, respectively, inferring that the ash content of stem wood has very little impact on the VM and FC contents – if there is a change in ash volume then this could yield varying FC contents. There is also very little difference in the slope and y-intercept values of the hardwood and softwood linear regression models, supporting the results of the independent *t*-tests; that there is no significant difference in the proximate values of hardwoods and softwoods. Consequently, the produced linear models will act as a reference point for the experimental data later in this chapter.

When considering the elemental data of fuels, a useful tool for comparing biomass sources is the Van Krevelen diagram. This utilises the atomic O:C and H:C ratios of a feedstock to ascertain its position on the diagram and its resulting suitability; the lower the ratio, the greater the materials energy content [34]. The Van Krevelen diagram in Figure 4.5 shows the atomic O:C and H:C ratios of the hardwood and softwood samples, calculated from the elemental data taken from the literature. As shown by the data plotted in Figure 4.5, the key elemental constituents of hardwoods and softwoods clearly differ from that of various medium- to high-rank coals. Fuels which are closely packed on the diagram are expected to behave similarly in thermal conversion processes.

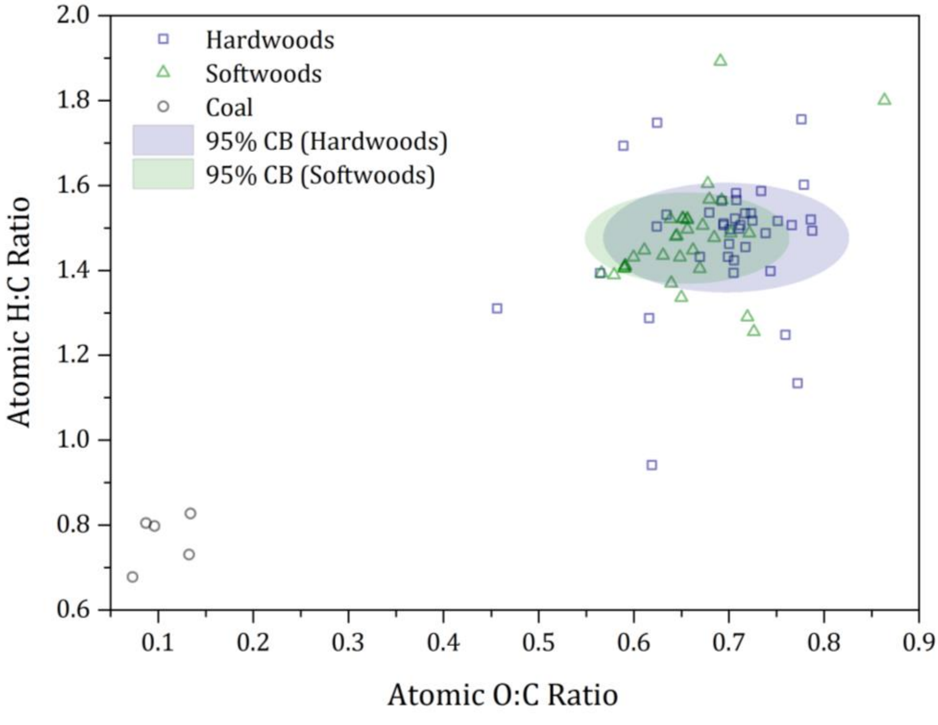


Figure 4.5 – **Van Krevelen diagram of hardwood and softwood samples (daf), sourced from published literature**

The calculated mean values of the hardwood O:C and H:C ratios – found in Table 4.5 – are 0.70 and 1.48, respectively, while for the softwood data these are 0.66 and 1.48. The consequent independent $t$-tests, given in Table 4.6, show that there is no statistically significant difference in the H:C ratio of hardwoods and softwoods. However, in relation to the O:C ratios of hardwoods and softwoods, there is a statistically significant difference evident; $t(69)=2.749$, $p=0.008$. The distribution of the hardwood and softwood data within the Van Krevelen diagram – specifically the distance of the data points from the calculated means – has been represented by circular functions, with the associated parameters located in Table 4.7. The softwood sample points are more tightly clustered together than the hardwoods, suggesting a greater level of homogeneity. This is shown by the difference in circle areas; the hardwood circle is 47% larger than the softwoods. Similar to the proximate linear functions, the literature parameters in Table 4.7 will act as a basis of comparison in the experimental analysis.

Table 4.7 – **Calculated circular function parameters; derived from Van Krevelen data (Figure 4.5 & 4.7)**

| | **Literature** | | **Experimental** | |
|---|---|---|---|---|
| | Hardwood | Softwood | Hardwood | Softwood |
| $x_c$ | *0.697* | *0.656* | *0.748* | *0.725* |
| $y_c$ | *1.477* | *1.476* | *1.580* | *1.618* |
| $r$ | *0.110* | *0.091* | *0.046* | *0.030* |
| **SE** | *0.019* | *0.017* | *0.005* | *0.003* |
| **Area ($1\text{x}10^2$ a.u.)** | *3.81* | *2.59* | *0.65* | *0.29* |

The results in Table 4.5 indicate that hardwoods (M=0.27, SD=0.19) have a larger nitrogen content than softwoods (M=0.21, SD=0.22), although the resulting independent $t$-test shows there is no significant difference; $t(69)=1.205$, $p=0.232$. There is however a statistically significant difference between the GCV values of hardwoods (M=19.14, SD=1.02) and softwoods (M=19.85, SD=0.85), found within the literature; $t(80)=-3.354$, $p=0.001$.

In addition to being published predominantly on an extractive free (EF) basis, a lot of the available lignocellulosic data combines the values of cellulose with hemicellulose, under the collective term of holocellulose. Therefore to ensure comparability – while increasing the amount of usable data – the cellulose and hemicellulose values have been combined, resulting in the production of lignin and holocellulose (L:H) ratios. An increased L:H ratio indicates a greater existence of non-carbohydrate aromatic polymers, compared to carbohydrate-based polysaccharides; these have been discussed in greater detail in Chapter 3. As a result, hardwoods (M=0.35, SD=0.10) have a statistically significant increase in carbohydrate contents when compared to softwoods (M=0.43, SD=0.11), which contain more lignin; $t(52)=-2.743$, $p=0.008$.

### 4.3.2. Comparison between Experimental & Literature

The literature review results in Section 4.3.3 focus on assembled stem wood samples, grouped under hardwood and softwood categories. Before any of the experimental data can be compared to the literature results, it must first be considered in a more comparable form. Of the 145 samples used during experimental analysis, 80 of these were sourced from the stems of UK-grown trees. These will therefore form the basis of this section's comparative analysis and have been assigned as either hardwood or softwood, grouping into 32 and 48 samples, respectively.

Table 4.8 displays the descriptive statistics – the mean, standard deviation, relative standard deviation (RSD) and interquartile range – of the experimental data, in the context of hardwoods and softwoods. The corresponding variance and independent *t*-test data can be found in Table 4.9. Unlike the literature-based data, which show homogeneity of variance between its data samples, some of the experimental data characteristics have unequal population variances; put simply, the variance of an affected characteristic is unlikely to have occurred due to random sampling. This is an important consideration when interpreting the produced *t*-test data and has been accounted for in the stated results. The individual Levene's tests indicate that the ash, nitrogen and L:H ratio display homogeneity of variance, while the remaining characteristics have differences in their population variances. These have been adjusted as appropriate.

From the 32 hardwood samples analysed, the VM and FC contents were determined as 88.60% and 11.12%, respectively. In comparison the softwood

Table 4.8 – **Characterisation of hardwood and softwood resource; descriptive statistics, based on experimental data**

| | **Hardwood** | | | | | **Softwood** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | n | Mean | Std. Dev. | RSD (%) | IQR | n | Mean | Std. Dev. | RSD (%) | IQR |
| **VM (Wt.% db)** | *32* | *88.60* | *2.43* | *2.7* | *5.06* | *48* | *88.16* | *0.92* | *1.0* | *0.86* |
| **FC (Wt.% db)** | *32* | *11.12* | *2.38* | *21.4* | *4.87* | *48* | *11.57* | *0.86* | *7.4* | *0.80* |
| **Ash (Wt.% db)** | *32* | *0.27* | *0.16* | *59.3* | *0.25* | *48* | *0.27* | *0.15* | *55.6* | *0.19* |
| **FC:VM Ratio** | *32* | *0.13* | *0.03* | *23.1* | *0.06* | *48* | *0.13* | *0.01* | *7.7* | *0.01* |
| **N (Wt.% db)** | *32* | *0.12* | *0.02* | *16.7* | *0.02* | *48* | *0.09* | *0.03* | *33.3* | *0.02* |
| **Atomic H:C Ratio** | *32* | *1.58* | *0.05* | *3.2* | *0.09* | *48* | *1.62* | *0.03* | *1.9* | *0.04* |
| **Atomic O:C Ratio** | *32* | *0.75* | *0.02* | *2.7* | *0.02* | *48* | *0.73* | *0.03* | *4.1* | *0.04* |
| **GCV (MJ/kg db)** | *32* | *18.56* | *0.22* | *1.2* | *0.28* | *48* | *18.86* | *0.37* | *2.0* | *0.58* |
| **L:H Ratio** | *32* | *0.31* | *0.05* | *16.1* | *0.10* | *48* | *0.41* | *0.05* | *12.2* | *0.07* |

Table 4.9 – **Characterisation of hardwood and softwood resource; Levene's Test and Independent *t*-test analysis (experimental)**

| | **Levene's Test** | | ***t*-test** | | |
|---|---|---|---|---|---|
| | F | Sig. | *t* | df | Sig. (2-tailed) |
| **VM (Wt.% db)** | *71.058* | *0.000* | *0.974* | *37* | *0.336* |
| **FC (Wt.% db)** | *77.991* | *0.000* | *-1.012* | *36* | *0.318* |
| **Ash (Wt.% db)** | *0.387* | *0.536* | *0.129* | *78* | *0.898* |
| **FC:VM Ratio** | *71.056* | *0.000* | *-0.885* | *37* | *0.382* |
| **N (Wt.% db)** | *0.051* | *0.821* | *7.075* | *78* | *0.000* |
| **Atomic H:C Ratio** | *24.080* | *0.000* | *-3.867* | *41* | *0.000* |
| **Atomic O:C Ratio** | *8.620* | *0.004* | *4.641* | *78* | *0.000* |
| **GCV (MJ/kg db)** | *11.546* | *0.001* | *-4.655* | *77* | *0.000* |
| **L:H Ratio** | *0.600* | *0.441* | *-8.449* | *78* | *0.000* |

values, calculated from 48 samples, are 88.16% and 11.57%. As per the literature results, the calculated means for the experimental proximate data – in the context of stem wood samples – are shown to have no statistically significant differences from one another. The individual VM and FC data points for both hardwood and softwood categories have been plotted in Figure 4.6. In addition to the data points, Figure 4.6 also displays the calculated linear functions, between the VM and FC contents. The differences in the hardwood standard deviation, RSD and IQR values, when compared to the softwoods, can be visually seen in Figure 4.6; the hardwood data points are spread out, while there is clear grouping of softwood data points, indicating increased homogenity.

As previously demonstrated in Figure 4.4, the $R^2$ values of the hardwood ($R^2$=0.996) and softwood ($R^2$=0.975) linear regression models indicate that – for the stem wood samples – the inherently-linked FC contents of wood are dictated by the VM, with little influence from the ash due to its reduced mass. This, coupled with the comparable calculated slope and y-intercept values, gives validity to the experimental results and the methods that have been utilised.

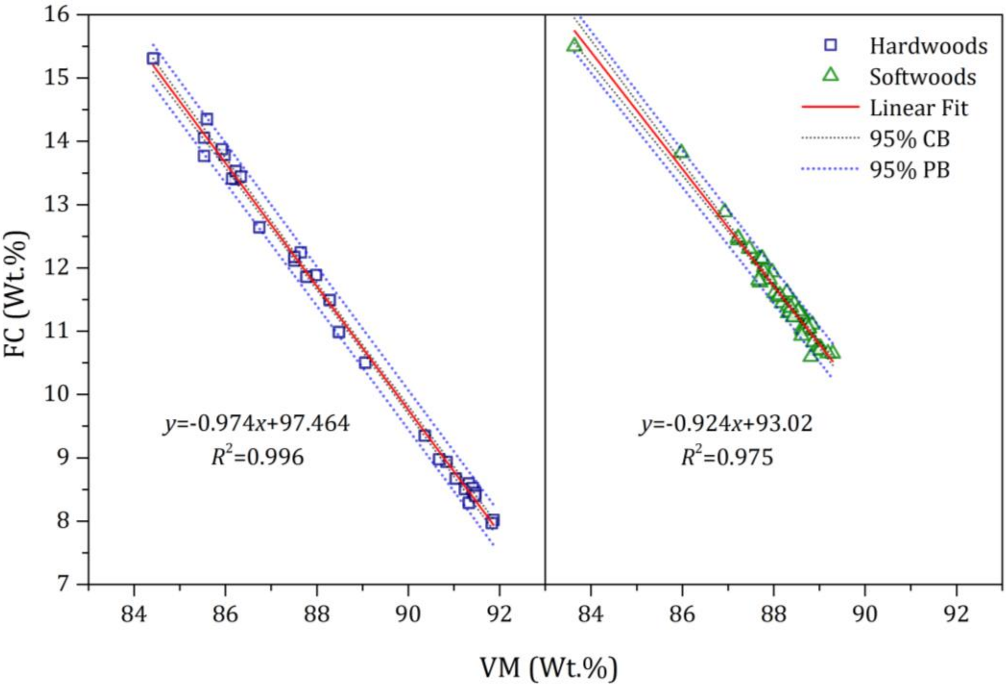


Figure 4.6 – **Linear relationship between VM and FC (on a dry basis); comparison between hardwood and softwood resource, based on experimental results**

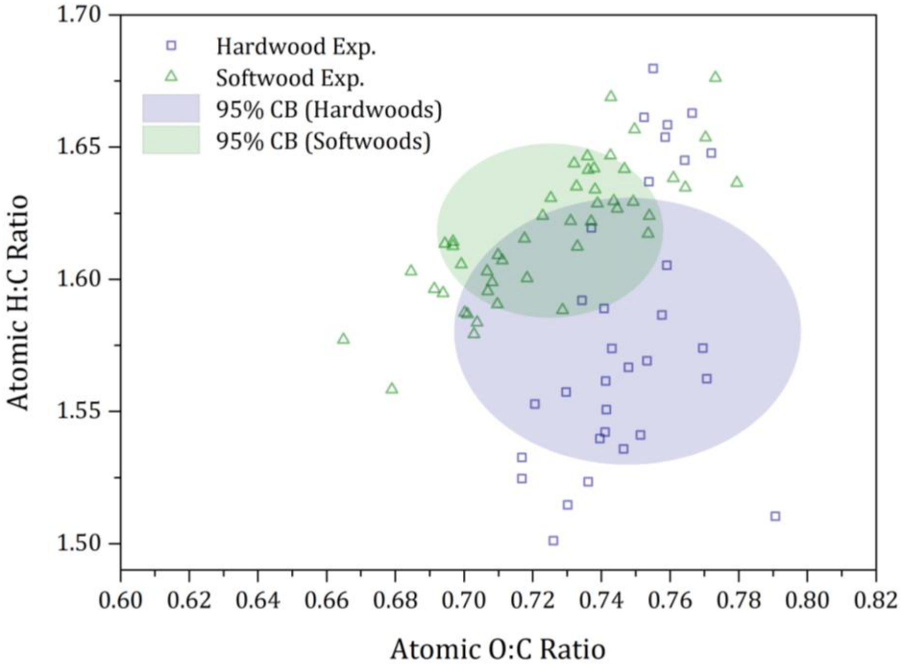


Figure 4.7 – **Van Krevelen diagram of hardwood and softwood samples (daf), based on experimental stemwood data**

The experimental mean values of the hardwoods O:C and H:C ratios, found in Table 4.8, are given as 0.75 and 1.58, respectively, while for the softwood data these are 0.73 and 1.62. Unlike the results from the literature, both of the ratios have statistically significantly differences between the hardwood and softwood samples; for the O:C ratio $t(78)=4.641$, $p<0.001$ and the H:C ratio $t(41)=-3.867$, $p<0.001$. The resulting Van Krevelen diagram in Figure 4.7 plots the calculated O:C and H:C data produced from the experimental work. Visually, there is a clear difference in both the location and the spread of the results for the hardwood and softwood samples. As with the literature data, the clustering around the mean value has been qualified via the creation of circular functions, with their parameters given in Table 4.7. In addition to the contrast in calculated means – depicted as the centre points of the circular functions – the differences in the clustering is represented by the circles areas. The hardwood data points are more widely dispersed from the mean than for the softwood samples, reflecting the findings from the literature. Subsequently, the calculated area of the hardwood circle is ~124% larger than that of the softwood. The relationship between the experimental and literature Van Krevelen data is shown in Figure 4.8, comparing the experimental results against the circular functions produced from the reviewed literature.

As evidenced in Figure 4.8, there is a clear difference in the experimental and literature circular functions, both in size and location. This is supported by the additional independent *t*-tests, located in Appendix C, which show that there are statistically significant differences between the experimental and literature-based calculated means for both hardwoods and softwoods. Considering the experimental hardwood results, a large amount of the data points fall within the literature-based 95% confidence band. This indicates that although there are differences in the UK's hardwood resource, the data is still representative of that currently published. Again, this is important, giving validity to the data and the methods employed in producing it.

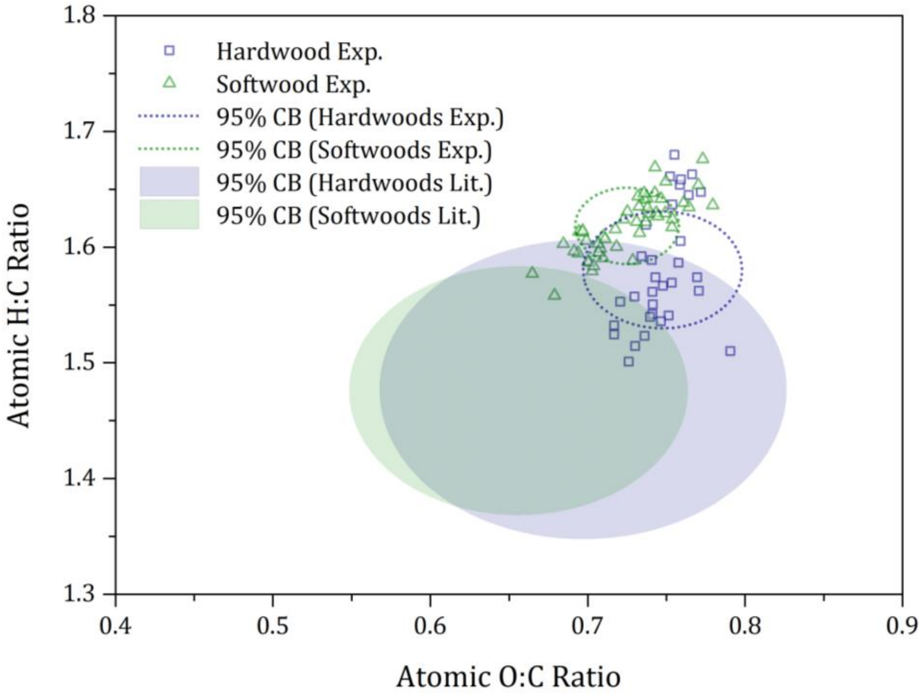


Figure 4.8 – **Van Krevelen diagram of hardwood and softwood samples; comparison of experimental and literature data**

This is further demonstrated by the box plots in Figure 4.9b and 4.9c, which highlight the spread of data and how this differs between the experimental and literature sources. The box plots for the atomic H:C and O:C ratios show that the data collated from the literature has a greater distribution than the experimental results, evident for both hardwoods and softwoods. The compact nature of the experimental data, specifically the lack of defined outliers, suggests that the experimental methods employed are replicable, increasing the confidence in the given results. The majority of the experimental results fall between the upper quartile and upper whisker for both hardwoods and softwoods alike, indicating

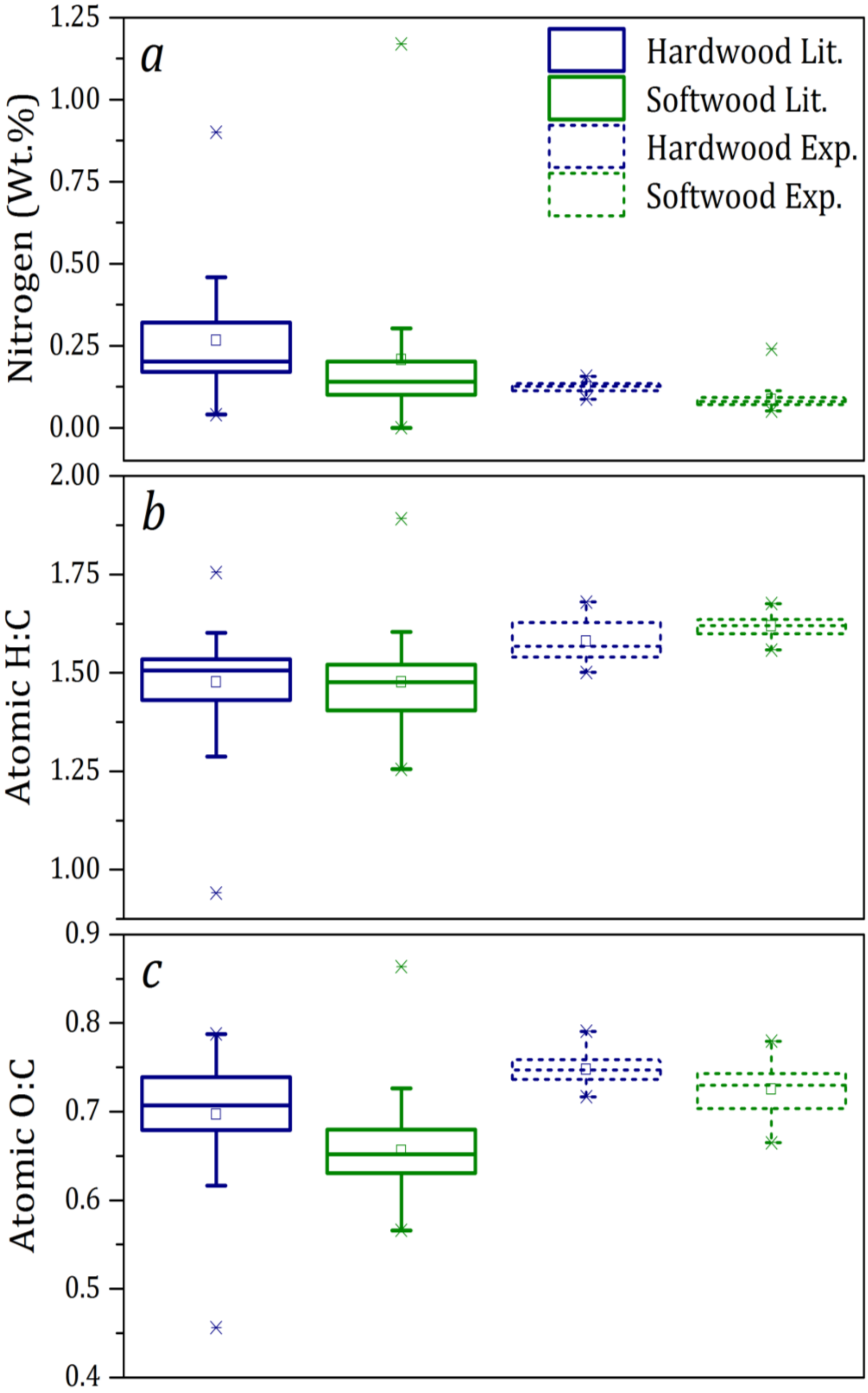


Figure 4.9 – **Comparative box plots between literature and experimental data, for hardwood and softwoods; a) Nitrogen content, b) H:C Ratios, and c) O:C Ratios**

that although the mean results differ from the literature, the data points are still comparable with one another. Additionally, Figure 4.9b shows that the UK's hardwoods have a greater variation in their H:C ratios than the softwood species, while Figure 4.9c shows that the O:C ratios of softwood have a larger distribution.

Tables 4.8 and 4.9 show that the nitrogen contents of the hardwood (M=0.12, SD=0.02) and softwood (M=0.09, SD=0.03) samples are statistically significantly different from each other; $t(78)=7.075$, $p<0.001$. This is illustrated by the box plots in Figure 4.9a which not only show the difference in the experimentally determined nitrogen content, but also how these compare to the results of the literature. As with the other elemental data, the literature-based results have a much larger distribution than the experimental results. The data sourced from the literature represents a diverse number of studies, each analysing wood obtained from different species, located in different parts of the world. In comparison, the experimental data is focused on just four species, collected exclusively from UK-grown trees. This heterogeneity of feedstock may go some way to explaining the differences in results, although these may also have been exacerbated by the chosen analytical method. The N contents of the UK species were produced using a low nitrogen analyser; other methods, using equipment with less accurate detection limits, may have resulted in the unintentional overestimation of stated N contents within the literature.

The distribution of experimental and literature-based GCV results are represented by the box plots in Figure 4.10a. The results in Tables 4.8 and 4.9 show that there is a statistically significant difference between the GCV's of hardwoods (M=18.56, SD=0.22) and softwoods (M=18.86, SD=0.37), which mirrors the results of the literature analysis; $t(77)=-4.655$, $p<0.001$. As with the previously discussed fundamental wood characteristics, there are statistically significant differences between the experimental and literature mean GCV results (Appendix C). However, as displayed in Figure 4.10a, the hardwood and softwood data points fall within the distributions of the collated literature results.

The data in Tables 4.8 and 4.9 show that there are statistically significant differences between the experimental L:H ratio mean values for hardwoods

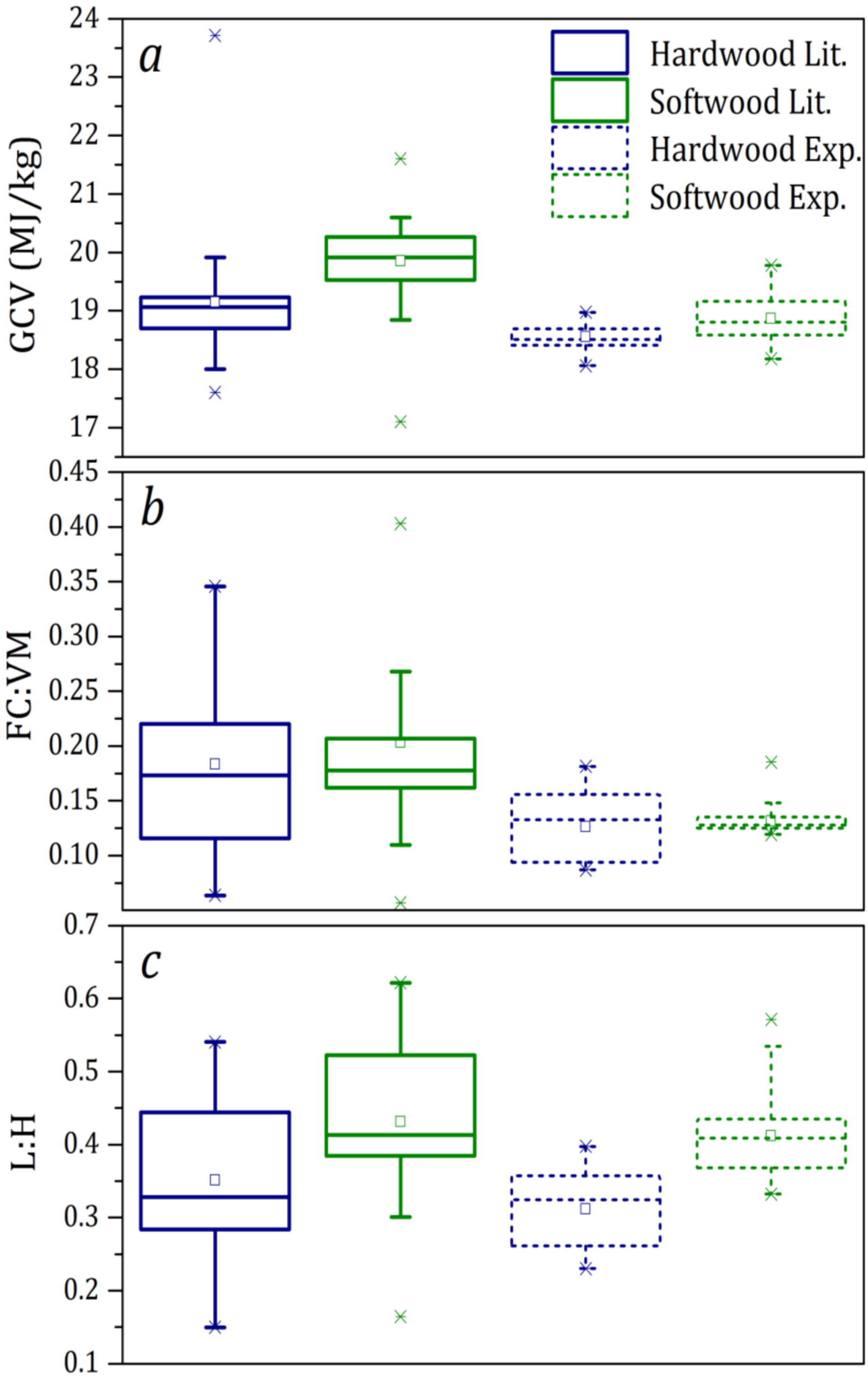


Figure 4.10 – **Comparative box plots between literature and experimental data, for hardwood and softwoods; a) Gross Calorific Values (MJ/kg), b) Fixed Carbon and Volatile Matter Ratios, and c) Lignin and Holocellulose Ratios**

(M=0.31, SD=0.05) and softwoods (M=0.41, SD=0.05); *t*(78)=-8449, *p*<0.001. The comparison of the experimental L:H ratios with that of the literature show that there are statistically significant  difference between the hardwoods but not for the softwoods. The box plots in Figure 4.10c display the relationship between the experimental and literature data for the L:H ratios. Although there are differences in the mean values for hardwoods, the experimental data for both the hardwood and softwood groups fall within the spread of the literature data.

### 4.3.3. Species & Tree Section – Experimental Data

The final part of this chapter's results section focuses specifically on the individual species within the wood sample set. This divides further, considering the variation between different sections of the tree; namely the stem, the roots and the branches. The proximate, ultimate, GCV and lignocellulosic results for each individual sample – calculated following the experimental analysis – has been collated and can be found in Appendix B. In addition to these, statistical analysis between this data has be completed and can be found in Appendix C.

#### 4.3.3.1. Proximate Results

The results of the proximate analysis can be found in Table 4.10, dividing between the four tree species and the individual tree sections. Consequently,

Table 4.10 – **Experimental proximate values and standard deviations for the UK-grown oak (OK), birch (BI), Scots pine (SP) and Sitka spruce (SS) samples. Comparison between their stem, root and branch wood**

| **Mean Proximate Analysis Values (mass% db)** | | | | | |
|---|---|---|---|---|---|
| | | n | Volatile Matter | Fixed Carbon | Ash |
| **OK** | Stem | *19* | *86.8 (±1.23)* | *12.9 (±1.25)* | *0.34 (±0.17)* |
| | Root | *5* | *83.5 (±2.56)* | *12.9 (±0.95)* | *3.68 (±2.34)* |
| | Branch | *16* | *86.1 (±1.27)* | *12.5 (±0.95)* | *1.43 (±0.59)* |
| **BI** | Stem | *13* | *91.3 (±0.43)* | *8.6 (±0.38)* | *0.20 (±0.11)* |
| | Root | *8* | *86.9 (±1.41)* | *12.6 (±1.35)* | *0.54 (±0.15)* |
| | Branch | *16* | *88.8 (±0.60)* | *10.5 (±0.45)* | *0.77 (±0.37)* |
| **SP** | Stem | *19* | *88.1 (±0.73)* | *11.6 (±0.76)* | *0.27 (±0.12)* |
| | Root | *5* | *85.4 (±0.87)* | *13.2 (±0.41)* | *1.32 (±0.63)* |
| | Branch | *3* | *85.3 (±0.40)* | *14.2 (±0.35)* | *0.51 (±0.07)* |
| **SS** | Stem | *29* | *88.2 (±1.03)* | *11.5 (±0.93)* | *0.27 (±0.17)* |
| | Root | *7* | *86.7 (±0.86)* | *12.9 (±0.65)* | *0.40 (±0.26)* |
| | Branch | *5* | *85.3 (±0.39)* | *14.4 (±0.33)* | *0.32 (±0.21)* |

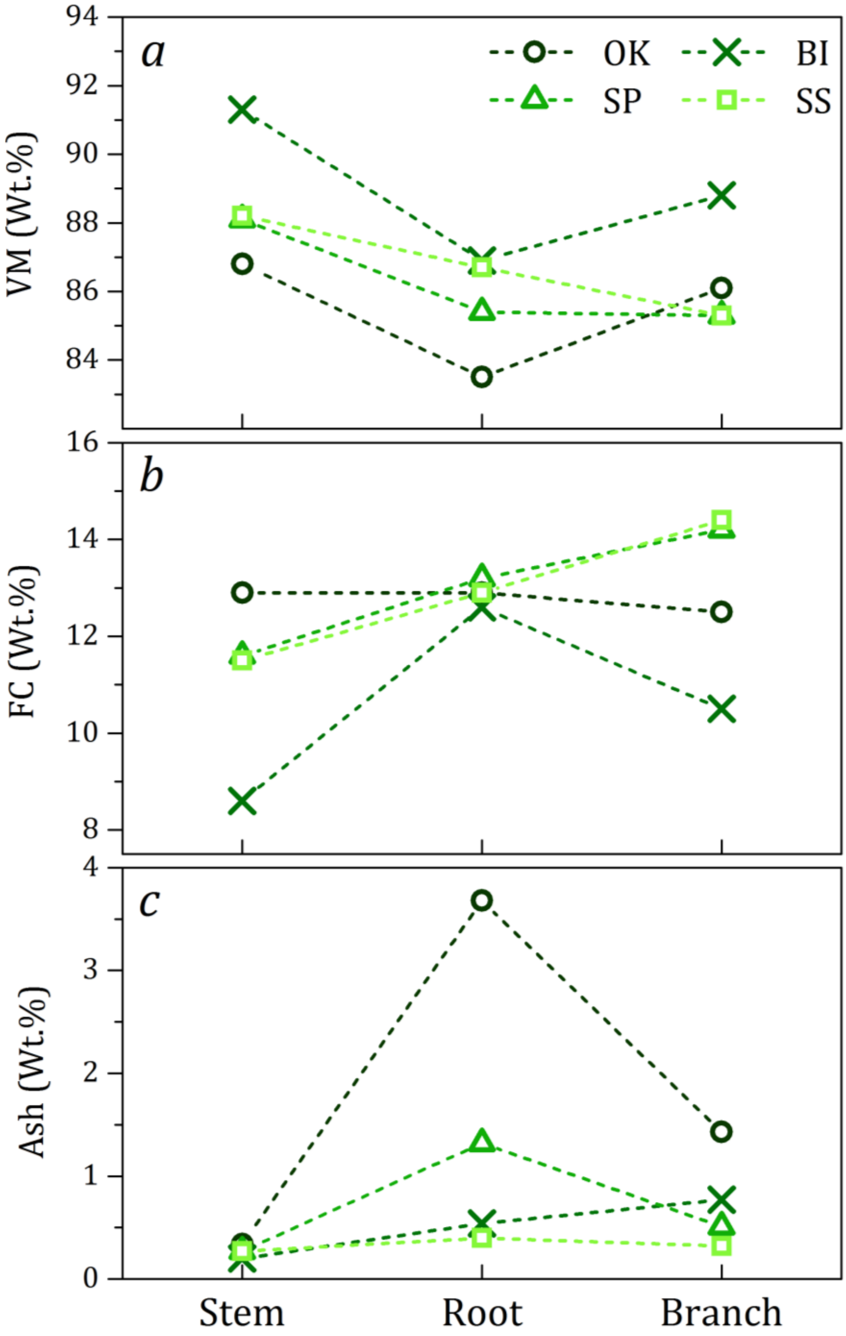


Figure 4.11 – **Calculated experimental mean values of a) Volatile Matter, b) Fixed Carbon, and c) ash contents (on a dry basis). Comparison between oak, birch, Scots pine and Sitka spruce species, including their stem, root and branch data**

Figure 4.11 illustrates the mean proximate results, displaying the differences between both the species and tree sections. When considering the proximate values for the stem wood, there is a visible difference between the hardwood species; the birch has the largest VM and smallest FC contents of the four species, at 91.3% and 8.6%, respectively, while the oak has the smallest VM content (86.8%) and the largest amount of FC (12.9%). In comparison, both softwood species have almost identical VM and FC contents, indicating a clear increase in homogeneity between species, when compared to the hardwoods.

As previously stated in this chapter, the FC content is a derived value, dependent upon the determined VM and ash contents. The variation between the VM and FC of the species' stem wood is clearly evident, however – as the ash contents show no clear, discernible differences – the stem wood can be typified by the same proximate relationship; as the VM decreases, the FC content increases. This highlights two important details for consideration when using stem wood in thermal conversion processes. Firstly, the small ash content of all four species indicate that species choice should not exacerbate the negative impacts associated with the ash constituents, which result in fouling and slagging [9, 19]. Additionally, avoiding stem wood sourced from species with larger VM contents – such as the birch – should coincide with a larger FC content; a feature often associated with fuel sources typified by higher calorific values [13].

Compared to the stem wood, each species displays a reduction in the VM content contained within their roots, maintaining the visible contrast between species. However, when considering their FC contents – unlike the stem wood – the clear link between FC and VM disappears, with all four species grouping close together at ∼13%. The ash contents of the roots differ between species, displaying a detachment from one another when compared to the stem wood; at 3.7%, the oak roots ash content is the largest, measuring nearly 3 times that of the next nearest root value. Meanwhile, though the birch and Sitka spruce species are from different genetic families, their roots have very similar ash contents to one another. The species-based separation in ash contents is also evident amongst the branch wood, although to a lesser extent, as illustrated in Figure 4.11. Again, this is essential when considering the potential of non-timber products – such as harvesting residues, stumps and roots – in bioenergy generation. The increased ash content of certain species – impacting upon both the fuel's relationship between VM and FC, while also indicating an increase in inhibitory elemental constituents – can limit their suitability as an additional fuel [9, 19, 50, 56].

The individual VM and FC data points for each sample have been plotted in Figure 4.12, displaying the differences that occur between the individual tree sections of the four species – indicating the increasing influence of ash content

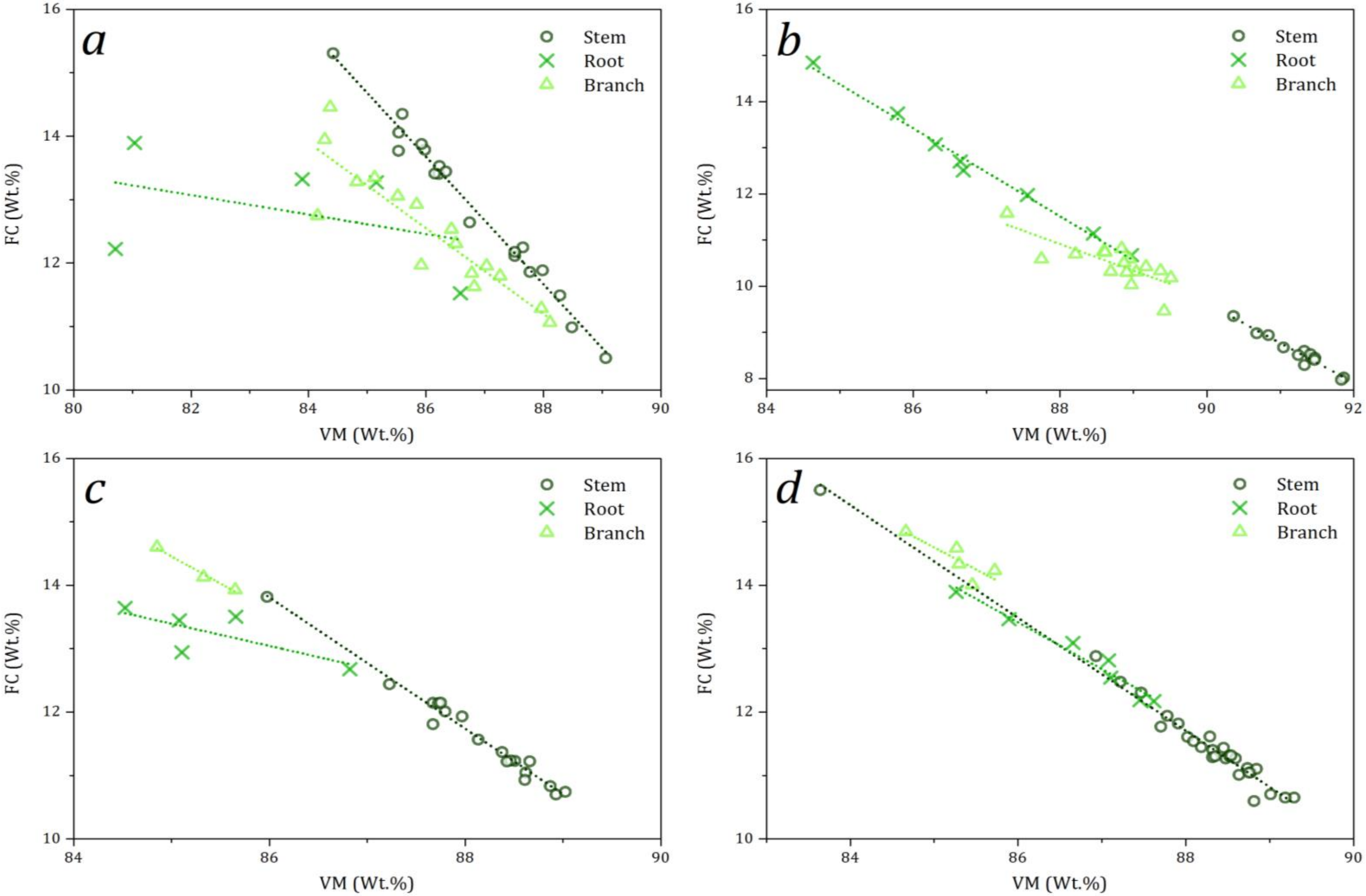


Figure 4.12 – **Linear relationships between VM (db) and FC (db) of tree sections and species; a) oak, b) birch, c) Scots pine, and c) Sitka spruce**

Table 4.11 – **Calculated linear and circular function data; Comparison between species and different tree sections**

| | **Stem** | | | | **Root** | | | | **Branch** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OK | BI | SP | SS | OK | BI | SP | SS | OK | BI | SP | SS |
| | | | | | | *Linear Functions* | | | | | | |
| **n** | *19* | *13* | *19* | *29* | *5* | *8* | *5* | *7* | *16* | *16* | *3* | *5* |
| $df$ | *17* | *11* | *17* | *27* | *3* | *6* | *3* | *5* | *14* | *14* | *1* | *3* |
| **Intercept** | *100.1* | *87.1* | *102.7* | *89.9* | *25.6* | *95.4* | *43.2* | *76.9* | *70.7* | *61.6* | *87.0* | *73.8* |
| **Slope** | *-1.005* | *-0.860* | *-1.033* | *-0.889* | *-0.153* | *-0.953* | *-0.351* | *-0.738* | *-0.676* | *-0.576* | *-0.853* | *-0.696* |
| $R^2$ | *-0.991* | *-0.973* | *-0.988* | *-0.991* | *-0.412* | *-0.995* | *-0.741* | *-0.981* | *-0.898* | *-0.769* | *-0.993* | *-0.835* |
| $\bar{R}^2$ | *0.980* | *0.942* | *0.976* | *0.980* | *-0.107* | *0.989* | *0.399* | *0.954* | *0.793* | *0.562* | *0.972* | *0.596* |
| | | | | | | *Circular functions* | | | | | | |
| $x_c$ | *0.738* | *0.762* | *0.713* | *0.733* | *0.743* | *0.681* | *0.726* | *0.721* | *0.712* | *0.713* | *0.707* | *0.701* |
| $y_c$ | *1.550* | *1.624* | *1.605* | *1.627* | *1.546* | *1.543* | *1.580* | *1.586* | *1.558* | *1.587* | *1.591* | *1.614* |
| $r$ | *0.023* | *0.040* | *0.027* | *0.026* | *0.019* | *0.022* | *0.016* | *0.022* | *0.026* | *0.026* | *0.008* | *0.016* |
| **SE** | *0.003* | *0.008* | *0.005* | *0.004* | *0.005* | *0.007* | *0.004* | *0.006* | *0.005* | *0.005* | *0.003* | *0.005* |
| **Area (1x10$^3$a.u.)** | *1.64* | *4.94* | *2.28* | *2.16* | *1.18* | *1.53* | *0.78* | *1.51* | *2.10* | *2.16* | *0.22* | *0.84* |

throughout the tree. In addition, Figure 4.12 displays calculated linear functions, depicting the different relationships between the VM and FC; the parameters of these functions can be found in Table 4.11. Of the four species, the UK-grown oak – found in Figure 4.12a – displays the largest amount of variation between the different tree sections. The linear function for the oak stem wood has a strong negative correlation ($R^2$=-0.991), which reduces slightly within its branches ($R^2$=-0.898). This suggests that there is still a sound connection between the branch VM and FC contents, but that the ash is more influential than in the stem wood. As illustrated, this clearly differs when considering the oak root data; the correlation is greatly reduced ($R^2$=-0.412), indicating that the FC content cannnot be directly inferred – with any real confidence – solely from the determined VM content. Furthermore, the oak's slope and intercept data, given in Table 4.11, both decrease in value as the ash content becomes more prominent within the sample.

This is important when considering oak as a potential fuel source, particularly if utilising the whole tree; the data and inferred relationships indicate that fuel homogeneity would be severally hindered by using oak stumps and residues. Although a member of the same genetic family (angiosperms), the increased heterogeneity – evident throughout oak trees – is not apparent for the birch data, shown in Figure 4.12b. Their calculated $R^2$ values demonstrate a reduction in the ash content variation, when compared to the oak, limiting its impact on the VM and FC in the different parts of the tree. This increased homogeneity between tree sections – an important attribute for a fuel and its subsequent use in conversion technologies – is also evident for the UK-grown Sitka spruce.

#### 4.3.3.2. Ultimate & GCV

The ultimate analysis and GCV data – produced as a result of the experimental work – can be found in Table 4.12, depicting the elemental and energy content differences between the four species and their tree sections. These differences have been visualised in Figure 4.13. Of the three tree sections, the carbon (C) content of the roots, on a dry basis, show the largest amount of variation between species. The C content of the oak roots, measured at 45.2%, is the smallest value,

Table 4.12 - **Experimental ultimate and GCV values with standard deviations for the UK-grown oak (OK), birch (BI), Scots pine (SP) and Sitka spruce (SS) samples. Comparison between their stem, root and branch wood**

| Mean Values (mass%) on a dry basis (db) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | n | C | H | N | O[1] | GCV[2] |
| **OK** | Stem | 19 | 47.1 (±0.39) | 6.1 (±0.09) | 0.14 (±0.02) | 46.3 (±0.37) | 18.68 (±0.16) |
| | Root | 5 | 45.2 (±1.14) | 5.8 (±0.18) | 0.34 (±0.07) | 44.9 (±1.21) | 17.93 (±0.45) |
| | Branch | 16 | 47.3 (±0.44) | 6.1 (±0.08) | 0.27 (±0.05) | 44.9 (±0.74) | 18.77 (±0.18) |
| **BI** | Stem | 13 | 46.3 (±0.35) | 6.3 (±0.21) | 0.11 (±0.01) | 47.1 (±0.44) | 18.38 (±0.16) |
| | Root | 8 | 48.7 (±0.79) | 6.3 (±0.08) | 0.27 (±0.05) | 44.2 (±0.91) | 19.42 (±0.37) |
| | Branch | 16 | 47.5 (±1.00) | 6.3 (±0.15) | 0.22 (±0.04) | 45.2 (±1.05) | 18.91 (±0.47) |
| **SP** | Stem | 19 | 47.8 (±0.83) | 6.4 (±0.07) | 0.09 (±0.02) | 45.4 (±0.82) | 19.04 (±0.37) |
| | Root | 5 | 46.9 (±0.55) | 6.2 (±0.06) | 0.17 (±0.02) | 45.4 (±0.57) | 18.61 (±0.23) |
| | Branch | 3 | 47.9 (±0.28) | 6.4 (±0.06) | 0.13 (±0.02) | 45.1 (±0.24) | 19.06 (±0.13) |
| **SS** | Stem | 31 | 47.2 (±0.75) | 6.4 (±0.07) | 0.08 (±0.03) | 46.1 (±0.80) | 18.75 (±0.33) |
| | Root | 7 | 47.5 (±0.53) | 6.3 (±0.06) | 0.14 (±0.02) | 45.7 (±0.58) | 18.89 (±0.23) |
| | Branch | 5 | 48.1 (±0.54) | 6.5 (±0.07) | 0.17 (±0.03) | 45.0 (±0.83) | 19.18 (±0.26) |

*[1] calculated by difference, [2] MJ/kg (calculated using Eq.4.30)*

while the mean birch root content (48.7%) is the largest. As shown in Figure 4.13b, the oak's hydrogen (H) values are smaller than all other species, evident throughout all sections of the tree; these have been calculated as 6.1%, 5.8% and 6.1% for the stem, root and branch, respectively. The largest H content can be found in the Sitka spruce branches, measuring at 6.5%, while for all four species the H content is larger in the branches than in their root wood. Previous research has suggested an association with the hydrogen and carbon contents of biomass – a result of the hydrocarbons and carbohydrates that exist within plant tissues [9]. The data illustrated in Figure 4.13 is in support of this; the carbon and hydrogen contents of the species and their tree sections – except the birch root wood – mirror one another, suggesting that a decrease in carbon often correlates with reduced hydrogen content. The birch anomaly might be a result of larger bark ratios existing in the roots, a feature potentially specific to the species.

Although it's the fourth most frequent element in wood, the nitrogen (N) content is usually small, most often ranging between 0.1-1% of the total content [19, 72]. Figure 4.13c highlights the difference in N content that exists between species and the different tree sections. The stem wood displays the lowest species-based difference, ranging from 0.08-0.14%, with the oak and birch samples containing larger contents than the softwoods. Considering the three analysed tree sections

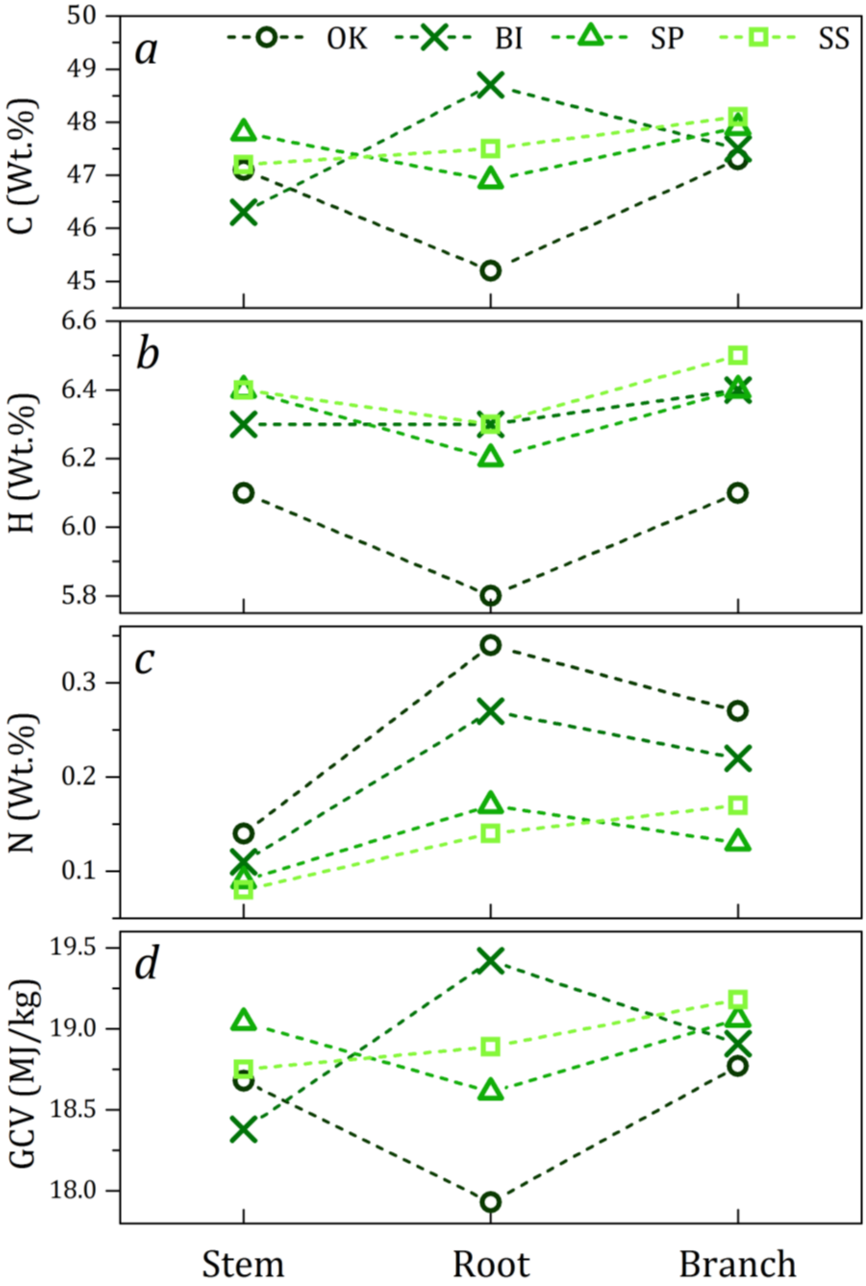


Figure 4.13 – **Calculated experimental mean values of a) Carbon, b) Hydrogen, c) Nitrogen, and d) Gross Calorific Values (db). Comparison between oak, birch, Scots pine and Sitka spruce species, including their stem, root and branch data**

within this research, oak has the largest N contents throughout; their root and branch wood contains 0.34% and 0.27%, respectively. As shown in Figure 4.13c, the hardwood species have a higher N content in their roots than in their branches; an attribute that is not apparent for both softwood species. The largest N content observed for Sitka spruce was in their branches, determined as 0.17%, while the Scots pine root wood contained its highest N contents (also 0.17%). Nitrogen is an essential macronutrient, with its increased access stimulating improved productivity and growth of the tree [73]. As discussed in Chapter 3, although N is an important component for the successful establishment of a tree, it can often accumulate in the wood tissue during its formation. These results indicate that a tree's growth focus may differ between species – outside the constraints of genetic families – with the Sitka spruce favouring growth within its canopy, while the remaining three species focus on their roots.

When considering the potential of different biomass feedstocks as prospective fuels, a key factor is their energy content. Figure 4.13d – and the data in Table 4.12 – show the differences in GCV between the samples. On a dry basis (db), Scots pine has the largest energy content compared to the other stem wood samples, calculated as 19.04 MJ/kg, while the birch has the smallest (18.38 MJ/kg). Unlike the stem wood samples, the birch roots have the largest energy content between all the species and tree sections, given as 19.42 MJ/kg. Finally, at 17.93 MJ/kg, the oak roots have the smallest calculated GCV. The increased energy content, displayed by the birch roots, may be a result of a larger content of phenolics and other secondary compounds. Indeed, plants grown in nitrogen-

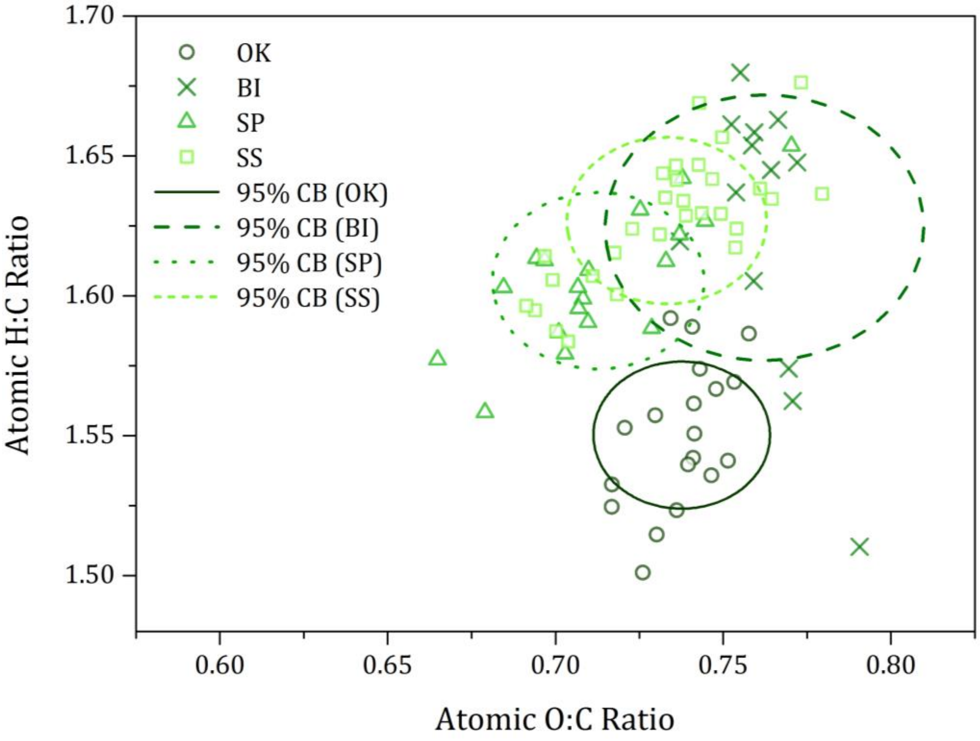


Figure 4.14 – **Van Krevelen diagram of UK grown oak, birch, Scots pine and Sitka spruce stem wood; experimental data and calculated circular functions, based on 95% confidence bands**

deficient soil will assign any additional carbon to the production of secondary compounds – aiding the tree's defence – rather than focussing on its growth; a feature demonstrated previously in birch species [74].

Figure 4.14 plots the O:C and H:C values for the stem wood of the four species considered within this chapter, calculated from the completed experimental work. In addition to the raw data, Figure 4.14 also shows the calculated circular functions, which show the dispersion of the samples from their calculated mean values; the parameters for these can be found in Table 4.11. Considering the circular functions of the softwood species, their location and area values – calculated as 2.28 and 2.16 ($1 \times 10^3$a.u.) – suggest a considerable level of homogeneity between the Scots pine and Sitka spruce stem wood. Figure 4.14 shows a visible difference between the hardwood species, supported by the parameters of their calculated circular functions. The oak stem wood results are the most tightly clustered of the four species, with an area of 1.64 ($1 \times 10^3$a.u.), while the birch values are the most dispersed; shown by a calculated area value of 4.94 ($1 \times 10^3$a.u.), more than three times the size of the oaks.

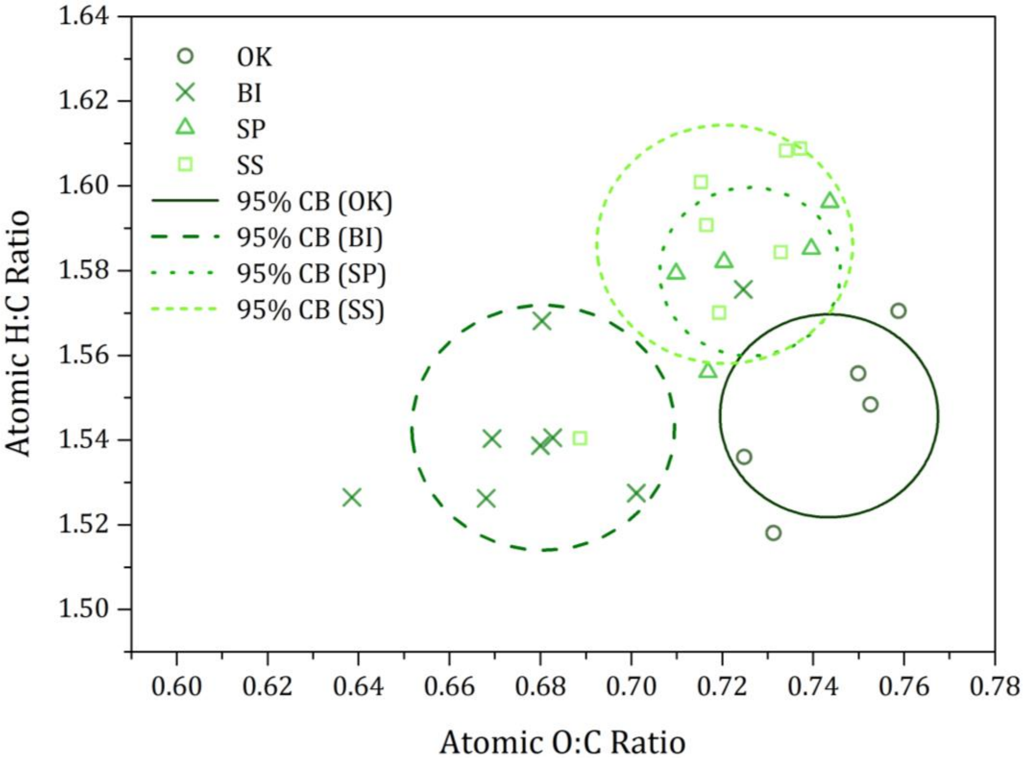


Figure 4.15 – **Van Krevelen diagram of UK grown oak, birch, Scots pine and Sitka spruce root wood; experimental data and calculated circular functions, based on 95% confidence bands**

Figure 4.15 plots the O:C and H:C values for the root wood of the oak, birch, Scots pine and Sitka spruce samples, calculated from the completed experimental work. Again, the circular function data can be found in Table 4.11. The experimental results and subsequent circular functions show that the Scots pine roots are grouped together the closest, with a calculated area of 0.78 (1x10$^3$a.u.). Although the mean O:C and H:C values for the Sitka spruce are similar to that of the Scot's pine, the calculated area is nearly twice its size. This suggests that the spruce roots have a greater variation than those of the pine. Again, the birch has the largest spread of values, however this is not to the same extent as its stem wood samples, found in Figure 4.14. Feedstocks with smaller O:C and H:C ratios, thus featuring towards the lower left hand side of a Van Krevelen diagram, are considered to have a greater suitability as a fuel. The centre point values for the birch root circular function ($x_c$=0.681, $y_c$=1.543) – dictated by the mean O:C and H:C values, respectively – are smaller than the root values for any of the other species, as shown in Table 4.11.

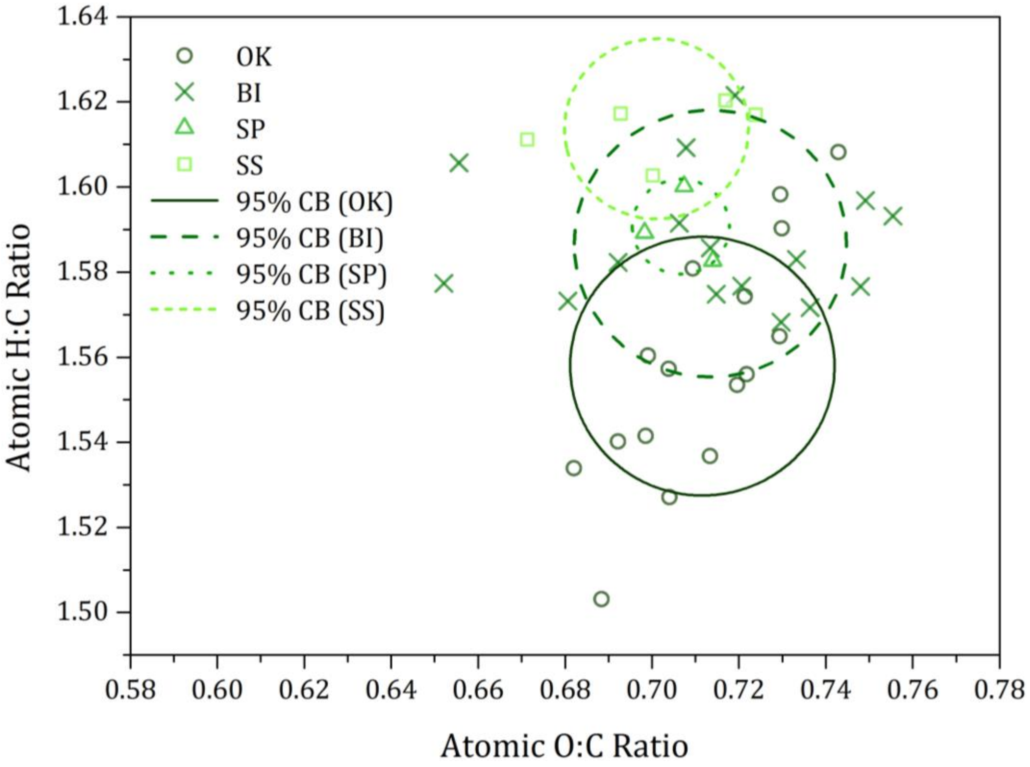


Figure 4.16 – **Van Krevelen diagram of UK grown oak, birch, Scots pine and Sitka spruce branch wood; experimental data and calculated circular functions, based on 95% confidence bands**

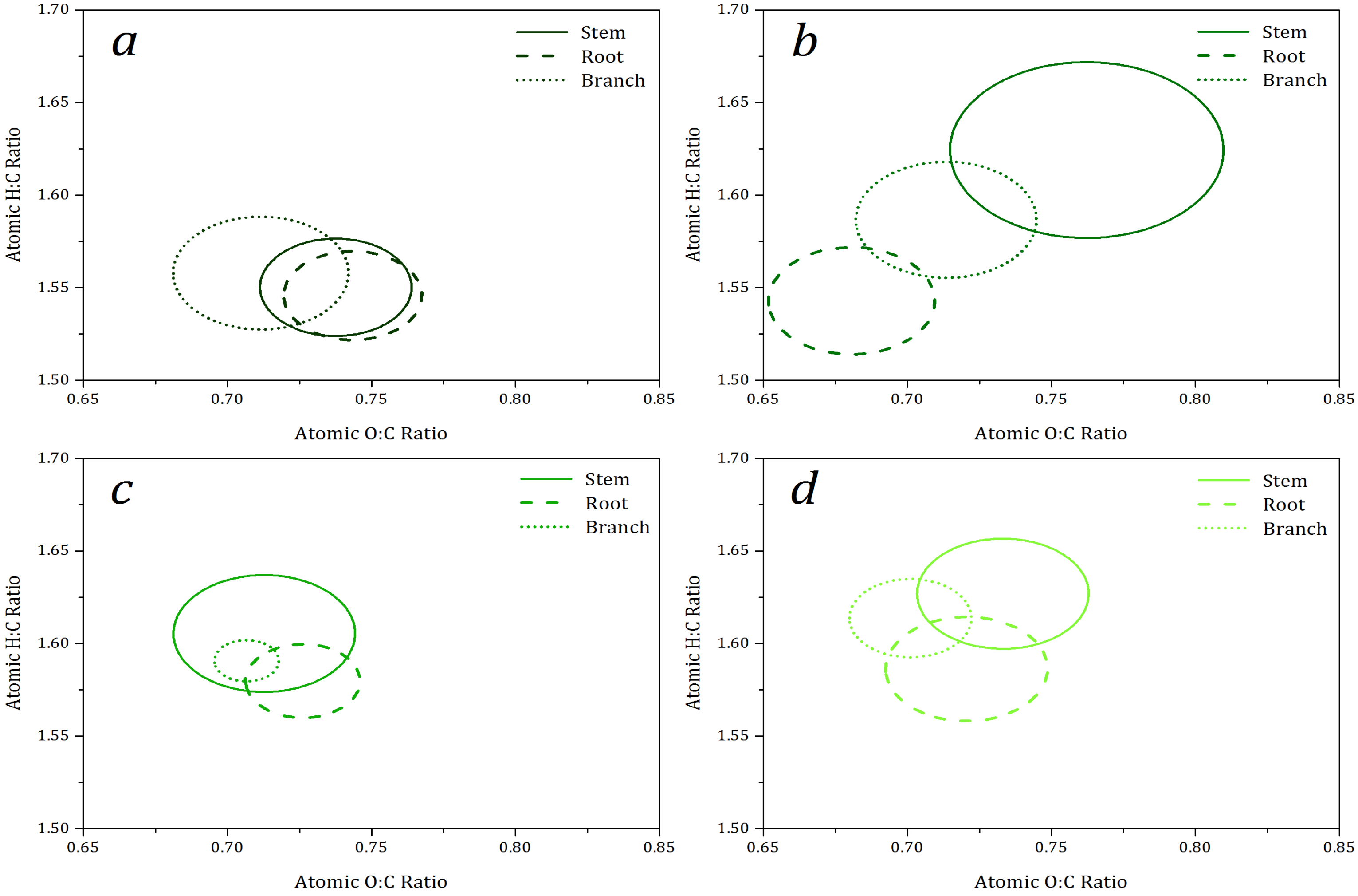


Figure 4.17 – **Circular functions for O:C and H:C ratios, comparing tree sections and species; a) oak, b) birch, c) Scots pine, and c) Sitka spruce**

The calculated O:C and H:C ratios for the experimental branch data can be found in Figure 4.16, with the subsequent circular parameters located in Table 4.11. As illustrated by Figure 4.16, there is very little difference in the calculated $x_c$ values for the four species, however this is not the case for their $y_c$ values; the oak branch samples have the smallest mean H:C ratio ($y_c$=1.558), while the Sitka spruce have the largest ($y_c$=1.614). The positioning of the birch and Scots pine circular functions are similar, however the clustering of the data points differ greatly. Although there are only three Scots pine data points, these are all close to one another resulting in a calculated area of 0.22 (1x$10^3$a.u.). The birch branch samples are more widely spread, resulting in an area of 2.16 (1x$10^3$a.u.) which is nearly an entire order of magnitude larger than that of the Scots pine.

The Van Krevelen diagrams in Figure 4.17 contain the calculated circular functions, depicting the relationships between the stem, root and branch data for each individual species. The location of the root and branch functions, for both the oak and the Scots pine samples – depicted in Figures 4.17a and 4.17c, respectively – indicate very little difference in the clustering when compared to the stem wood. However, as shown in Figures 4.17b and 4.17d, the location of the branch and root wood samples for the birch and Sitka spruce is closer to the bottom left of the Van Krevelen diagram. This suggests they could, potentially, have an increased suitability for use as fuel.

#### 4.3.3.3. Lignocellulosic Analysis

The final set of experimental analysis contained within this chapter relates to the lignocellulosic content of the wood samples, with their calculated mean results and standard deviations found in Table 4.13. In addition, Figure 4.18 shows the lignocellulosic contents on an extractive free (EF) and dry basis, highlighting the differences between the individual cellulose, hemicellulose and lignin contents.

As shown by the data in Table 4.13, the most sizeable cellulose content for all four species is found in the stem wood, with both their branches and roots containing less. Of the species considered in this research, the Scots pine samples showed the smallest amount of variation in their results, evidenced by the calculated standard deviations, while the largest variation in cellulose content is found in the Sitka spruce roots, which have a calculated relative error of 14.7%. When considering the hemicellulose within the wood samples, the birch stems have the largest content – measured at 23.8% – while the Scots pine roots have the smallest (11.5%). This concurs with existing published research, in that hardwood species are typified by larger hemicellulose concentrations [2, 75]. Instead of the increased polysaccharide contents attributed to hardwoods, the softwood stems contain a greater concentration of lignin; the Sitka spruce and Scots pine samples have mean lignin values of 26.8% and 28.1%, respectively, while for the oak and birch they are 24.7% and 20.1%. These lignin contents fall comfortably within an accepted range of 18-38% for wood [36, 76], giving validity to the results and the utilised methods. Of the four species, in respect of the different tree sections, the birch stem wood contains the smallest lignin contents, while the Scots pine branches have the largest (32.9%).

The mean extractive results in Table 4.13 – which have been calculated by difference – highlight that both of the hardwood species have small extractive contents within their wood, when compared to their remaining structural components. Furthermore, the extractive content of the birch and oak show very little difference in their distribution within the tree. This is, however, not the case for the softwood species; the extractive contents of both the Sitka spruce and

Table 4.13 – **Experimental lignocellulosic values with standard deviations for the UK-grown oak (OK), birch (BI), Scots pine (SP) and Sitka spruce (SS) samples. Comparison between their stem, root and branch wood**

| | | **Mean Values (mass% db)** | | | | |
|---|---|---|---|---|---|---|
| | | N | Lignin | Cellulose | Hemicellulose | Extractives[1] |
| **OK** | Stem | 19 | 24.7 (±1.41) | 50.8 (±1.56) | 20.3 (±0.84) | 3.9 (±1.88) |
| | Root | 5 | 26.8 (±2.65) | 47.6 (±2.47) | 18.3 (±0.86) | 3.7 (±3.71) |
| | Branch | 16 | 29.6 (±2.01) | 46.5 (±3.14) | 17.9 (±1.55) | 4.5 (±2.49) |
| **BI** | Stem | 13 | 20.1 (±0.94) | 54.0 (±1.42) | 23.8 (±0.64) | 2.0 (±1.11) |
| | Root | 8 | 30.6 (±3.99) | 46.9 (±3.38) | 18.9 (±2.51) | 3.0 (±1.80) |
| | Branch | 16 | 26.0 (±2.64) | 49.7 (±2.21) | 21.4 (±1.22) | 2.1 (±1.49) |
| **SP** | Stem | 19 | 28.1 (±2.14) | 50.6 (±1.69) | 14.6 (±0.82) | 6.4 (±1.02) |
| | Root | 5 | 29.4 (±0.95) | 49.8 (±1.07) | 11.5 (±1.04) | 8.0 (±1.43) |
| | Branch | 3 | 32.9 (±0.32) | 45.2 (±0.93) | 13.6 (±1.21) | 7.8 (±0.64) |
| **SS** | Stem | 29 | 26.8 (±2.13) | 53.2 (±2.73) | 14.3 (±1.72) | 5.4 (±2.33) |
| | Root | 7 | 30.2 (±2.98) | 46.6 (±6.87) | 13.2 (±1.27) | 9.7 (±4.54) |
| | Branch | 5 | 31.8 (±0.84) | 42.0 (±1.09) | 13.6 (±0.95) | 12.3 (±1.69) |

*[1] Calculated by difference*

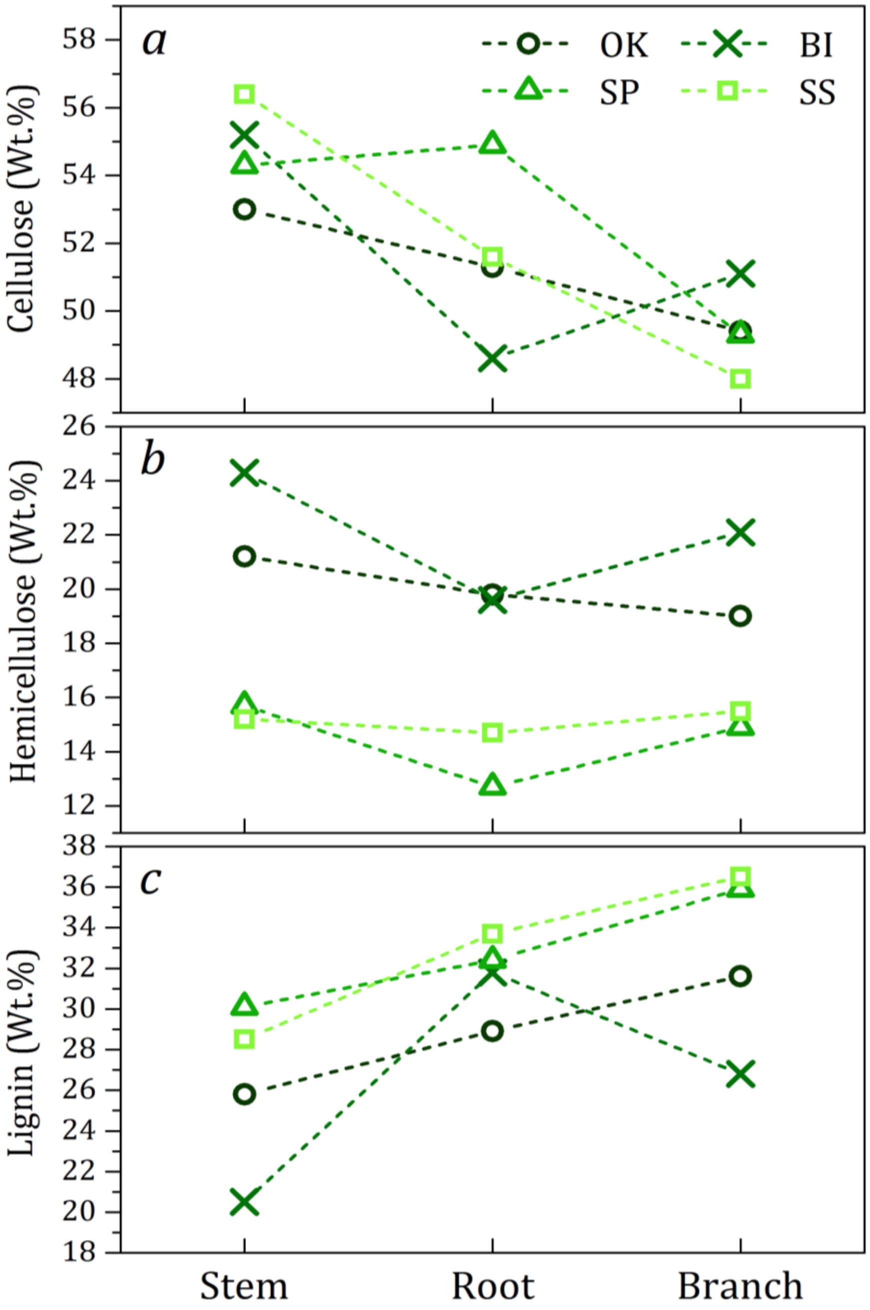


Figure 4.18 – **Calculated experimental mean values of a) Cellulose, b) Hemicellulose, and c) Lignin on an extractive free (EF) basis. Comparison between oak, birch, Scots pine and Sitka spruce species, including their stem, root and branch data**

Scots pine stem wood is larger than that of the hardwoods, with further increases to their concentration evident within the branch and root wood. Of these, the variation in extractive content – existing throughout the tree – is greatest for the analysed Sitka spruce. Its root and branch extractives, determined as 9.7% and 12.3%, respectively, represent a clear increase on those found within the stem wood (5.4%). Although influenced by an array of external factors, the extractive content – representing a diverse group, discussed in detail in Section 3.2.1.5 – is greater in the bark than the wood [76, 77]. This indicates that the roots and branch wood of Scots pine and Sitka spruce may have a larger bark content, although increased stocking density – a common feature of softwood plantations – can also result in greater quantities of extractives [77].

Figure 4.18 shows the cellulose, hemicellulose and lignin contents – calculated on an extractive free basis (EF) – demonstrating the differences between the structural components of the wood samples. A comparison of the hemicellulose contents, given in Figure 4.18b, shows there are visible differences between the hardwood and softwood species; the birch and oak samples have an increased content of hemicellulose throughout the tree which, as discussed above, is in accordance with the literature. For the two hardwood species, the hemicellulose content of their roots are very similar, however there are visible differences in the stem and branch wood, with birch containing a larger content than oak. Alternatively, the hemicellulose contents of the Sitka spruce and Scots pine stem and branch wood are similar, while a difference exists between their roots. For all four species, the lignin content of their branch and root wood is higher than that of their stem wood. Wood production is a complex set of processes, with the programmed cell death – and consequent lignification – representing the end product of plant growth [29, 36, 76-78]. As both the roots and branches, which form a key component of a tree's canopy, are inherently connected with the growth process, the increased lignin contents found within these sections are unsurprising.

In general there is a relationship between the lignin and cellulose contents of the oak, birch and Sitka spruce, as shown in Figure 4.18; an increase in lignin content result in a decreased cellulose content. However, this is not the case for the Scots pine – when considering its root wood, both the lignin and cellulose content increase, while it's hemicellulose decreases. Unlike the heterogeneous mix of carbohydrates that characterise hemicellulose, cellulose is instead a well-defined polysaccharide [76, 78]. This would therefore suggest that the structural components of Scots pine root wood may actually be more homogeneous than those found within the rest of the tree. Finally, the smallest lignin concentrations exist within the stem of the tree – evident for all four of the analysed species. The oak, Scots pine and Sitka spruce all display an increased lignin content within their roots, which increases again in their branches. Although the birch roots and branches both contain more lignin than its stem wood, it is their roots which contain the largest concentrations of lignin within the tree, indicating that this is where its growth is focused. Indeed, the success of birch as a pioneer species – one that can naturally regenerate on poor quality sites – may be directly linked to its preference for root growth [79].

#### 4.3.3.4. ANOVA Results

In addition to the determined experimental values given throughout this section, analysis of variance (ANOVA) and Tukey's HSD post-hoc analysis has been completed on the data, establishing the variation evident between species and their different tree sections. The resulting data matrices – detailing the post-hoc analysis between tree species and tree sections, in their entirety – represent a large volume of data, located in Appendix C. However, a concentrated version – cataloguing some of the important statistically significant differences, contained within the data – is in Table 4.14. Again, it's important to note that this is based on a relatively small sample set, when compared to the total forest resource.

Table 4.14 – **A selection of the calculated statistically significant differences between tree species and their different tree sections, applied to the produced experimental data (adapted from Appendix C)**

| | **Statistically Significant Differences (≠)** | |
|---|---|---|
| | **Between Sections** | **Between Species** |
| **Proximate** | **OK**(*VM*:R≠S,B; *Ash*:R≠S≠B), **BI**(*FC*:R≠S≠B), **SP**(*FC*:S≠R,B; *Ash*:S≠R), **SS**(*FC*:S≠R,B) | **VM**(*R*:OK≠BI,SS, *B*:BI≠SP,SS), **FC**(*S*:OK≠BI,SP,SS), **Ash**(*R*:OK≠BI,SP,SS) |
| **Ultimate & GCV** | **OK**(*N*:R≠S≠B), **BI**(*N,HC,OC,GCV*:R≠S≠B), **SP**(*N*:S≠R), **SS**(*N*:S≠R,B) | **N**(*R,B*:OK≠BI,SP,SS; *R*:BI≠SP,SS), **HC**(*S*:OK≠BI,SP,SS), **OC**(*S,R*:BI≠OK,SP,SS), **GCV**(*S*:BI≠SP,SS; *R*:BI≠OK,SP,SS) |
| **Lignocellulosic** | **OK**(*Ce,He,Li*:S≠B), **BI**(*He,Li*:S≠R≠B), **SP**(*He*:S≠R; *Li*:S≠B), **SS**(*Ce,Li*:S≠R,B) | **Ce**(*S*:OK≠BI; *B*:OK≠BI,SS), **He**(*S*:BI≠OK,SP,SS; *R*:OK,BI≠SP,SS; *B*:BI≠OK,SP,SS), **Li**(*S,B*:BI≠OK,SP,SS) |

*OK=oak, BI=birch, SP=Scots pine, SS=Sitka spruce, S=stem, R=root, B=branch, VM=volatile matter, FC=fixed carbon, N=nitrogen, HC=atomic H:C ratio, OC=atomic O:C ratio, GCV=gross calorific value, Ce=cellulose, He=hemicellulose, Li=lignin*

As shown in the post-hoc data found in Table C.2 – summarised in Table 4.14 – the increased number of statistically significant differences, evident between the experimentally-determined characteristic values of the stem, root and branch wood, are most prevalent in hardwood species. This is particularly noticeably for the analysed birch wood; the calculated VM, FC, nitrogen, gross calorific values (GCV), hemicellulose, lignin and the H:C and O:C ratio data for the birch stem, root and branch wood are all statistically significantly different from one another. The number of statistically significant differences for oak is not as pronounced as the birch, however both its nitrogen and ash contents differ significantly throughout the different sections of the tree. Considering the importance of nitrogen and ash as fuel characteristics, in particular their propensity to cause issues during the combustion process [13, 69], a lack of homogeneity between the stem, root and branch wood of oak – which has been shown to be significantly different – could severely limit the use of the entire tree as a fuel. In comparison, both softwood species display increased heterogeneity when considering the analysed fuel characteristics, particularly between their branch and root wood. Observable in both the Scots pine and Sitka spruce data; there are no calculated statistically significant differences between their branch and root wood, for any of the 10 classified characteristics. This indicates that the combined use of their residues, stump and root wood would culminate in a potentially homogenous fuel.

Table C.3 contains the results of the completed Tukey's HSD post-hoc analysis, displaying the statistically significant differences between the four species. Again, a range of these relationships have been condensed into Table 4.14. Similarly to the different tree sections, understanding the parallels that exist between-species is also important; this can help establish the potential for combining two, or more, different wood types together as a fuel source. As discussed previously in this chapter – and extensively in Chapter 3 – biomass contains a number of potentially inhibitory inorganic constituents, which can cause problems during thermal conversion processes [9, 69]. These are mostly concentrated in the ash, produced following their combustion, therefore an appreciation of the ash content – and how this differs between species – is important. The debarked stem wood of the four species have minimal ash contents, with their mean values ranging between 0.20-0.34%. The completed statistical analysis indicates that there is no significant difference between any combination of species, suggesting that – in terms of their ash content – using any mixture of oak, birch, Scots pine and Sitka spruce wood would not be prohibitive. In addition, there are no significant differences between the mean FC contents – or the carbon-rich lignin – contained within the roots of the four tree species. This is a notable result, not only when considering the use of the stumps and roots as a fuel, but also when defining how their removal may impact the volume of carbon sequestered within a forested site. There is an acceptance that the contents of both the lignin and carbon contained within hardwood and softwood species differs, with the latter's stem wood considered an increased sink for carbon [36, 46, 80]. Indeed, the experimental results – and consequent statistical analysis – completed in this chapter are in agreement with the literature, establishing statistically significant differences between the stems of the hardwood and softwood species. This therefore gives validity to the stated root results which, if correct, could prove important in improving the accuracy of carbon accounting for below-ground biomass, located within forests.

## 4.4. Discussion

The world's forests epitomise diversity; they are filled with an assortment of visually-distinct tree species, located across a range of biomes, representing different social, environmental and economic benefits to those that utilise them. Maintaining diversity is important, however this can only be achieved by first establishing a detailed understanding of what makes forests – and the wood contained within them – different. This has been the central focus of Chapter 4, utilising the vast array of available resources – in combination with extensive lab-based characterisation work – to better appreciate our forest feedstocks.

Extracting and reviewing previously published wood characterisation data allows for the creation of a base set of results, forming an initial point of comparison for the completed experimental work. This has the additional benefit of giving an insight into the current global wood resource, as reported by the scientific community. The results contained in Section 4.3.1 are in consensus with those previously published, establishing the differences – existing between the fundamental chemical and elemental characteristics of hardwood and softwood species – while highlighting the known heterogeneity of the world's wood resource. Of the two main genetically-defined tree categories, softwoods are more homogenous than hardwoods, a feature relating predominantly to their cellular constituents. This is a widely accepted characteristic of softwoods; one which has been further enhanced through the cultivation of seedlings in nurseries, resulting in the expansion of single-species forest stands that are even-aged and uniform in appearance [29, 35]. The collection and subsequent statistical analysis of data, obtained from published literature, has demonstrated increased homogeneity between softwood species. This specifically concerns differences in energy content, atomic O:C ratio and the volume of lignin contained within the stem wood. Although these differences are previously well documented, the creation of tangible values – based on extensive sources of referenceable data – are invaluable, allowing for the direct comparison and validation of the experimental work with the literature.

Further to the in-depth analysis of the literature-sourced data, this research has also produced a substantial dataset (located in Appendix B), detailing important characterisation values that are specific to UK-grown wood species. Again, the statistical analysis results – completed using the experimental data – support the assertion of increased homogeneity in softwoods, specific to UK-grown species. Evidenced by their larger standard deviations, relative standard deviations (RSD) and interquartile ranges, the increased heterogeneity of UK-grown hardwoods is apparent for all the variables, except the calculated nitrogen contents and GCV's of their stem wood tissue. The relationship similarities between softwoods and hardwoods, evident for both the experimental and literature-based data, gives credence to both the stated results and the employed analytical procedures.

Although the experimental work – based entirely on UK-grown wood samples – displays the same characteristics as those established in the literature, there are also important differences which should not be ignored. The literature data utilised published results, collated from a variety of different wood species sourced from countries around the world. In comparison, the experimental results were produced from a total of four species – consisting of two hardwoods and two softwoods – which were all grown within the UK. Therefore, the range of results is understandably greater for the literature-sourced data, representing a considerably larger genetic pool of species and differing examples of growth conditions and analytical methods. The distinctions between the literature and experimental data are best illustrated using box plots; these allow for the clear comparison of the data's variation, incorporating the known hardwood and softwood features. As a result, all the experimental data – found in Section 4.3.4 – is contained within the outliers of the literature box plots and, more often than not, within their whiskers. These represent the upper and lower quartiles of the data, highlighting that although the experimental values clearly differ, it still falls within the spread of the literature results. This is important, indicating that the variation between the experimental and literature data is likely a result of differences in the actual characteristics of the samples, instead of the characterisation methods used. The confidence in the experimental methods, utilised within this chapter, are further strengthened by their discernible replicability, evidenced by the small RSD values.

Though the range of values contained within the literature are explainable, the reduced prominence placed on the process of feedstock characterisation should not be ignored. The wood characteristic data sourced from the literature often signified just a small part of the published research, which instead focused principally on additional processing such as torrefaction, pyrolysis or biofuel production [39-43, 51-57]. As recognised by the substantial amount of work conducted in this chapter, the characterisation of biomass feedstocks can be a laborious and painstaking process; this is a result of the countless hours required to prepare samples and complete the experimental processes, which can often require additional re-runs. Applying a thorough and considerate approach to characterisation helps ensure confidence in the produced results, however this is undoubtedly time consuming; it would therefore be unsurprising if this does not always receive the care and attention it should. When there are outliers, which appear to either severely under- or overestimate the calculated data – when compared to the other published values – the legitimacy and, perhaps more importantly, the quality of their results should be challenged.

During the last decade, the importance of wood as a fuel has continued to increase – not just within the UK, but on a global scale. Consequently, the statistically significant differences of the energy contents, calculated between hardwoods and softwoods, is an important consideration. The completed analysis illustrates, both visually and statistically, that softwood species have a significantly increased energy content when compared to hardwoods. As asserted previously in this chapter, when considering the real world application of wood as a fuel, the net calorific value (on a wet basis) is a more important figure [24]. However, the moisture content of wood is dictated by a large array of variables – such as felling date, site conditions and its storage – therefore the use of calculated GCV figures, on a dry basis, allows for their comparison at a fundamental level. This is important when considering the potential upgrading of wood feedstocks for use in energy generation; understanding the fundamental energy limitations of a feedstock is a necessity, helping to ensure the viability of a process – such as pelleting or pyrolysis – and its final product. Another key difference between hardwoods and softwoods – linking directly to their energy content – is found within their structural components; the softwoods display a statistically significant increase in lignin, when compared to hardwoods. As outlined in the previous chapter, lignin is a complex phenolic polymer which, as a result of its embodied aromatic monomers, has a larger energy content than carbohydrates [36]. The increased lignin content of softwoods, evidenced in the literature and experimental data, can help explain their statistically significantly larger calorific values.

This chapter has identified clear variations that exist between the two most simply defined taxonomical categories of trees; angiosperms (hardwoods) and gymnosperms (softwoods). However, the completed experimental analysis of 145 wood samples – representing four different UK-grown species, sourced from three separate tree sections – goes even further, helping to highlight the species-specific differences that exist between the determined characteristics. Although the distinction between species is observable – especially for attributes such as nitrogen content or the wood's structural components – the influence of the tree section is important when considering the deviations in wood characteristics. This is apparent when considering the calculated proximate data, particularly the FC and ash contents of the different tree sections. Indeed, the ash content of the debarked stem wood is similar for all four species, suggesting that the concentration of inorganic constituents is limited within the stem's wood, no matter the species. However, when examining the ash content of the branch and root samples this variation increases considerably. The inorganic constituents found within wood are important for plant growth, consisting predominantly of minerals and minor elements. As a result, the increased ash content could be attributed to two factors; 1) an increased volume of bark associated with the roots and branches, and 2) localised soil conditions, influencing the volume of minerals and macronutrients that are passively absorbed by roots [9, 76]. Of the four species, it appears that oak is the most susceptible to accumulating the constituents associated with ash content, within its roots and branches, while Sitka spruce is the least. Interestingly, the statistical analysis of the stump wood's FC contents – which are derived, utilising the other proximate values – show no significant difference between the four species. This is not the case for the other tree sections, indicating that although there is above- and below-ground variation apparent for certain fuel characteristics, the accumulation of fixed carbon in the roots does not appear to be dictated by species.

Of the main elemental constituents that exist within biomass, the carbon (C), hydrogen (H) and oxygen (O) are of great importance when considering the end-use of the potential fuel. Indeed, the lower the calculated ratios of atomic O:C and H:C, the greater the fuel's suitability [34]. Assessing this suitability within this chapter – specific to the array of species and tree sections – has identified statistically significant differences between the individual wood sources. Of these, the most important – in relation to their fuel potential – concern the birch and Sitka spruce. The results, evident for both species, indicate that their root and branch wood have greater energy contents and are more suitable for use as a fuel, than their stem wood. Consequently, the combination of stem wood with the remaining brash, harvesting residues and stump wood – applicable to either the birch or Sitka spruce – could decrease their atomic O:C and H:C ratios, while increasing the volume of biomass available for use. Indeed, blending different biomass resources can be used to improve fuel quality, particularly the ash composition [81]. As both the birch and Sitka spruce samples have low calculated ash contents throughout the tree – especially when compared to other biomass species –the potential issues attributed to inorganic content should be partially negated.

## 4.5. Conclusions

The principle aim of this chapter was to help improve the understanding of the existing wood resource, not just in quantifying the UK's forest feedstocks, but also by establishing how these compare to global sources. From the physical and visual attributes of a tree, through to the composition of its produced wood, the variation that exists between species is often easy to evidence. This heterogeneous nature of wood is widely accepted, however quantifying these differences – defining comprehensive species-specific values – has, to date, been previously overlooked. This relies upon the creation of dependable experimental data, such as that produced in this chapter; the results – and their associated raw data, published in Appendix B – represent hundreds of hours of meticulous sample preparation and experimental lab work. Considering the size of the dataset and the evident replicable nature of the utilised experimental methodologies, the data produced as part of this chapter could represent the start of a major library of wood characterisation data, specific to UK-grown species. The governments' desire to increase the UK's forest cover could indeed make these results invaluable. It is however important that the processes used for biomass characterisation – particularly those employed in larger research projects – should receive greater care and attention. Neglecting these fundamental procedures will only serve to reduce the confidence in stated results, produced from technologies utilising biomass; indeed, when you put rubbish in, you get rubbish out.

Woodlands and forests have dominated our global landscape for thousands of years yet, even today, there is still a great deal to learn about the heterogeneity of wood and its suitability for a variety of uses. The analysis of the different wood samples has identified the potential of two prominent UK-grown species – birch and Sitka spruce – for further investigation into their use in energy generation. Focusing on combustion, Chapter 5 will consider the two species – and their different tree sections – in greater detail, establishing their suitability for use as a fuel while defining any potential differences or relationships that may exist.

## 4.6. References

[1]. Keenan R. J., Reams G. A., Achard F., de Freitas J. V., Grainger A. and Lindquist E. 2015. Dynamics of global forest area: results from the FAO Global Forest Resource Assessment 2015. *Forest Ecology and Management*, 352, pp9-20

[2]. Spellman F. R. 2011. *Forest-based biomass energy – concepts and applications*. CRC Press, Taylor & Francis Group

[3]. Ho R. 2013. *Handbook of univariate and multivariate data analysis with IBM SPSS*. 2nd Edition. Chapman and Hall, CRC Press

[4]. Watier N., Lamontagne C. and Chartier S. 2014. Chapter 1. Descriptive statistics. In: Guisasola J. ed. *Probability and statistics. A didactic introduction*. CRC Press, Taylor & Francis Group, pp1-37

[5]. Griffiths M. 2014. Chapter 6. Tests of hypotheses. In: Guisasola J. ed. *Probability and statistics. A didactic introduction*. CRC Press, Taylor & Francis Group, pp252-292

[6]. Trumpower D. L. and Atas S. 2014. Chapter 7. Analysis of variance. In: Guisasola J. ed. *Probability and statistics. A didactic introduction*. CRC Press, Taylor & Francis Group, pp293-329

[7]. Khuri A. I. 2009. *Linear Model Methodology*. Chapman and Hall, CRC Press

[8]. Chernov N. 2010. *Circular and linear regression. Fitting circles and lines by least squares*. CRC Press, Taylor & Francis Group

[9]. Vassilev S. V., Baxter D., Anderson L. K. and Vassileva C. G. 2010. An overview of the chemical composition of biomass. *Fuel*, 89, pp913-933

[10]. C. E. N. Standard. 2011. *Solid biofuels – Sample preparation*. BS EN 14780:2011. BSI

[11]. Rémond R., Passard J. and Perré P. 2007. The effect of temperature and moisture content on the mechanical behaviour of wood: a comprehensive model applied to drying and bending. *European Journal of Mechanics A/Solids*, 26, pp558-572

[12]. C. E. N. Standard. 2009. *Solid biofuels – Determination of moisture content – Oven dry method – Part 3: Moisture in general analysis sample*. BS EN 14774-3:2009. BSI

[13]. Demirbas A. 2004. Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science*, 30, pp219-230

[14]. C. E. N. Standard. 2009. *Solid biofuels – Determination of the content of volatile matter*. BS EN 15148:2009. BSI

[15]. C. E. N. Standard. 2009. *Solid biofuels – Determination of ash content*. BS EN 14775:2009. BSI

[16]. Coats A. W. and Redfern J. P. 1963. Thermogravimetric analysis. A review. *Analyst*, 88, pp906-924

[17]. GarcÍa R., Pizarro C., LavÍn A. G. and Bueno J. L. 2013. Biomass proximate analysis using thermogravimetry. *Bioresource Technology*, 139, pp1-4

[18]. Gusiatin Z. M. and Pawlowski A. 2016. Biomass for fuels – classification and composition. In: Bulkowska K. ed. *Biomass for Biofuels*. CRC Press, Taylor & Francis Group, pp15-36

[19]. Jenkins B. M., Baxter L. L., Miles Jr T. R. and Miles T. R. 1998. Combustion properties of biomass. *Fuel Processing Technology*, 54, pp17-46

[20]. C.E.N. Standard. 2011. *Solid biofuels – Determination of total content of carbon, hydrogen and nitrogen – Instrumental methods*. BS EN 15104:2011. BSI

[21]. Chandrasekaran S. R., Hopke P. K., Rector L., Allen G. and Lin L. 2012. Chemical composition of wood chips and wood pellets. *Energy & Fuels*, 26, pp4932-4937

[22]. Phillips D., Mitchell E. J. S., Lea-Langton A. R., Parmar K. R., Jones J. M. and Williams A. 2016. The use of conservation biomass feedstocks as potential bioenergy resources in the United Kingdom. *Bioresource Technology*, 212, pp271-279

[23]. Yan X. 2002. Sulfur and nitrogen chemiluminescence detection in gas chromatographic analysis. *Journal of Chromatography A*, 976, pp3-10

[24]. Friedl A., Padouvas E., Rotter H. and Varmuza K. 2005. Prediction of heating values of biomass fuel from elemental composition. *Analytica Chimica Acta*, 544, pp191-198

[25]. Sheng C. and Azevedo J. L. T. 2005. Estimating the higher heating value of biomass fuels from basis analysis data. *Biomass and Bioenergy*, 28, pp499-507

[26]. C.E.N. Standard. 2009. *Solid biofuels – Determination of calorific value*. BS EN 14918:2009. BSI

[27]. Hughes M. K. 1971. Seasonal calorific values from a deciduous woodland in England. *Ecology*, 52(5), pp923-926

[28]. Rhén C. 2004. Chemical composition and gross calorific value of the above-ground biomass component of young *Picea abies*. *Scandinavian Journal of Forest Research*, 19, pp72-81

[29]. Plomion C., Leprovost G. and Stokes A. 2001. Wood formation in trees. *Plant Physiology*, 127(4), pp1513-1523

[30]. Goering H. K. and Van Soest P. J. 1970. *Forage fiber analyses (apparatus, reagents, procedures and some applications).* Agriculture Handbook No. 379, Agricultural Research Service, United States Department of Agriculture, Washington D.C.

[31]. I.S.O. Standard. 2008. *Animal feeding stuffs – Determination of acid detergent fibre (ADF) and acid detergent lignin (ADL) contents*. ISO 13906:2008.

[32]. I.S.O. Standard. 2006. *Animal feeding stuffs – Determination of amylase-treated neutral detergent fibre content (aNDF).* ISO 16372:2006.

[33]. ASTM. Standard. 2013. *Standard test method for acid-insoluble lignin in wood*. ASTM D1106 – 96(2013). ASTM International, PA

[34]. McKendry P. 2002. Energy production from biomass (part 2): conversion technologies. *Bioresource Technology*, 83, pp47-54

[35]. Macdonald E., Gardiner B. and Mason W. 2010. The effects of transformation of even-aged stands to continuous cover forestry on conifer log quality and wood properties in the UK. *Forestry*, 83(1), pp1-16

[36]. Novaes C., Kirst M., Chiang V., Winter-Sederoff H. and Sederoff R. 2010. Lignin and biomass: A negative correlation for wood formation and lignin content in trees. *Plant Physiology*, 154, pp555-561

[37]. Antal Jr. M. J., Allen S. G., Dai X., Shimizu B., Tam M. S. and Grønli M. 2000. Attainment of the theoretical yield of carbon from biomass. *Industrial and Engineering Chemistry Research*, 39(11), pp4024-4031

[38]. Azeez A. M., Meier D., Odermatt J. and Willner T. 2010. Fast pyrolysis of African and European lignocellulosic biomasses using Py-GC/MS and fluidized bed reactor. *Energy Fuels*, 24, pp2078-2085

[39]. Branca C., Di Blasi C., Galgano A. and Broström M. 2014. Effects of the torrefaction conditions on the fixed-bed pyrolysis of Norway spruce. *Energy Fuels*, 28, pp5882-5891

[40]. Chiodo V., Zafarana G., Maisano S., Freni S. and Urbani F. 2016. Pyrolysis of different biomass: direct Comparison among *Posidonia oceanica*, Lacustrine alga and White-pine. *Fuels*, 164, pp220-227

[41]. Choi Y. S., Johnston P. A., Brown R. C., Shanks B. H. and Lee K. 2014. Detailed characterization of Red oak-derived pyrolysis oil: integrated use of GC, HPLC, IC, GPC and Karl-Fischer. *Journal of Analytical and Applied Pyrolysis*, 110, pp147-154

[42]. Dall'Ora M., Jensen P. A. and Jensen A. D. 2008. Suspension combustion of wood: influence of pyrolysis conditions on char yield, morphology, and reactivity. *Energy Fuels*, 22(5), pp2955-2962

[43]. Della Rocca P. A., Cerrella E. G., Bonelli P. R. and Cukierman A. L. 1999. Pyrolysis of Hardwoods Residues: on Kinetics and Chars Characterization. *Biomass and Bioenergy*, 16, pp79-88

[44]. Demirbaş A. 1997. Calculation of higher heating values of biomass fuels. *Fuel*, 76(5), pp431-434

[45]. Demirbaş A. 2001. Relationships between lignin contents and heating values of biomass. *Energy Conversion and Management*, 42, pp183-188

[46]. Demirbaş A. 2003. Fuelwood characteristics of six indigenous wood species from the Eastern Black Sea region. *Energy Sources*, 25, pp309-316

[47]. Evtyugina M., Alves C., Calvo A., Nunes T., Tarelho L., Duarte M., Prozil S. O., Evtuguin D. V. and Pio C. 2014. VOC emissions from residential combustion of Southern and mid-European woods. *Atmospheric Environment*, 83, pp90-98

[48]. Fernandes A. P., Alves C. A., Gonçalves C.,Tarelho L., Pio C., Schimdl C. and Bauer H. 2011. Emission factors from residential combustion appliances burning Portuguese biomass fuels. *Journal of Environmental Monitoring*, 13, pp3196-3206

[49]. Gucho E. M., Shahzad K., Bramer E. A., Akhtar N. A. and Brem G. 2015. Experimental study on dry torrefaction of beech wood and miscanthus. *Energies*, 8, pp3903-3923

[50]. Jiménez L. and González F. 1991. Study of the physical and chemical properties of lignocellulosic residues with a view to the production of fuels. *Fuel*, 70(8), pp947-950

[51]. Liu Z., Zhang F. and Wu J. 2010. Characterization and application of chars produced from pinewood pyrolysis and hydrothermal treatment. *Fuel*, 89, pp510-514

[52]. Liu Z. and Han G. 2015. Production of solid fuel biochar from waste biomass by low temperature pyrolysis. *Fuel*, 158, pp159-165

[53]. Medina C. H., Sattar H., Phylaktou H. N., Andrews G. E. and Gibbs B. M. 2015. Explosion reactivity characterisation of pulverised torrefied spruce wood. *Journal of Loss Prevention in the Process Industries*, 36, pp287-295

[54]. Naik S., Goud V. V., Rout P. K., Jacobson K. and Dalai A. K. 2010. Characterization of Canadian biomass for alternative renewable biofuel. *Renewable Energy*, 35(8), pp1624-1631

[55]. Nanda S., Mohanty P., Pant K. K., Naik S., Kozinski J. A. and Dalai A. K. 2013. Characterization of North American lignocellulosic biomass and biochars in terms of their candidacy for alternative renewable fuels. *BioEnergy Research*, 6(2), pp663-677

[56]. Oasmaa A., Kuoppala E., Gust S. and Solantausta Y. 2003. Fast pyrolysis of forestry residue. 1. Effect of extractives on phase separation of pyrolysis liquids. *Energy Fuels*, 17(1), pp1-12

[57]. Oasmaa A., Solantausta Y., Arpiainen V., Kuoppala E. and Sipilä K. 2010. Fast pyrolysis bio-oils from wood and agricultural residues. *Energy Fuels*, 24, pp1380-1388

[58]. Parikh J., Channiwala S. A. and Ghosal G. K. 2005. A correlation for calculating HHV from proximate analysis of solid fuels. *Fuel*, 84(5), pp487-494

[59]. Rabemanolontsoa H., Ayada S. and Saka S. 2011. Quantitative method applicable for various biomass species to determine their chemical composition. *Biomass and Bioenergy*, 35, pp4630-4635

[60]. Saeed M. A., Andrews G. E., Phylaktou H. N. and Gibbs B. M. 2016. Global kinetics of the rate of volatile release from biomasses in comparison to coal. *Fuel*, 181, pp347-357

[61]. Saldarriaga J. F., Aguado R., Pablos A., Amutio M., Olazar M. and Bilbao J. 2015. Fast characterization of biomass fuels by thermogravimetric analysis (TGA). *Fuel*, 140, pp744-751

[62]. Shen D. K., Gu S., Luo K. H. and Bridgwater A. V. 2009. Analysis of wood structural changes under thermal radiation. *Energy Fuels*, 23(2), pp1081-1088

[63]. Sommersacher P., Kienzl N., Brunner T. and Obernberger I. 2016. Simultaneous online determination of S, Cl, K, Na, Zn, and Pb release from a single particle during biomass combustion. Part 2: Results from test runs with spruce and straw pellets. *Energy Fuels*, 30(4), pp3428-3440

[64]. Tapasvi D., Khalil R., Skreiberg Ø., Tran K. and Grønli M. 2012. Torrefaction of Norwegian birch and spruce: An experimental study using macro-TGA. *Energy Fuels*, 26(8), pp5232-5240

[65]. Telmo C. and Lousada J. 2011. The explained variation by lignin and extractive contents on higher heating value of wood. *Biomass and Bioenergy*, 35, pp1663-1667

[66]. Telmo C., Lousada J. and Moreira N. 2010. Proximate analysis, backwards stepwise regression between gross calorific value, ultimate and chemical analysis of wood. *Bioresource Technology*, 101, pp3808-3815

[67]. Tsalidis G., Voulgaris K., Anastasakis K., De Jong W. and Kiel J. H. A. 2015. Influence of torrefaction pretreatment on reactivity and permanent gas formation during devolatilization of spruce. *Energy and Fuels*, 29(9), pp5825-5834

[68]. Vicente E. D., Tarelho L. A. C., Teixeira E. R., Duarte M., Nunes T., Colombi C., Gianelle V., da Rocha G. O., de la Campa A. and Alves C. A. 2016. Emissions from the combustion of eucalypt and pine chips in a fluidized bed reactor. Journal of Environmental Sciences, 42, pp246-258

[69]. Williams A., Jones J. M., Ma L. and Pourkashanian M. 2012. Pollutants from the combustion of solid biomass fuels. Progress in Energy and Combustion Science, 38, pp113-137

[70]. Xing P., Darvell L. I., Jones J. M., Ma L., Pourkashanian M. and Williams A. 2016. Experimental and theoretical methods for evaluating ash properties of pine and El Cerrejon coal used in co-firing. *Fuel*, 183, pp39-54

[71]. Guo X., Wang S., Wang K., Liu Q. and Luo Z. 2010. Influence of extractives on mechanism of biomass pyrolysis. *Journal of Fuel Chemistry and Technology*, 38(1), pp42-46

[72]. Speight J. G. 2011. *The biofuels handbook*. RSC Energy Series No.5, Royal Society of Chemistry, Thomas Graham House, Cambridge

[73]. Millard P. and Grelet G-A. 2010. Nitrogen storage and remobilization by trees: ecophysiological relevance in a changing world. *Tree Physiology*, 30, pp1083-1095

[74]. Keski-Saari S. and Julkunen-Tiitto R. 2003. Resource allocation in different parts of juvenile mountain birch plants: effect of nitrogen supply on seedling phenolics and growth. *Physiologia Plantarum*, 118, pp114-126

[75]. Hon D. N-S. and Shiraishi N. 2001. *Wood and cellulosic chemistry*, 2nd Edition. Marcel Dekker, Inc. New York

[76]. Browning B. L. 1963. *The chemistry of wood*. Interscience Publishers, John Wiley & Sons, Inc. New York

[77]. Senelwa K. and Sims R. E. H. 1999. Fuel characteristics of short rotation forest biomass. *Biomass and Bioenergy*, 17, pp127-140

[78]. Gibson L. J. 2012. The hierarchical structure and mechanics of plant materials. *Journal of the Royal Society Interface*, 9, pp2749-2766

[79]. Koski V. and Rousi M. 2005. A review of the promises and constraints of breeding silver birch (*Betula pendula* Roth) in Finland. *Forestry*, 78(2), pp187-198

[80]. Wu H., Xiang W., Fang X., Lei P., Ouyang S. and Deng X. 2017. Tree functional types simplify forest carbon stock estimates induced by carbon concentration variations among species in a subtropical area. *Scientific Reports*, 7:4992, pp1-11

[81]. Zeng T., Pollex A., Weller N., Lenz V. and Nelles M. 2018. Blended biomass pellets as fuel for small scale combustion appliances: Effect of blending on slag formation in the bottom ash and pre-evaluation options. *Fuel*, 212, pp108-116

# Chapter 5. The combustion of UK-grown birch & Sitka spruce

*"Birch and fir logs burn too fast, blaze up bright and do not last"* – *Celia Congreve*

## 5.1. Introduction

As highlighted in the previous chapter, the UK's wood resource represents a diverse feedstock, containing a wide array of native and non-native tree species. This diversity is evident in the fundamental properties of its wood, not just between species, but also in the different sections of individual trees. The results in Chapter 4 – both from the experimental work and the consequent statistical analysis – outline differences in the proximate, ultimate, lignocellulose and energy contents of UK-grown oak, birch, Scots pine and Sitka spruce wood. Understanding the fundamental differences of wood properties is a vital first step in establishing the suitability of different tree species as potential bioenergy feedstocks, however it is important that this knowledge is then built upon.

The utilisation of biomass for energy generation has continued to increase, driven by the desire to exploit previously unused woody residues, achieve $CO_2$ neutrality and, where possible, use local sustainable feedstocks [1]. Combustion technologies, particularly those developed for use with solid fuels, are the most mature and readily available for utilising biomass in energy generation. These are by no means perfect; issues still exist with regards to their emissions and efficiencies. However, as a source of short-cycle carbon, the combustion of wood biomass – using both native and non-native species – offers a large potential for future bioenergy production, in particular domestic bio-heat [1-3]. This is evidenced itself within the UK, with wood combustion accounting for 76% of the 148 PJ associated with renewable heating in 2015. Of this total, 79.9 PJ were attributed to domestic wood combustion and a further 32.6 PJ was used within the industrial sector [4]. Utilising wood for renewable heating in the UK could prompt a growth in demand for local sources of wood biomass. Indeed, as discussed in Chapter 1, the UK governments recently published *Clean Growth Strategy* outlines their intention to increase England's forest cover, while better utilising it as a resource. The fundamental analysis completed in the previous chapter may therefore become increasingly beneficial, particularly in helping inform decision-makers on which species to plant for use as woodfuel. In addition to understanding a fuel's fundamental features, for combustion-based end-use technologies it is beneficial to understand the wood's fundamental combustion characteristics. Of the four species considered in Chapter 4, the results demonstrate that UK-grown birch and Sitka spruce are potentially interesting sources of locally obtainable wood fuel. This is due to their reduced ash and increased energy contents; evidenced throughout the whole tree, including its stem, branches and roots.

Figure 5.3 – **UK-grown, naturally regenerated silver birch (*Betula pendula*)**

The *Betula* genus is diverse, containing around 50 species in total. Of these, there are two naturally occurring birch tree species found abundantly across Europe;

silver birch (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.). In the UK, birch species have historically been considered worthless – due to the poor form of its timber – and a competitive hindrance on other, more valuable conifer species. Although castigated in the UK, other nations – such as Finland – utilise birch wood extensively, particularly in the manufacture of plywood, veneer and pulp [5-7]. As a pioneer species, during the juvenile period silver birch trees can display rapid growth under favourable conditions, achieving height increases in excess of 1m $yr^{-1}$. This, coupled with the ability of birch to successfully naturally regenerate, has resulted in the establishment of ~23.2 million $m^3$ of standing timber within Great Britain [5, 8]. An example of naturally regenerated silver birch can be found in Figure 5.1, highlighting the commonly occurring issues of poor timber form found in UK-grown birch trees.

The dominant conifer species – featuring heavily in UK commercial forestry – is the non-native Sitka spruce (*Picea sitchensis* (Bong.) Carr.), which represents more than half of the total volume of sawn timber produced in the UK. Although the mild climate, associated with the UK, results in the ideal growing conditions for Sitka spruce, its subsequent rapid growth can produce poor quality timber. This is attributed to the wide growth rings, low density and the size and frequency of knots within the wood [9-11]. Estimated at ~181 million $m^3$ of standing timber, covering more than 650,000 ha of land, the UK's current Sitka spruce resource is significantly larger than that of the silver birch – a factor attributed to its well established timber market [8]. There are numerous markets for UK timber, however the most valuable of these for home-grown softwoods is structural-grade sawn timber, which has rigorous requirements relating to the mechanical properties, dimensions and dimensional stability of the wood. Timber that doesn't meet these requirements is resigned to less valuable wood products; these markets are saturated, a result of the large amounts of low-grade timber currently available in the UK [11].

The fundamental characterisation results of Chapter 4, combined with the UK's substantial volume of Sitka spruce resource – and that UK-grown birch wood holds little timber value – has dictated the focus of the present chapter; namely the suitability of these two species as fuel. Wood combustion has established itself as a key transitional energy generation technology in the UK, however the interest in firewood and how it burns spans more than a century. From peer-reviewed scientific research, to literature based upon traditional folk tales – such as *The Firewood Poem*, written by Celia Congreve in 1930 [12] – there has been a historic desire to understand and describe the properties of woodfuel. Although there is plenty of published research on the fundamental combustion characteristics, there is very little which focuses specifically on UK-grown wood and, perhaps more importantly, the differences between the stem, root and branch wood. This chapter will therefore rectify this.

## 5.2. Methodology

Unlike *The Firewood Poem*, which based its descriptions of firewood properties for different species upon simple visual observations, the experimental work completed in this chapter will quantify the combustion characteristics of two UK-grown species; birch and Sitka spruce. As a continuation of the previous chapter – building upon the work already conducted – this research will focus on a refined section of the initial 145 samples, analysing these in greater detail.

Table 5.1 – **Site data and number of birch and Sitka spruce trees analysed**

| Site Name | Species | Trees (n) | Longitude & Latitude | Planting Year | Soil |
|---|---|---|---|---|---|
| Haldon, Exeter | BI | *4* | *50.61937, -3.5435727* | *1953* | *Podzol* |
| Wheldrake, York | BI | *2* | *53.919369, -0.98743347* | *1960* | *Podzol* |
| Whitestone, Exeter | BI | *1* | *50.75155, -3.6117105* | *1950* | *Brown Earth* |
| Ae Village, Dumfries | SS | *2* | *55.173172, -3.5935832* | *1970* | *Peaty Gley* |
| Dartmoor National Park | SS | *3* | *50.643443, -3.9205897* | *1950* | *Acidic Peat* |

### 5.2.1. Sample Details

The initial selection of 145 UK-grown wood samples have been reduced for this chapter, concentrating the additional analysis on just 36 of these. Consequently, the species, number of trees and site details of the refined sample set are detailed in Table 5.1. The combustion analysis will be completed on samples from seven individual birch trees – collected from three sites – and five Sitka spruce trees from a further two sites. For each individual tree there have been samples collected from their stem, roots and branches. The birch samples have been obtained from sites which differ from one another, either geographically – York is ~400km from Exeter – or by the soil condition of the site; Podzol's tend to be acidic, while Brown earth is often composed of alkaline organic matter. The two Sitka spruce sites are both characterised by similar wetland gley soil conditions, however there is a significant distance of ~500km separating the locations.

### 5.2.2. Characterisation Overview

Although the main focus of this chapter will be the combustion analysis of the selected samples, it is vital that their fundamental characteristics are considered. The proximate, ultimate and lignocellulosic results that will be reported were produced as a part of the analysis in Chapter 4, using the experimental methodology's described in Section 4.2.3. Any additional statistical analysis – specific to the stated 36 samples – will be completed using the techniques outlined in Section 4.2.2.

As with the previous experimental work, the additional analysis utilises the finely milled wood samples, sieved to ≤ 90 μm. Bridgeman *et al.*, (2007) highlighted the differences that particle size can have on both the combustion profiles of biomass and the concentrations of inorganic and organic material contained within the sample. Larger particle sizes contain increased carbon and volatile matter contents, resulting in an increased calorific value; this will consequently impact upon the combustion behaviour of the sample [13]. The principle focus of this chapter is to demonstrate the variation that exists between the samples – relating either to the different species or specific tree sections – not in the size of particles. It is therefore important that homogeneity of particle size is maintained for all 36 samples, ensuring the comparisons are valid. Considering the conclusions of Bridgeman *et al*., (2007), it can be expected that using particle sizes ≤ 90 μm will result in the decomposition rates of the analysed samples being less than if the particles were larger. However, the reduced size will aid in achieving sample homogeneity, thus increasing the validity of the attained results.

### 5.2.3. Potassium Content

Biomass resource – in all of its forms – contain an array of nutrients and inorganic compounds, representing a key part of the variability that exists between different feedstocks. This includes elements such as potassium (K), phosphorus (P), calcium (Ca) and magnesium (Mg), which differ in concentration due to changes in site and growing conditions, or the time in which the biomass is harvested [3]. Some of these elements are important aids in the successful development and function of the plant, helping with physiological roles related to growth; K is essential for cell expansion, maintaining water and salt concentrations and also during photosynthesis [14]. As well as its role in plant growth, K is also a key inorganic constituent which can impact the ash-melting temperatures of biomass – during combustion – and the corrosive behaviour of the gases released as a consequence [15, 16]. Although there is a limited quantity of each sample, available for this present study, considering the importance of K in both physiological- and combustion-based processes, conducting further analysis into the existing macronutrients of the birch and Sitka spruce specimens would be clearly beneficial.

#### 5.2.3.1. Acid Digestions

Quantifying the inorganic contents of biomass can be achieved by digesting the sample material in acid, with a standard method for determining the major inorganic elements contained within solid biofuels described in BS EN ISO 16967:2015 [17]. Although different reagents can be used within the digestion process, for this analysis nitric acid ($HNO_3$) has been utilised. The individual digestions were completed using 0.5g of weighed raw sample and 10ml of $HNO_3$; these were placed in flat bottom conical flasks – fitted with reflux cones – and placed on a hotplate (as shown in Appendix A). Once completed, the digested sample was brought back into solution by adding a further 5ml of $HNO_3$. Using deionised water the individual digestions were diluted up to 50ml, ready for further analysis.

#### 5.2.3.2. Atomic Absorption Spectrometry

Once digested, the inorganic concentrations can be detected using an array of different methods – such as inductively coupled plasma mass spectrometry (ICP-MS) – however for this research, atomic absorption spectrometry (AAS) has been utilised. AAS allows for the determination of chemical elements present in a sample; this is achieved by measuring the absorption of light wavelengths transmitted through the sample. Different elements have their own distinct wavelengths, allowing for their concentration within a sample to be established [18]. The AAS analysis was completed using a *Varian* 240FS AA atomic absorption system, fitted with an acetylene burner, which can be found in Appendix A. The absorbance of the digested samples is measured against a calibration curve, using standards with a known concentration. Using the specific potassium lamp, each sample was analysed for its elemental content in duplicate.

### 5.2.4. Nitrogen Partitioning

Nitrogen (N) is an essential component for life – the growth and survival of all living organisms is driven by the successful attainment of metabolically useable nitrogen. This is prevalent in forest growth, with increased productivity linked to an increase in availability. The location and quantities of nitrogen contained within wood are dependent upon both external influences, such as the nitrogen taken up through soil solutions, and internal factors which are driven by seasonal storage and growth necessities [19, 20]. The existence of nitrogen is also an important factor when considering the role of wood biomass as a fuel. During combustion, the nitrogen contained within woodfuel is released as nitric oxide (NO) and nitrogen dioxide ($NO_2$) – collectively referred to as $NO_x$ – which have associated human- and environmental-based issues. In addition to these, combustion at lower temperatures can increase the emission of nitrous oxide ($N_2O$), which is a potent greenhouse gas (GHG) that is detrimental to the ozone layer [21-23]. $NO_x$ emissions can be decreased by control of stoichiometry in combustion zones, impacting upon the temperatures and potential reduction mechanisms. The partitioning of N during devolatilisation is an important parameter for $NO_x$ reduction strategies; indeed char-$NO_x$ – which is produced from the nitrogen retained in the char – is an important source of $NO_x$. The fraction of char-$NO_x$ is fuel dependent, however N-partitioning can be altered during combustion, following changes to the temperature and residence time; increased temperatures and residence time prompts N-depletion in the char [23, 24]. Establishing the nitrogen partitioning that exists between different fuels – before they are impacted by other attributing factors – is beneficial in optimising combustion systems to minimise $NO_x$ emissions.

The most common method for calculating nitrogen partitioning is to produce a char from the fuel, calculating the elemental contents of both, before performing a material balance between the two sets of results [24]. This method contains two separate processes – the char creation, followed by the elemental analysis of the fuels – which increases the potential for experimental error to be incurred during the process. Additionally, this method requires a significant increase in the amount of initial sample used within the analysis, particularly since the char yield from biomass is in the order of 10-20%.

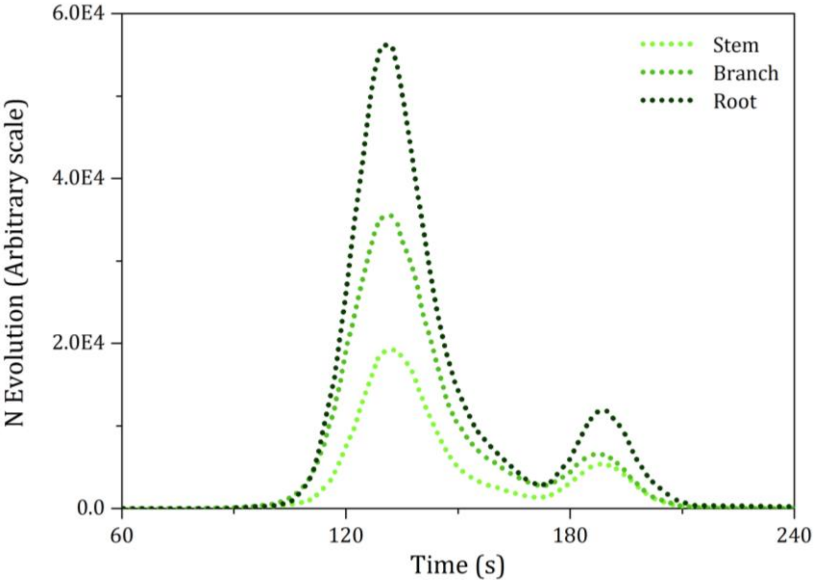


Figure 5.2 – **Chromatogram examples of nitrogen evolution profiles produced from an elemental analyser, equipped with a chemiluminesence detector**

In this current study, the nitrogen analysis has been completed using an elemental analyser equipped with a chemiluminesence detector which, further to giving a total value for nitrogen, also produces individual chromatograms for each completed analysis. This is demonstrated in Figure 5.2, showing the nitrogen evolution profiles produced following the analysis of stem, root and branch samples taken from the same tree – as a result, the area under the curve corresponds to the total nitrogen content. As described in Section 4.2.3.4, the process for determining the nitrogen content first involves the pyrolysis of the sample in an inert atmosphere, before being combusted in oxygen. It would therefore be reasonable to equate the two defined peaks – evident in Figure 5.2 – to the nitrogen contained within the volatile matter and the char. Consequently, by calculating the area under the curve for each peak it is possible to establish the partitioning of the nitrogen.

### 5.2.5. Thermogravimetric Analysis

Thermogravimetric analysis (TGA) is a versatile procedure, utilising a precision balance and a furnace to measure the changes of a samples weight as a function of increasing temperature over time. Although used extensively for evaluating the combustion performance and behaviour of coals, this form of analysis can

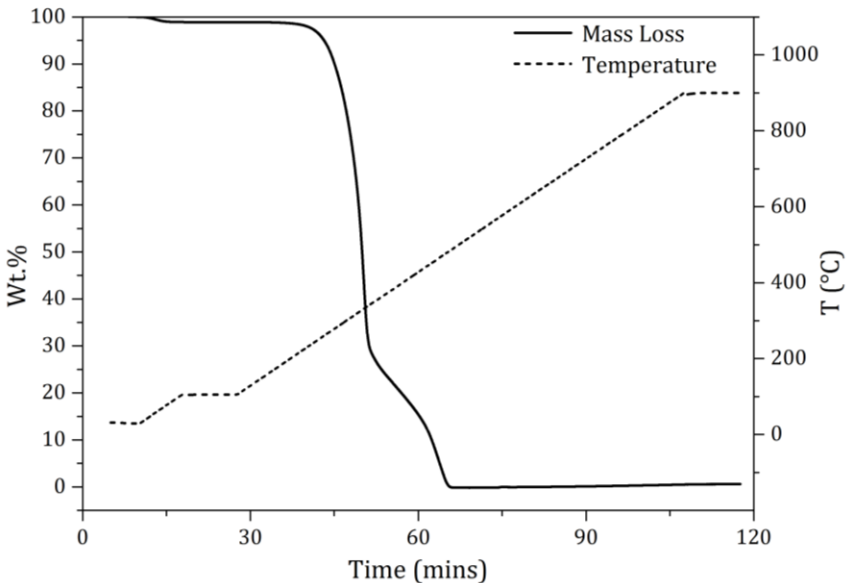


Figure 5.3 – **Temperature profile of programmed TGA combustion process and consequently produced mass loss curve**

also be applied to the large range of existing biomass feedstocks [2, 25-27]. In addition to establishing the proximate values, TGA can also be used to determine the combustion behaviour (burning profiles) of the selected birch and Sitka spruce samples.

The combustion analysis was completed using the *TA Instruments* TGA Q5000 thermogravimetric analyser, as discussed previously. The milled wood samples, sieved to ≤ 90 µm, were spread in a thin layer on the platinum sample pans, using ~5mg of sample for each individual combustion run. The TGA instrument was programmed to increase its temperature, demonstrated in Figure 5.3, simulating the combustion process. Once the furnace has been purged with nitrogen, the sample pan is held with a supply of air, before the temperature is increased by 10°C $\text{min}^{-1}$ up to 105°C and then kept isothermal for 10 minutes. Following this the temperature is again increased, rising by 10°C $\text{min}^{-1}$ to 900°C before being kept isothermal for a further 10 minutes, ensuring the complete combustion of the sample. As the sample pan is held on a precision balance, the programmed temperature simulation invokes the mass loss of the sample, shown in Figure 5.3.

Table 5.2 – **Lignocellulose-based standards, used in combustion analysis**

| | **Lignocellulose Standards**[a] | | |
|---|---|---|---|
| | **Name** | **Formula** | **Quality** |
| **Hemicellulose** | *Arabinose* | $C_5H_{10}O_5$ | *≥98%* |
| | *Glucose* | $C_6H_{12}O_6$ | *≥99.5%* |
| | *Mannose (from wood)* | $C_6H_{12}O_6$ | *≥99%* |
| | *Xylan (beechwood)* | - | *≥90%* |
| | *Xylose* | $C_5H_{10}O_5$ | *≥99%* |
| **Cellulose** | *Cellulose, microcrystaline* | - | - |
| **Lignin** | *Lignin, alkali* | - | - |

[a] *sourced from SIGMA-ALDRICH*

Each of the samples were analysed in triplicate, ensuring the replicability of the process and uniformity in the stated results. As the lignocellulosic values for each of the samples is known, further to the combustion analysis of the birch and Sitka spruce samples, additional runs – under the same conditions – were completed on different lignocellulose-based compounds. These are detailed in Table 5.2. The data produced from the TGA analysis highlights the changes in weight of the sample, as a function of increasing temperature over time. As a result, the rates of mass loss (Wt.% $s^{-1}$) that occur during the combustion process can be derived using the following equation;

$$dm/dt = \frac{(m_1 - m_2)}{(t_2 - t_1)} \tag{5.1}$$

where:

$m_{1,2}$ is the mass at points 1 and 2, respectively

$t_{1,2}$ is the time (s) at points 1 and 2, respectively

The derived rates of mass loss – and the calculated 2nd derivative – can be utilised to establish the peak mass loss rates and the consequent characteristic temperatures that these occur, for key points during the combustion of the different samples. An example of the calculated 1st and 2nd derivatives, produced using experimental combustion data, are shown in Figure 5.4.

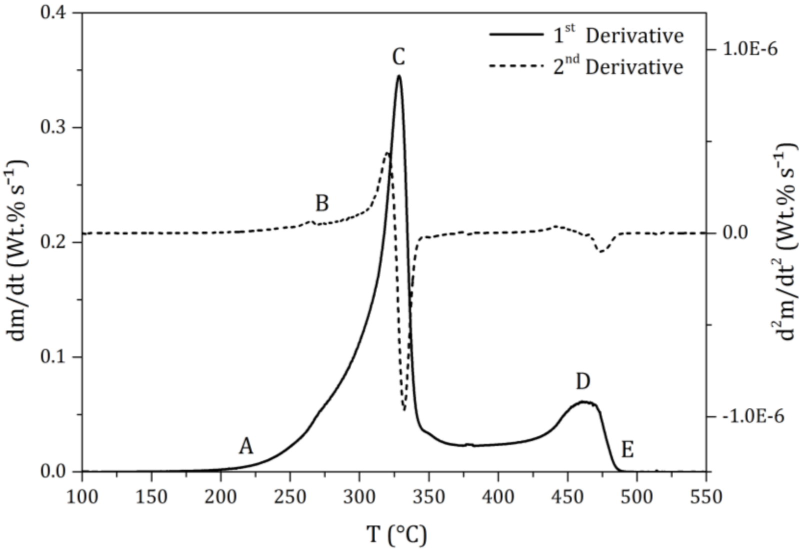


Figure 5.4 – **Calculated 1st & 2nd derivatives from combustion data; initial mass loss (A), peak shoulder (B), peak volatile (C), peak char (D) and burnout (E) of the sample**

As highlighted in Figure 5.4, the characteristic temperature for the initial mass loss signifies the start of the combustion process (point A), and is defined as where the rate of mass loss reaches 1% $min^{-1}$. The burnout of the sample, marking the end of combustion, is taken at the point E – once the rate of mass loss falls below 1% $min^{-1}$. The figure for determining the start and end points of the combustion process is based upon existing combustion literature [28, 29].

The 1st derivative of the mass loss has two clear peaks; the first relating to the combustion of the volatile matter and the second, the combustion of the char. As a result, the temperature values and maximum rates of devolatilisation and char combustion are taken at the apex of points C and D, respectively. Of the three structural lignocellulosic compounds contained within biomass, hemicellulose is the most reactive; as a result, its decomposition occurs at lower temperatures rates than the peak mass loss of the volatiles. Therefore, the existence of hemicellulose produces a visible shoulder on the volatiles' peak [30, 31]. The shoulder's peak decomposition rate and temperature values are calculated using the 2nd derivative, taken at point B in Figure 5.4, which is the lowest point in the trough.

### 5.2.6. Kinetic Modelling

The analysis of experimental combustion data gives a qualitative representation of the variation evident between samples, while allowing for the identification of temperature and reactivity differences that exist in the derived data. This is certainly valuable; however it is also vital to quantify this variation. The thermal degradation of biomass occurs as a result of a number of simultaneous reactions. Understanding these interactions – between both the chemical and physical processes – is beneficial, especially when considering biomass combustion in stoves and boilers. It's also useful when considering hazards such as the ignition and smouldering of stored biomass [27, 32-35]. The thermal degradation of biomass can be modelled using chemical kinetics, which describe the relationships that exist between physical and chemical processes.

These relationships often focus on the lignocellulosic components, which differ in their reactivity and the temperatures at which degradation begins. As a result, a number of decomposition models for biomass have been produced; some suggesting the simultaneous reactions of the three constituents, while others suggest a level of interaction under certain conditions [33, 34]. The aim of the experimental analysis completed within this chapter is to ascertain the differences that exist between the wood samples and the role that hemicellulose, cellulose and lignin content plays in this. The kinetic modelling therefore – taking the chapter to its logical conclusion – will follow suit, establishing if these differences can be directly associated with the chemical reactions that occur.

The extraction of kinetic parameters has been based upon the widely used *Reaction Rate Constant Method;* a simple mathematical-based process that utilises TGA experimental data to derive the pre-exponential factor and activation energy [33]. This follows the Arrhenius function, given in the following equation;

$$k = A \exp\left(-\frac{E}{RT}\right) \tag{5.2}$$

where:

| | |
|---|---|
| $k$ | is the reaction rate constant |
| $A$ | is the pre-exponential factor ($s^{-1}$) |
| $E$ | is the activation energy (kJ $mol^{-1}$) |
| $R$ | is the gas constant (8.314 kJ $mol^{-1}$. $K^{-1}$) |
| $T$ | is the temperature (K) |

Assuming that the mass loss profiles of the TGA experiments are a result of one or more first-order reactions, then this can be described as;

$$k_i = -\frac{1}{(m_i - m_\infty)} \times \frac{dm_i}{dt} \tag{5.3}$$

where:

| | |
|---|---|
| $k_i$ | is the reaction rate constant of the $i^{th}$ group (i=1, 2, …, n) |
| $m_i$ | is the initial mass of the $i^{th}$ group (i=1, 2, …, n) |
| $m_\infty$ | is the terminal mass |

It should be noted that the designated terminal mass value is a vital constituent, greatly impacting the calculated value of $k$ [33]. Once the reaction rate constant has been calculated, Equation 5.4 – taking the logarithm of the initial Arrhenius function – is used to determine the $A$ and $E$.

$$\ln k_i = \ln A - \frac{E}{RT_i} \tag{5.4}$$

This is achieved by plotting ln $k_i$ against $1/T_i$, before calculating a simple linear regression; the intercept $(\alpha)$ and slope $(\beta)$ values of the produced straight line correspond to $A$ and $E$, respectively.

$$A = e^{\alpha} \tag{5.5}$$

$$E = R\beta \tag{5.6}$$

The kinetics model used in this chapter utilises this simple method as its basis, however this is further developed upon to make use of the experimental lignocellulose data. As discussed in Chapter 3, once dried, the thermal degradation of the structural compounds of biomass – the hemicellulose, cellulose and lignin – occurs across two distinct phases; devolatilization and then char combustion. Although hemicellulose is the least thermally-stable structural component, its decomposition does not just occur during devolatilization – partially degraded hemicellulose still exists within the char, especially under rapid reaction conditions such as fast pyrolysis [36, 37]. Consequently, the multistep kinetics model produced for use in this chapter – simulating the entire combustion process – attributes the known lignocellulosic mass fraction to their equivalent $A$ and $E$ values. This is described in the following equation;

$$\frac{dm}{dt} = -A_n \, exp\left(-\frac{E_n}{RT_i}\right)(m_i - m_{\infty})n_x \tag{5.7}$$

where:

| | |
|---|---|
| $n$ | is the stated step, related to the structural component |
| $n_x$ | is the mass fraction of the structural component |

Using the final weight value recorded at the end the combustion experiments as the terminal mass, Eq. 5.7 is used to model the decomposition rates of each defined lignocellulosic-based reaction, through to burnout. By attributing the appropriate calculated mass fraction to each individual model, combining these will show how the interactions of the different structural components combine to replicate the complete mass loss. This will act as a framework to show the kinetic variation that exists between species, driven by the known lignocellulosic contents.

## 5.3. Results

The following results section will be broken down into four main areas; 1) an overview of the fundamental characteristics of the wood samples, including the partitioning of nitrogen and their potassium contents, 2) the relationships that exist between the different characteristics, 3) the combustion characteristics produced from the TGA experimental work, and 4) the results of the kinetics model, based upon the completed experimental work.

### 5.3.1. Wood Sample Characteristics

As stated previously, the focus of this research is on a total of 36 samples; comprised of wood sourced from the stem, root and branches of 12 individual trees (7 birch and 5 Sitka spruce). This is a refined selection of the samples used in Chapter 4. Although the aim of this chapter is to understand and quantify the combustion differences that exist between different species and tree sections, it is also vital that the elemental, chemical and lignocellulosic values are first considered.

#### 5.3.1.1. Proximate & Ultimate Results

The mean proximate and ultimate values for the analysed birch and Sitka spruce samples – and their corresponding standard deviations – can be found in Table 5.3. The elemental and chemical results show that the characteristics of the wood differ, not only between species, but also between the different tree sections. This variation has been illustrated in the radar diagrams, located in Figure 5.5.

Sitka spruce stem wood has larger carbon and hydrogen contents than that of the birch, however the amount of nitrogen is smaller; for both species the content is low when compared to other types of biomass feedstocks, such as grasses and straws [3, 22, 23, 38]. The distribution of carbon within the tree differs between the two species; for Sitka spruce there is very little difference in the carbon contents of its stem, root and branch wood, while for the birch there is a clear increase in the root and branch carbon when compared to its stem. This suggests that there is a contrast in the growth focus and the location for carbon

Table 5.3 – **Experimental mean values and calculated standard deviations; Ultimate, Proximate and Gross Calorific Values from seven birch (BI) and five Sitka spruce (SS) trees. Comparison between their stem, root and branch wood**

| | | **Ultimate$^a$** | | | | **Proximate$^a$** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | C | H | N | O$^b$ | VM | FC | Ash | GCV$^{ac}$ |
| **BI** | Stem | *46.5 (±0.28)* | *6.4 (±0.05)* | *0.10 (±0.01)* | *46.8 (±0.25)* | *91.5 (±0.32)* | *8.4 (±0.31)* | *0.13 (±0.06)* | *18.5 (±0.12)* |
| | Root | *48.8 (±0.79)* | *6.3 (±0.08)* | *0.26 (±0.05)* | *44.2 (±0.92)* | *86.9 (±1.41)* | *12.6 (±1.35)* | *0.50 (±0.10)* | *19.4 (±0.36)* |
| | Branch | *48.3 (±0.84)* | *6.4 (±0.12)* | *0.23 (±0.03)* | *44.7 (±1.04)* | *89.0 (±0.35)* | *10.5 (±0.22)* | *0.47 (±0.13)* | *19.3 (±0.40)* |
| **SS** | Stem | *47.8 (±0.52)* | *6.5 (±0.02)* | *0.07 (±0.01)* | *45.5 (±0.58)* | *88.5 (±0.68)* | *11.5 (±0.62)* | *0.16 (±0.08)* | *19.0 (±0.23)* |
| | Root | *47.5 (±0.29)* | *6.3 (±0.04)* | *0.14 (±0.01)* | *45.8 (±0.31)* | *87.2 (±0.34)* | *12.6 (±0.36)* | *0.26 (±0.09)* | *18.9 (±0.12)* |
| | Branch | *48.1 (±0.48)* | *6.5 (±0.06)* | *0.17 (±0.03)* | *45.1 (±0.58)* | *85.3 (±0.35)* | *14.4 (±0.29)* | *0.32 (±0.19)* | *19.2 (±0.23)* |

$^a$ *calculated on a dry basis,* $^b$ *calculated by difference,* $^c$ *Gross Calorific Value (MJ/kg)*

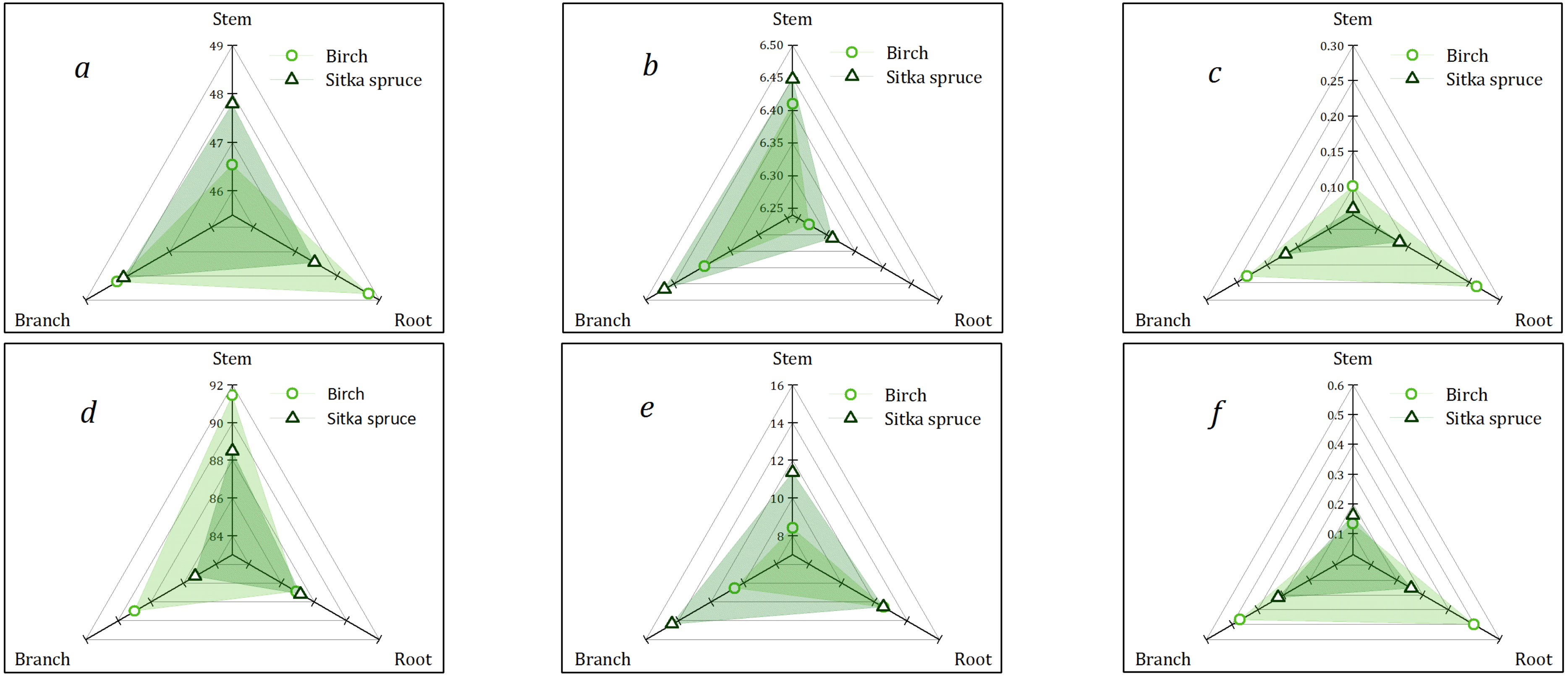


Figure 5.5 – **Calculated experimental mean values (Wt.% on a dry basis) of a) Carbon, b) Hydrogen, c) Nitrogen, d) Volatile Matter, e) Fixed Carbon, and f) Ash; comparison between the stem, root and branch of UK-grown birch and Sitka spruce. Corresponding data found in Table 5.3**

accumulation between different species. The ultimate analysis also highlights that Sitka spruce has larger hydrogen and smaller nitrogen contents, throughout the entirety of the tree, when compared to birch. Of the considered samples, the birch roots contain the largest quantities of nitrogen.

This variation is also evident in the proximate analysis results. The differences between the volatile matter (VM) and fixed carbon (FC) of the species are most pronounced in the stem and branch wood; birch stems and branches are typified by larger contents of VM than that found in Sitka spruce, while the latter have more FC. As shown by Figure 5.5 – and the data contained in Table 5.3 – the ash contents of the stem wood is similar, with Sitka spruce having slightly more than the birch. This is not the case when considering the other sections of the trees as birch have larger ash contents. This is most apparent in the birch roots, which have statistically significant larger ash contents than Sitka spruce; $t(10)=3.861$, $p=0.003$. In addition to the differences between species and different tree sections, there is also a level of variation between individual trees. This is especially apparent for birch which, in most instances, has the greatest variance between its mean elemental and chemical values – as evidenced by the standard deviations, reported in Table 5.3. The results indicate that the birch is more heterogeneous than the Sitka spruce, which is supported extensively in the existing literature [39, 40].

#### 5.3.1.2. Nitrogen Partitioning

Nitrogen and biomass have an important association, a result of the elements key role in the growth process and the potential implications that can arise through its existence within fuel. It is therefore vital to understand the behaviour of the nitrogen content of biomass feedstocks, especially when considering how best to utilise it as a resource. The nitrogen contents of the different wood species and tree sections can be found in Table 5.3; however, to supplement this, further analysis has been conducted on the partitioning of fuel-N between the volatile and char phases of combustion. This data is given in Table 5.4. The calculated fuel atomic N:C ratios of the birch are larger throughout the tree, when compared to the spruce, indicating that nitrogen is more prevalent in hardwood species.

Table 5.4 – **Calculated nitrogen partitioning data and theoretical char yields of birch (BI) and Sitka spruce (SS); comparison between stem, root and branch**

| | | Fuel-N Partitioning (%) | | | | |
|---|---|---|---|---|---|---|
| | | Fuel N:C | Volatiles | Char | Std. Dev. | TCY[a] |
| **BI** | Stem | *0.002* | *84.5* | *15.5* | *±2.33* | *8.6* |
| | Root | *0.005* | *87.3* | *12.7* | *±0.84* | *13.1* |
| | Branch | *0.005* | *88.1* | *11.9* | *±1.83* | *11.0* |
| **SS** | Stem | *0.001* | *89.9* | *10.1* | *±1.54* | *11.5* |
| | Root | *0.003* | *88.3* | *11.7* | *±1.50* | *12.8* |
| | Branch | *0.004* | *87.1* | *12.9* | *±1.73* | *14.7* |

[a] *Theoretical Char Yield (FC + ash Wt.% determined by proximate analysis)*

The partitioning of fuel-N for a number of different biomass feedstocks have previously been studied, reporting the release of nitrogen – associated with the volatile phase – as between 72.3% and 90.97%. These values were calculated by completing a material balance between the nitrogen contents of a raw fuel and its subsequently produced char [24, 31]. The nitrogen partitioning results, stated in Table 5.4, were produced using the alternative method described in Section 5.2.4; however, these are comparable to the results reported in the literature, giving confidence to this alternative methodology. For the Sitka spruce samples, the partitioning of nitrogen in the volatile phase is fairly uniform throughout the tree; calculated as 87.1%, 88.3% and 89.9% for the branch, root and stem wood, respectively. Although the birch root and branch wood is comparable to that of the Sitka spruce, the partitioning of nitrogen in the stem wood – calculated as 84.5% – shows a clear difference. Indeed, the difference between the birch and the Sitka spruce stem wood is statistically significant; $t(10)=-4.076$, $p=0.002$.

Table 5.4 also gives values for the theoretical char yield (TCY) of the species and their different sections – calculated as the sum of the fixed carbon and ash, on a dry basis. This is necessary for establishing how nitrogen partitioning could impact upon the concentrations of nitrogen existing within a produced char, potentially affecting the end use of a raw biomass source. Processes such as torrefaction and carbonisation – aimed at improving the fuel quality of raw biomass – reduce their moisture and volatile contents, while increasing the concentrations of fixed carbon [31, 41]. Alternatively, biomass-derived chars can be applied to soils to improve their condition; they reduce the loss of nutrients, via leaching, prompting increased growth productivity of the existing plants [42]. Understanding how different wood feedstocks impact the partitioning of nitrogen – in the case of this research, differences relating to species and tree sections – is clearly important. Consequently, Figure 5.6 shows the differences that exist in the nitrogen contents of the birch and Sitka spruce, highlighting how partitioning would impact the nitrogen content of theoretically-produced chars.

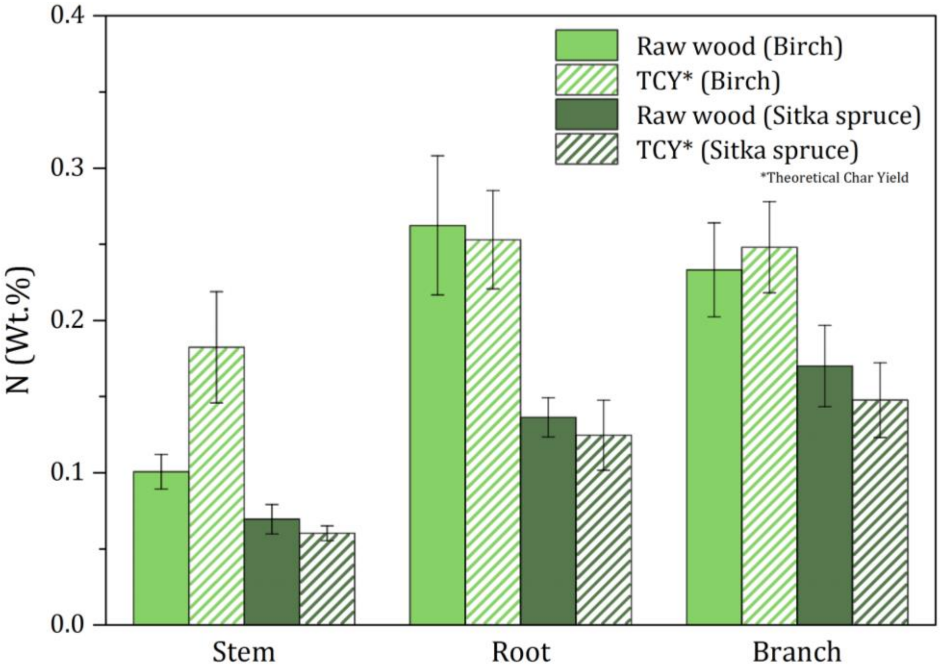


Figure 5.6 – **Influence of nitrogen partitioning on the fuel-N content of calculated Theoretical Char Yields (on a dry basis); comparison between different species and tree sections**

The nitrogen partitioning results suggest that for Sitka spruce, the nitrogen contents (Wt.% on a dry basis) of the theoretical char slightly reduces; this is apparent throughout the different tree sections. Although this reduction is evident in the birch roots, the results indicate that the theoretical chars produced from other sections of a birch tree would have increased concentrations of nitrogen. This is most visible for the birch stem wood which, even when considering the associated error, shows a definite increase in nitrogen concentration. The mean values indicate that producing chars from birch stem wood would increase the nitrogen content, from 0.1% to 0.18%.

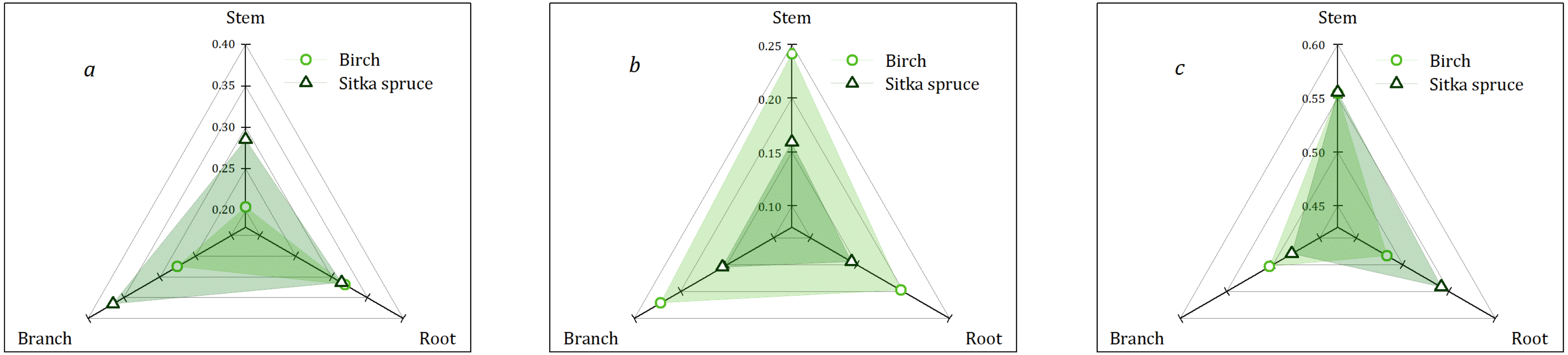


Figure 5.7 – **Calculated experimental lignocellulosic fractions (EF, db) for birch and Sitka spruce; a) Lignin, b) Hemicellulose, and c) Cellulose. Data in Table 5.5**

Table 5.5 – **Lignocellulosic fractions (EF, db) and standard deviations for birch (BI) and Sitka spruce (SS)**

| | | **Hemicellulose** | **Cellulose** | **Lignin** |
|---|---|---|---|---|
| **BI** | Stem | *0.24 (±0.01)* | *0.55 (±0.01)* | *0.20 (±0.01)* |
| | Root | *0.20 (±0.02)* | *0.48 (±0.03)* | *0.32 (±0.05)* |
| | Branch | *0.22 (±0.01)* | *0.50 (±0.02)* | *0.28 (±0.03)* |
| **SS** | Stem | *0.16 (±0.01)* | *0.56 (±0.01)* | *0.29 (±0.01)* |
| | Root | *0.14 (±0.01)* | *0.54 (±0.02)* | *0.31 (±0.02)* |
| | Branch | *0.16 (±0.01)* | *0.48 (±0.01)* | *0.37 (±0.01)* |

#### 5.3.1.3. Lignocellulosic Content

The relationship between the structural components of biomass – its lignin, cellulose and hemicellulose – and the combustion process is well documented, prompting a wide range of researchers to investigate their decomposition and the chemical kinetics that relate to this [27, 32-35]. As this chapter is concerned with the combustion characteristics of the birch and Sitka spruce samples, it is important to properly document their lignocellulosic composition. Figure 5.7 illustrates the lignocellulosic components of the birch and Sitka spruce samples, with the supporting data located in Table 5.5. The values have been reported on an extractive free basis, focusing on the differences in the known structural components; the digestive analysis, discussed in Section 4.2.3.6, did not include lab-based extractive determination. It should be noted that, as discussed in the previous chapter, the extractive contents of Sitka spruce – which were calculated by difference – are greater than that of birch, particularly in their root and branch wood.

The hemicellulose contents of the two species clearly differ; the birch is characterised by an increased hemicellulose content, evident throughout the entirety of the tree. The largest quantities of hemicellulose are located in the birch stem, calculated at ~50% more than that of the Sitka spruce. Although the quantities differ, the roots of both species contain the smallest amounts of hemicellulose. In keeping with the homogenous nature of the coniferous Sitka spruce [39, 40], there is very little variation in the hemicellulose content of their stem and branch wood – even when combined, the calculated relative error of the two is less than 5%. Supported by the data in Table 5.5, cellulose represents the key structural component of both birch and Sitka spruce [32, 40]. As shown, the quantity of cellulose is similar between the two species; the stem wood of both contain the largest fractions, determined as 0.55 and 0.56 for the birch and Sitka spruce, respectively. There is, however, evident variation in cellulose content throughout the other sections of the tree. The stem and root wood of Sitka spruce contain similar cellulose contents, before displaying a clear decrease in its branch wood. In comparison, both the cellulose contents of birch root and branch wood are reduced.

Lignin is an important structural component of wood; the lignification of the secondary cell wall – occurring during the seasonal growth process – produces cells which are both rigid and impermeable. The strengthened cells are, subsequently, suitable for transport and support – key attributes for growth. Representing a major carbon sink, their existence is species dependent, with hardwoods containing between 20%-28%, while this is slightly increased for softwoods, 24%-33% [27, 40, 43]. The lignin contents of birch and Sitka spruce, found in Table 5.5, are comparable to those contained within the literature, giving validity to the stated results. For both species, the lignin contents of the tree are smallest in the stem wood, although this is significantly higher in the Sitka spruce. Effectively, the birch stem wood samples are typified by increased hemicellulose contents, at the expense of lignin, while the Sitka spruce samples are the inverse of this. The role of lignified cells in resource transportation and support within the tree, indicates that higher concentrations of lignin will exist in key growth areas. The results therefore imply, interestingly, that the growth focus differs between the two species; new growth in birch trees will be most prominent in the roots, while Sitka spruce focuses this in its branches and canopy.

Table 5.6 – **Calculated potassium contents of individual birch (BI) and Sitka spruce (SS) trees; comparison between stem, root and branch**

| | | Potassium (mg/kg)[a] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Mean | %$E$ |
| **BI** | Stem | *618* | *1084* | *710* | *923* | *691* | *617* | *1138* | *826* | *24.7* |
| | Root | *1199* | *1355* | *1378* | *871* | *1010* | *1360* | *1005* | *1168* | *16.4* |
| | Branch | *741* | *1201* | *810* | *1124* | *983* | *945* | *856* | *951* | *16.2* |
| **SS** | Stem | *495* | *503* | *665* | *612* | *513* | - | - | *558* | *12.3* |
| | Root | *771* | *645* | *939* | *998* | *1127* | - | - | *896* | *19.0* |
| | Branch | *740* | *801* | *732* | *757* | *835* | - | - | *773* | *5.0* |

[a] *on a dry basis*

### 5.3.1.4. Potassium

One of the key inorganic constituents of biomass is potassium, which plays a vital role in both physiological- and combustion-based processes. The potassium contents of the two species, produced by atomic absorption spectrometry, can be found in Table 5.6; these are comparable to previously published results, giving validity to the stated values [15, 16]. Table 5.6 details the individual results for the seven birch and five Sitka spruce trees analysed; these have been visualised in Figure 5.8, highlighting the variation between species and tree sections. The mean potassium results, stated in Table 5.6, indicate that birch have higher concentrations than Sitka spruce; this is evident throughout the entirety of the tree. Although the values differ, comparable patterns between the two species are apparent – the stems contain the smallest concentrations, while the roots contain the highest.

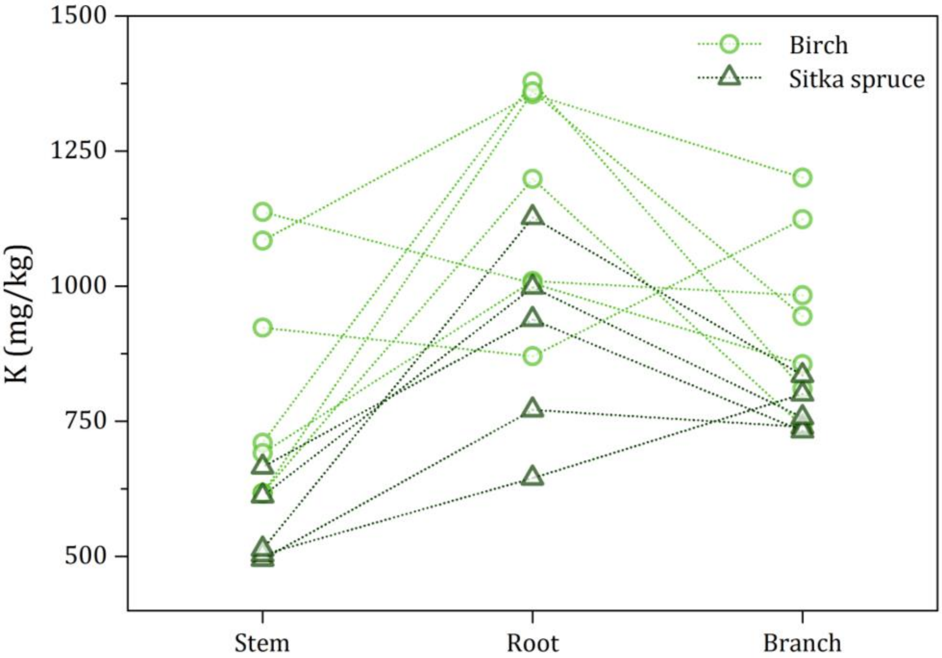


Figure 5.8 – **Calculated potassium values (on a dry basis) for birch and Sitka spruce; comparison between stem, root and branch wood**

The calculated relative errors for the different tree sections indicate that certain parts of the tree have larger degrees of variation, which is apparent for both species. As illustrated in Figure 5.8, the variation in potassium concentrations between the Sitka spruce samples are much lower in the stem and branch wood, while their roots have a larger spread of results. This variation in the roots can, potentially, be explained by the geographical location of the analysed specimens; the first two Sitka spruce trees in Table 5.6 were sourced from Dumfries, while the remaining three (3, 4 and 5) were attained from Dartmoor. Increased concentrations of nutrients in the soil, which are accessed via a plant's root system, invoke improved biomass growth [44, 45]. Therefore the potassium results suggest that, firstly, there is a difference in the soil quality at the two locations; the Dartmoor site is potentially more conducive to growth. Secondly, and perhaps more pertinently, the results indicate that although site conditions can influence variability in the potassium concentrations of Sitka spruce roots, their stems and branches appear less susceptible to site conditions. This is important when considering the suitability of the species as a fuel; homogeneity of wood resource – especially when sourced from different locations – will result in a more reliable fuel.

As with the other elemental and chemical analysis discussed previously in this chapter, the heterogeneous nature of the birch samples is again evident, this time in its potassium concentrations. Table 5.6 and Figure 5.8 show that, throughout each section of the tree, there are large ranges in the stated values. There are some site-related similarities (Tree 1, 2, 3 and 4 were from Haldon, numbers 6 and 7 were from Wheldrake and 5 was from Whitestone), however these are certainly not as clear as with the Sitka spruce – indeed, any comparisons could not be made with high-levels of confidence. In addition to growth, the potassium content is also a prominent factor during the combustion process and this will be considered later in the chapter.

### 5.3.2. Elemental & Component Relationships

The previous section contains the results of the proximate, ultimate, nutrient and lignocellulosic analysis for the individual birch and Sitka spruce samples, considered within this research. Understanding these in isolation is valuable, however using the data to infer different relationships between the elemental, chemical and structural components of the samples can allow conclusions to be proposed, extending beyond the considered data set. This section will therefore look to establish and clarify these potential relationships.

#### 5.3.2.1. Fixed Carbon

Proximate analysis is one of the simplest, yet most important, characterisation methods available for evaluating thermal conversion properties; determining the moisture, volatile matter, fixed carbon and ash contents of a given fuel. Of these, the moisture and ash contents have the greatest propensity to negatively impact the properties of biomass, either impacting the amount of useable energy or – in the case of ash – causing issues with corrosion and slag formation [15, 22, 46]. When considering the proximate properties, the ash, volatile matter (VM) and fixed carbon (FC) components are inherently linked; FC is a derived value, utilising the measured ash, moisture and VM contents of a sample.

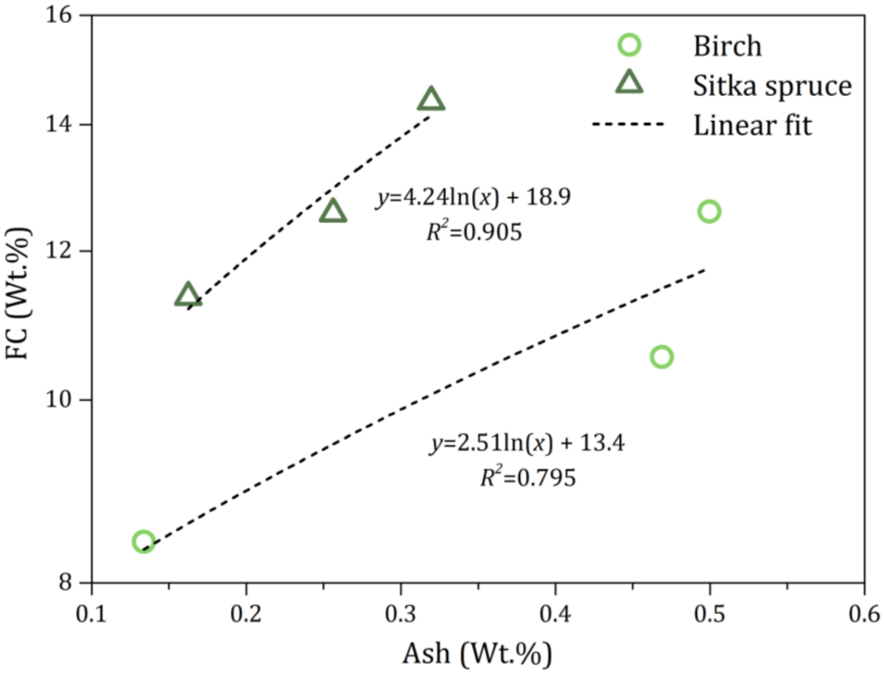


Figure 5.9 – **Logarithmic relationship between fixed carbon and ash content (on a dry basis) within the tree; mean values of stem, root and branch data**

Using the calculated mean values for the stem, root and branch data, Figure 5.9 highlights a positive correlation between the ash and FC contents of the two species; an increase in ash content coincides with increased levels of fixed carbon, evident throughout the tree. Although this is apparent for both the birch and Sitka spruce, their relationships with FC and ash differ, indicating that this is species dependent – this is supported by the produced nonlinear regressions in Figure 5.9. The ash and FC represent two of the four existing variables within a known mass, therefore logarithmic functions have been used; recognition that the pairs increased values cannot continue indefinitely.

The slope value for the Sitka spruce – which is larger than that of the birch – demonstrates that the increases in FC content within Sitka spruce incur ash accumulation at a reduced rate, compared to the birch. Considering the negative impacts associated with ash, the results indicate that Sitka spruce – evaluating the tree in its entirety – is more suitable for use as woodfuel, or for further carbonisation improvements, than birch. The functions – produced using the mean values of the stem, root and branch data – achieve strong correlation, demonstrated by their calculated $R^2$ values. However, to ensure that the produced values – using the regression functions – are representative of the experimental data, it is important that they are validated. As previously stated, the samples analysed within this research are a subgroup of the larger dataset used in Chapter 4. Applying the regression functions to the 37 birch and 41 Sitka spruce ash values, determined in the previous chapter, will produce estimations of their FC contents. These can be used in combination with the known experimental values to calculate the relative error. Consequently, the errors for the modelled birch and Sitka spruce FC contents are 8.2% and 9.8%, respectively. With the FC content being relatively low, the calculated errors are acceptable, therefore suggesting the regressions produce a good fit for both species.

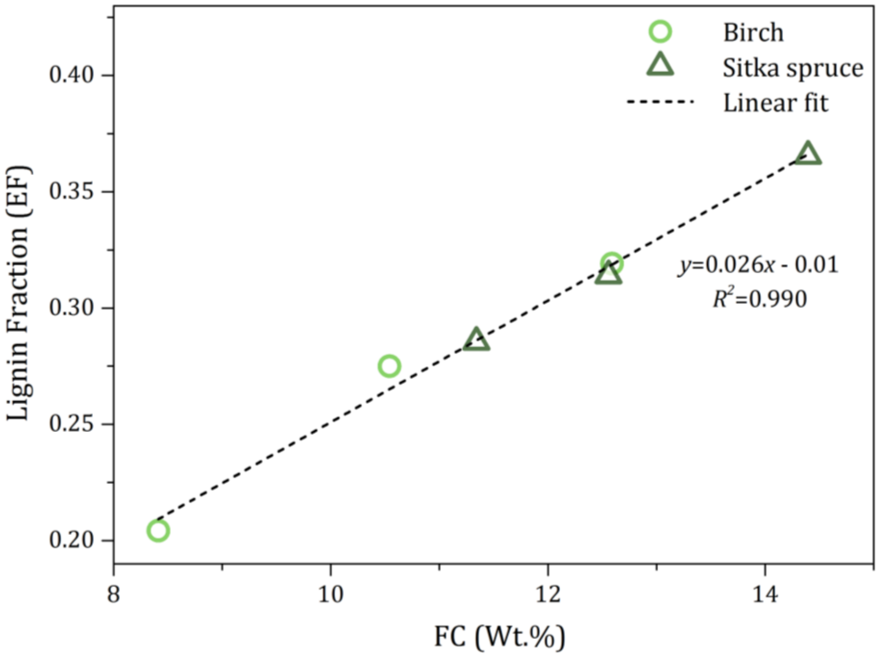


Figure 5.10 – **Relationship between fixed carbon and lignin content (on a dry basis) within the tree; mean values of stem, root and branch data**

The relationship between the FC and lignin contents of biomass have been previously investigated, considering an array of feedstocks with high and low lignin contents [47]. While proximate analysis is a simple process that can be completed relatively quickly and robustly, the method for determining lignin is the opposite; it includes digesting, filtering and washing the sample, which is time consuming and requires extensive lab-based expertise. The benefits of identifying and defining a relationship between lignin and FC are twofold; it would allow the lignin content to be confidently estimated using quick and cheap characterisation methods, while also giving the experimentally obtained lignin results a comparison value, helping validate their experimental process. Figure 5.10 identifies a strong positive correlation between the FC content and the extractive free lignin fractions of the two species – the increase of FC coincides with an increase in the lignin fraction of the structural components. Although there is species variation, the produced linear function is representative of a combined relationship that exists between lignin and fixed carbon, evidenced by its corresponding $R^2$ value ($R^2$=0.990). For a diverse set of biomass feedstocks with low lignin contents, Demirbaş (2003) suggested the following nonlinear function to determine lignin from the FC value;

$$Lig_x = 0.0608x^2 - 1.7057x + 27.2309 \qquad (5.8)$$

Applying Equation 5.8 to the FC contents of the 36 samples – considered within this chapter – produces a relative error of 9.5%. In comparison, the linear function in Figure 5.10 produces a relative error of 3.8% for the same set of samples. As a result, the function produced in this chapter – detailed in Eq. 5.9 – is better constructed to model the relationship between lignin and FC for birch and Sitka spruce. The stark difference in error values supports the extensively documented statement, that large-scale variability exists between biomass feedstocks [3, 22, 46, 47]. Therefore, by instead focusing on specific species it is possible to refine the functions to best describe the experimental data.

$$Lig_x = 0.026x - 0.01 \qquad (5.9)$$

This section has identified relationships that exist between FC and ash, and then, between FC and lignin, evidencing strong positive correlations in both cases.

Considering the results contained within Figures 5.9 and 5.10, it would be acceptable to assume that there is a species dependent relationship between a tree's ash content and its lignin. Indeed, within the cells secondary walls – which undergo extensive lignification during growth – detectable concentrations of key inorganic species exist, including chlorine, calcium, sulphur and potassium [39]. Additional literature also supports an interaction between ash and lignin; particularly the existence of potassium and sodium – two important inorganic components contained within lignin – which prompt increased char yields [48, 49]. While the FC content is derived – dependent upon the correct measurement of the other proximate variables – the ash content can be easily determined directly from experimental analysis, making it a preferable characteristic to base modelled data upon. Individual nonlinear functions for birch and Sitka spruce – depicting the relationship between ash and lignin content – can be produced by combining the previously determined functions. As a result, Figure 5.11 depicts these functions, specific to the two species considered.

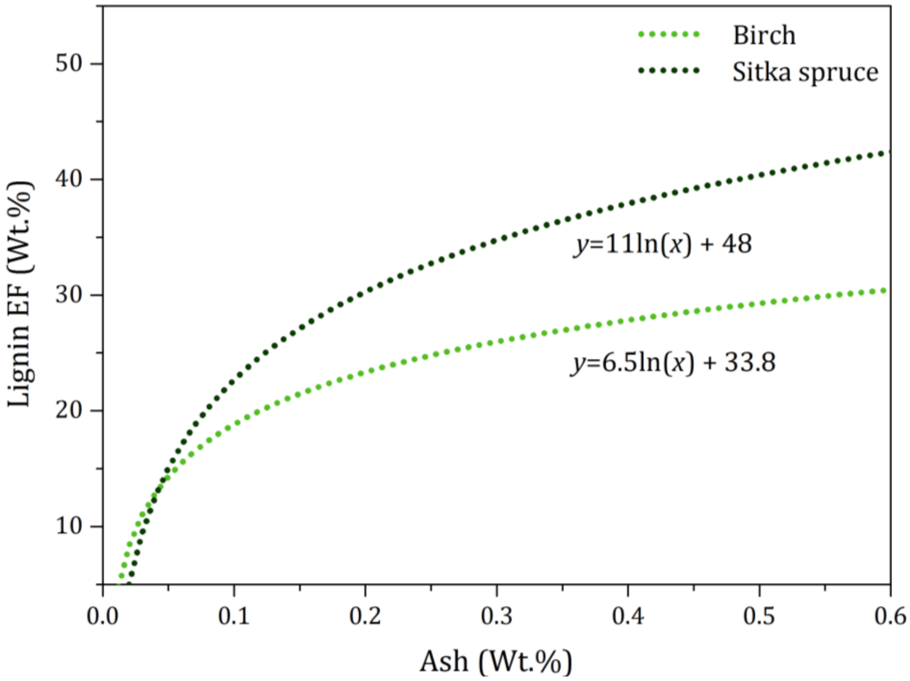


Figure 5.11 – **Modelled relationship between ash and extractive free lignin contents (on a dry basis) for birch and Sitka spruce**

Again, validating the produced models against experimental data is important, therefore the ash contents of the 37 birch and 41 Sitka spruce samples from the previous chapter were used. Subsequently, the results produced from the birch function – when compared to their experimental lignin results – have a relative error of 5.9%. For the Sitka spruce model the relative error is slightly larger, calculated at 7.7%.

### 5.3.2.2. Nitrogen Interactions

Nitrogen and potassium are important constituents of biomass, both having key influences on the growth process and during combustion. Establishing their contents within wood biomass is clearly important on an individual basis, however identifying potential relationships between the two would help infer conclusions that are applicable outside this research. Consequently, Figure 5.12 highlights a negative influence of potassium content on that of the nitrogen, contained within the stem wood of birch and Sitka spruce species. Considering the previous characterisation results, the stem wood samples show the smallest amounts of variation, when compared to the rest of the tree. However, the existing relationship between nitrogen and potassium clearly highlights that interspecies differences in homogeneity are still evident within the stem wood.

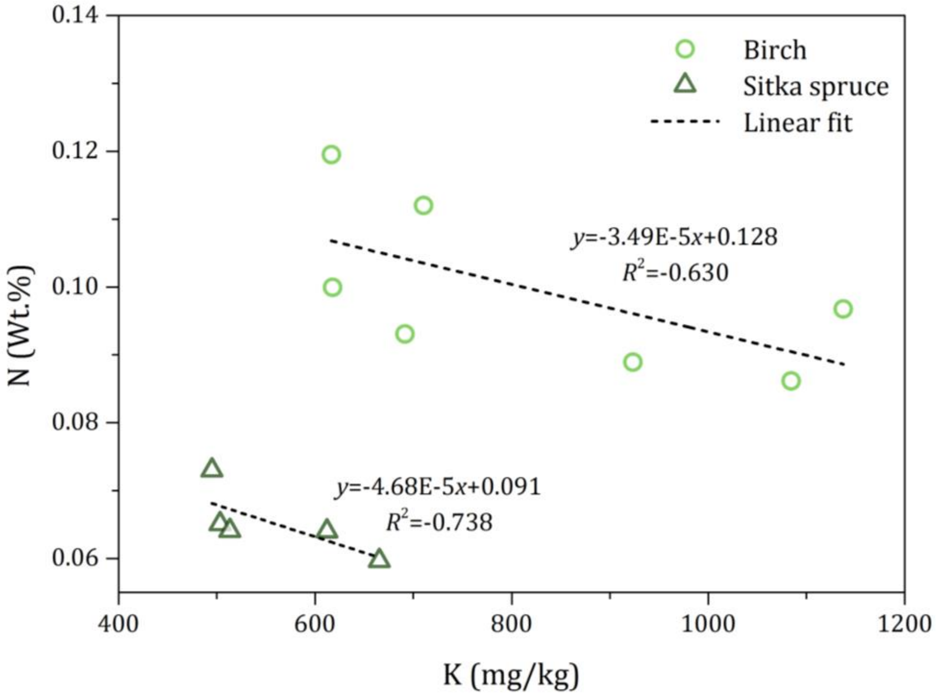


Figure 5.12 – **Linear relationship of nitrogen and potassium (on a dry basis) within birch and Sitka spruce stem wood**

The linear regressions contained within Figure 5.12 indicate that increased concentrations of potassium, within the stem wood, coincide with a reduction in nitrogen. Although there are differences in the determined values, a negative correlation is apparent for both the birch and the Sitka spruce samples, analysed within this research. These results suggest that, firstly, the growth of birch stem wood is more dependent upon nitrogen and potassium than Sitka spruce, requiring a larger supply of the nutrients. Secondly, the negative correlations between the two elements – apparent for both species – imply that their stem wood may have boundaries for nutrient saturation; where increases in available nitrogen and potassium will only increase stem wood growth to a certain level, before depositing in other sections of the tree. This would have implications on nutrient management practices, such as fertiliser application, which form a key part of forest silviculture; the identification of potential areas of nutrient wastage is vital for improving the economics of biomass [45].

This relationship is also important when considering the thermal conversion of birch and Sitka spruce stem wood. As previously discussed, the potassium content affects the reactivity of the wood and can influence fouling and slagging, while nitrogen – and the consequent production of $NO_x$ – has negative effects on the environment and human health [16, 24, 29, 49]. The interactions between the contents of the two elemental constituents, illustrated in Figure 5.12, suggest that increased or reduced nitrogen contents will coincide inversely, with that of the potassium. Previous research on domestic wood combustion, which focused on wood with larger nitrogen contents than the species analysed in this chapter, determined that $NO_x$ emissions were reduced, across the entire combustion process, when compared to fuels such as coal [50]. Therefore, when considering the potential use of the two species as fossil fuel replacements, the reduced nitrogen and potassium contents – coupled with its increased homogeneity – make the Sitka spruce stem wood a more preferable source. Alternatively, if utilising birch as a fuel, the linear relationship in Figure 5.12 indicates that stem wood with an increased nitrogen content – which is still low when compared to other biomass sources – should be preferred, as this would result in a reduced potassium content.

### 5.3.3. Combustion Characteristics

So far this chapter has established the characteristics of the two species, focussing on how these differ between one another and within the tree itself. Building upon this, the potential relationships and how these may impact the combustion properties have also been considered. Consequently, this next section will focus on the completed TGA experimental work, considering the variations in combustion characteristics displayed by the birch and Sitka spruce.

#### 5.3.3.1. Lignocellulosic Combustion

Offering context and a reference for comparison, the combustion characteristics of a number of lignocellulose-based standards have also been analysed. Utilising the same combustion conditions used for the birch and Sitka spruce, the analysed standards include examples of cellulose, lignin and hemicellulose. Unlike cellulose, which is well defined, hemicellulose is heterogeneous in nature and consists of polysaccharides that differ in their structural and physiochemical properties [51]. Consequently, a total of four monosaccharide standards and one polysaccharide standard – all associated with hemicellulose – where analysed; their derived rates of mass loss (Wt.% $s^{-1}$), produced using TGA combustion data, is located in Figure 5.13.

The derived mass loss data highlights the variation that exists between the hemicellulose-based standards, particularly the reactivity characteristics that occur between 100°C and 300°C. This temperature range is in keeping with those reported in existing combustion literature [32, 34]. Firstly, the initial mass loss temperature of the standards differ; arabinose is the most reactive, initiating its mass loss at ~125°C, while the mannose, xylose, glucose and xylan all begin to decay at higher temperatures, in the region of 150°C. Once the thermal decomposition has commenced, the standards exhibit differing peak rates of reactivity, occurring at different temperatures. This demonstrates that the heterogeneity that exists within hemicellulose, as previously reported [51], extends to their combustion characteristics. The thermal degradation of the monosaccharides produce two clearly defined reactivity peaks that occur before 300°C; this differs for the polysaccharide, xylan, which instead contains a shoulder before reaching peak reactivity. The stated range of temperatures suggest that the two peaks are associated with the devolotilization phase.

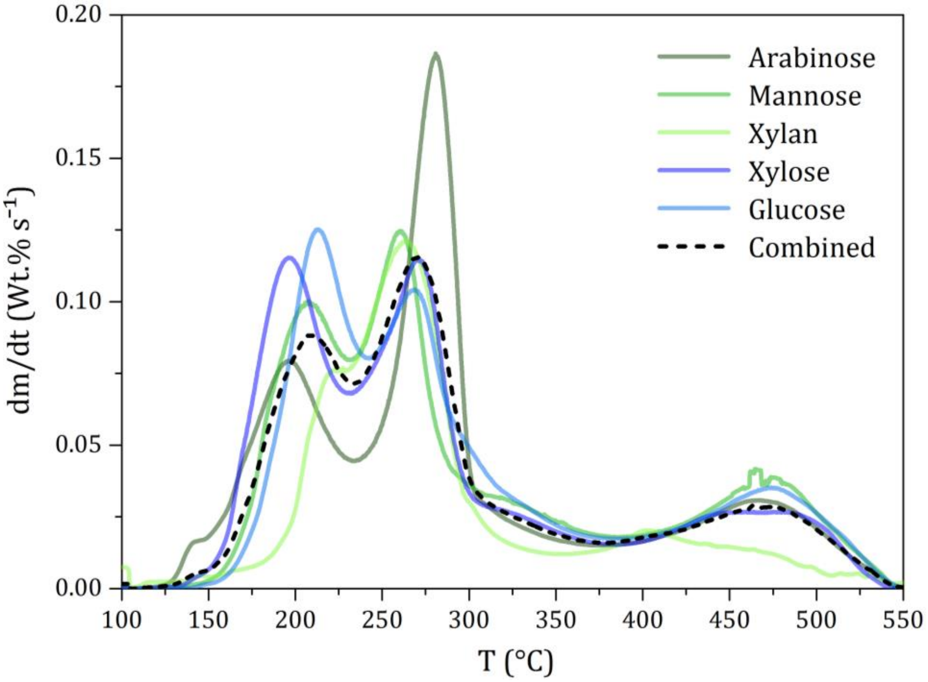


Figure 5.13 – **Comparison of the derived rates of mass loss (Wt.% s$^{-1}$) of different hemicellulose-based monosaccharide standards during temperature programmed combustion**

As presented in Figure 5.13, a distinct third peak exists, occurring between 400°C and 500°C; this is observable for all five standards, although the peak is reduced for the polysaccharide. Unlike the previous two peaks, the third is associated with char combustion, indicating that hemicellulose decomposition generates both volatiles and char – albeit the remaining carbon enriched residue, left after devolatilisation, is in much smaller quantity [36, 37]. Importantly, this gives validity to the assumption made previously in Section 5.2.6; that the thermal degradation of hemicellulose occurs across both the devolotilization and char combustion phases. In addition to the analysed standards, a combined plot has been produced to represent the hemicellulose group and its diverse nature. The combination and quality of the polysaccharides that comprise hemicellulose, differ greatly between species; the xylans found in hardwoods tend to contain more glucose monosaccharides, while those contained within softwoods have more mannose and arabinose monomeric groups within the polymer [39, 51]. Consequently, different xylan compositions will result in different profiles, making the production of a single plot – representative of hemicellulose – inherently difficult. Therefore, in this instance, an even weighting of 0.2 has between applied to the five standards.

Figure 5.14 depicts the reactivity differences that exist between the structural components, found within wood biomass. The cellulose and lignin plots have been produced using their combustion data, while the hemicellulose plot is the weighted combination of the five standards, previously illustrated in Figure 5.13.

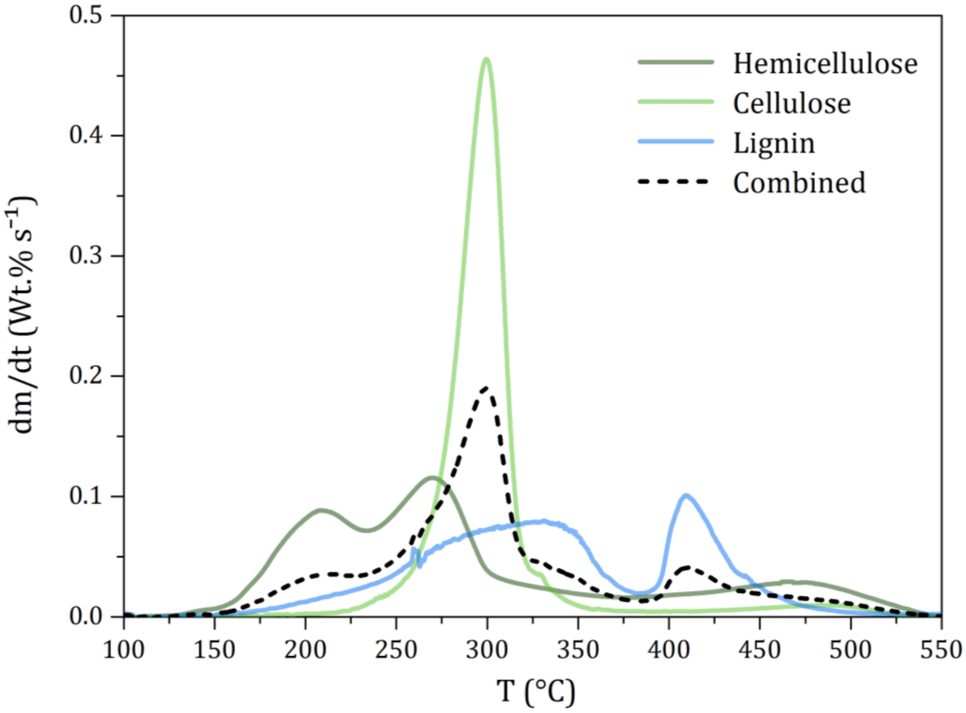


Figure 5.14 – C**ombustion of structural components; derived rates of mass loss (Wt.% s$^{-1}$) for hemicellulose, cellulose, lignin and combined lignocellulose**

The initial decomposition of cellulose occurs at a higher temperature than both the hemicellulose and the lignin; a factor, again, supported in the literature, giving validity to the combustion methodology used and its consequent results [32]. However, unlike the hemicellulose and lignin – both typified by relatively slow increases in reactivity – cellulose decomposes rapidly, over a short period of time, due to its simple polymeric structure. This results in the production of a single defined peak, with its maximum rate of reactivity far exceeding that of the other structural components. The analysed lignin standard – which has an initial mass loss temperature falling between that of the hemicellulose and cellulose –

contains two distinct peaks of reactivity. The degradation of the lignin is a slow process, occurring over a larger temperature range than the polysaccharide-based hemicellulose and cellulose. During the devolatilisation stage, the lignin decomposition produces aromatic compounds and char. Indeed, of the structural components existing in wood, lignin accounts for the largest fraction of the produced char [24]. As shown in Figure 5.14, the char combustion of the lignin sample occurs at ~400°C.

As previously evidenced in this chapter, the mass distribution between the hemicellulose, cellulose and lignin differs between species. For simplicity, an even weighting has been applied to the three structural components – combining them into a single plot – which is located in Figure 5.14. Although produced purely from 'off-the-shelf' standards, the plot highlights the relationship that the three separate components – and their subsequent mass contents – have during the entire combustion process.

#### 5.3.3.2. Combustion of birch & Sitka spruce

This chapter has considered the combustion characteristics of 36 samples in total, consisting of wood taken from the stem, root and branches of seven birch and five Sitka spruce trees. The results of the combustion analysis are presented in Figure 5.15 and Figure 5.16 for the birch and Sitka spruce, respectively. The extracted temperature and peak reactivity data – accompanying Figures 5.15 and 5.16 – can be found in Table 5.7 and Table 5.8, respectively.

Table 5.7 – **Determined mean temperatures (°C) from mass loss data for birch (BI) and Sitka spruce (SI); comparison between stem, root and branch wood**

| | | **Combustion Temperatures (°C)** | | | | | **Potassium (mg/kg)[a]** |
|---|---|---|---|---|---|---|---|
| | | $T_1$ | $T_s$ | $T_v$ | $T_c$ | $T_2$ | |
| **BI** | Stem | *240 (±1.4)* | *288 (±2.1)* | *326 (±1.8)* | *457 (±4.5)* | *472 (±3.1)* | *826* |
| | Root | *239 (±2.1)* | *291 (±1.7)* | *327 (±1.7)* | *445 (±4.9)* | *471 (±2.8)* | *1168* |
| | Branch | *233 (±0.9)* | *287 (±2.1)* | *324 (±1.4)* | *448 (±2.6)* | *473 (±5.4)* | *951* |
| **SS** | Stem | *246 (±1.5)* | *273 (±2.7)* | *328 (±0.8)* | *463 (±4.2)* | *481 (±3.3)* | *558* |
| | Root | *244 (±1.0)* | *274 (±2.9)* | *328 (±1.1)* | *462 (±3.2)* | *477 (±2.0)* | *896* |
| | Branch | *240 (±2.5)* | *269 (±6.7)* | *325 (±1.6)* | *457 (±3.9)* | *478 (±4.5)* | *773* |

*$_1$ Initial Mass loss, s Shoulder, v Peak Volatile, c Peak Char, $_2$ Burnout, $^a$ mean values from Table 5.6*

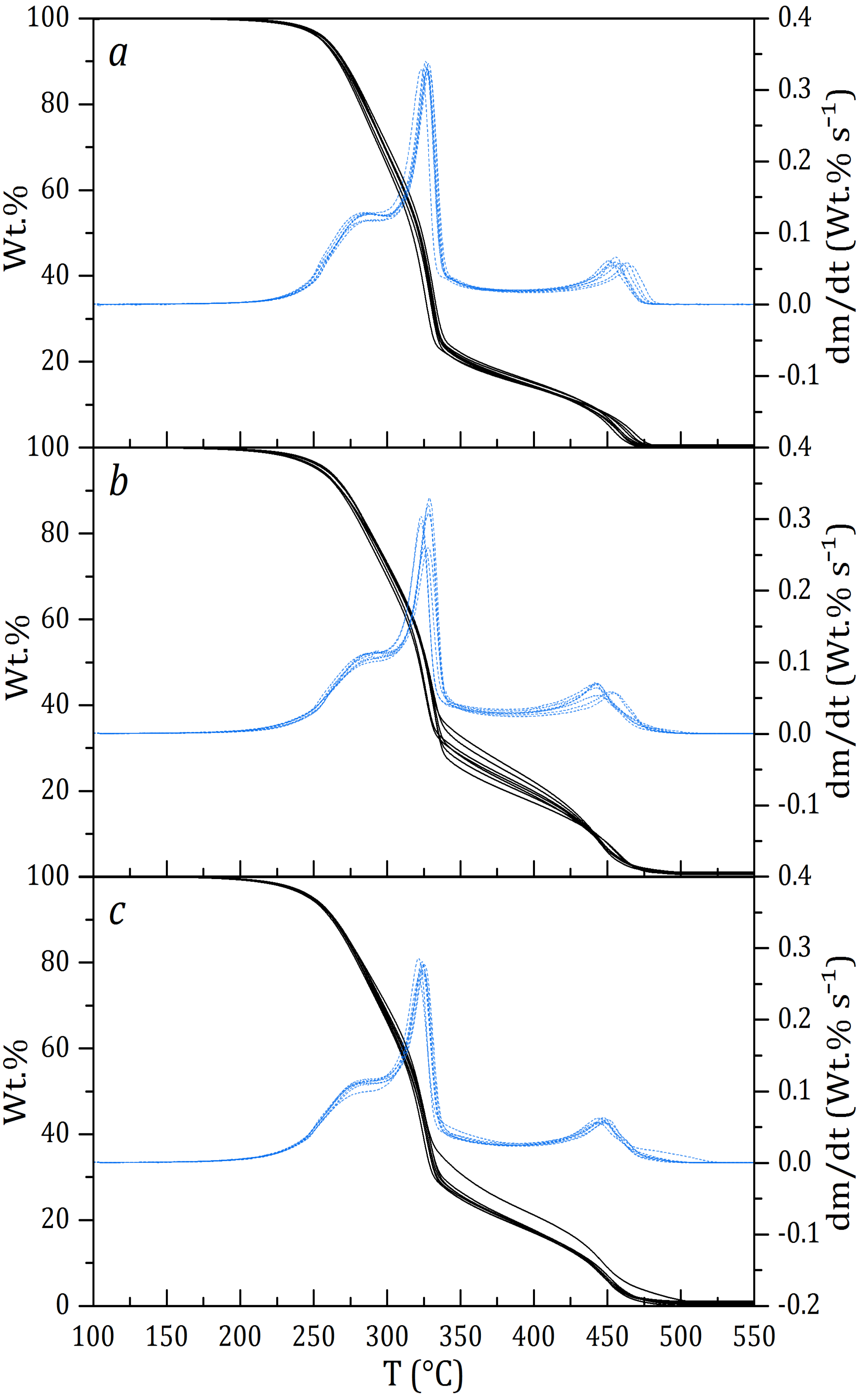


Figure 5.15 – **Mass loss profiles and derived rates of reactivity (on a dry basis) produced from the combustion of seven individual birch trees; comparison between their stem (a), their root (b) and branch (c) wood**

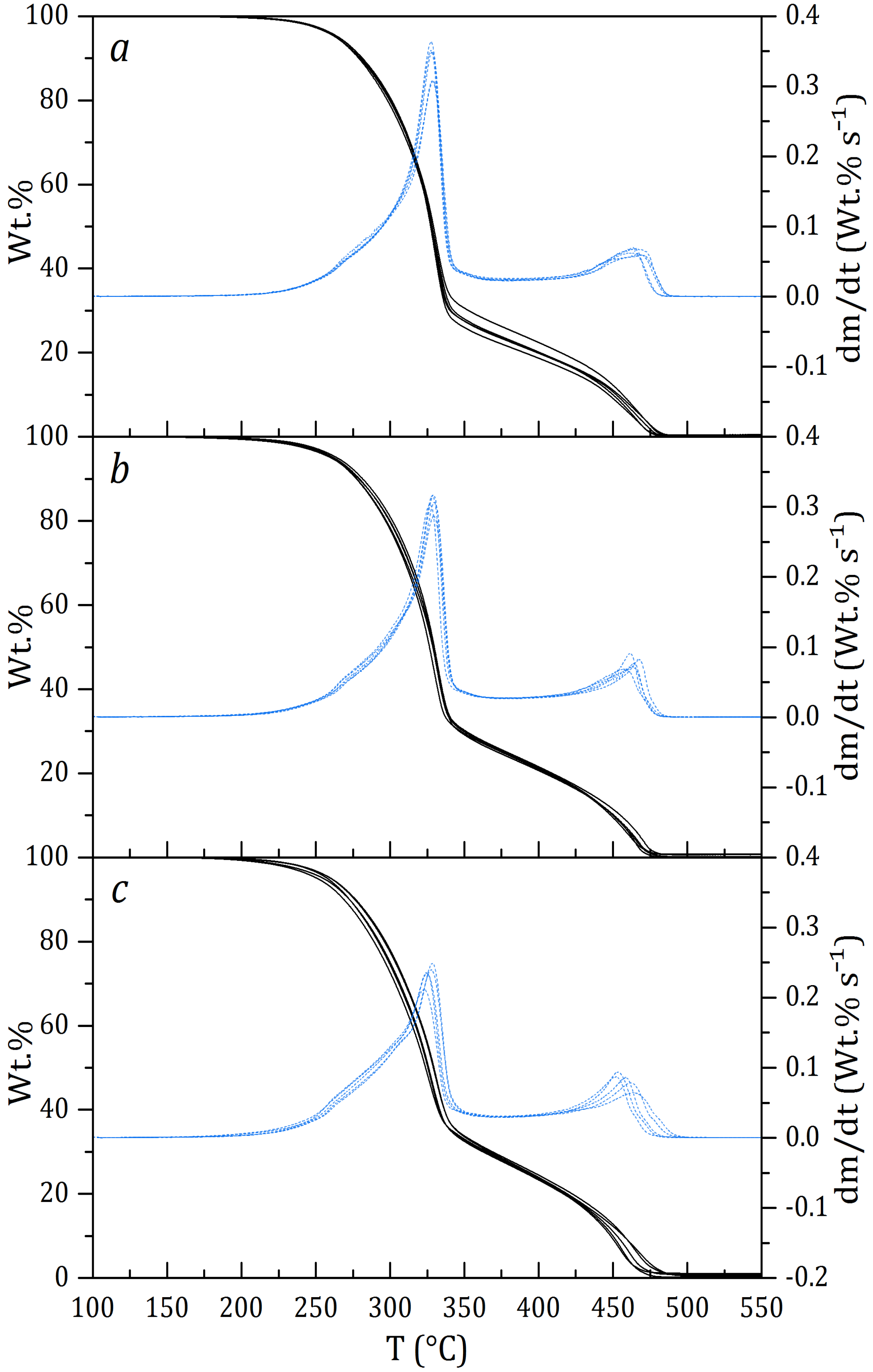


Figure 5.16 – **Mass loss profiles and derived rates of reactivity (on a dry basis) produced from the combustion of five individual Sitka spruce trees; comparison between their stem (a), their root (b) and branch (c) wood**

Table 5.8 – **Determined mean peak reactivity rates for key points during the combustion of birch (BI) and Sitka spruce (SI); comparison between stem, root and branch wood**

| | | dm/dt (Wt.% s$^{-1}$) | | |
|---|---|---|---|---|
| | | Shoulder | Peak Volatile | Peak Char |
| **BI** | Stem | 0.12 (±0.005) | 0.33 (±0.006) | 0.06 (±0.005) |
| | Root | 0.11 (±0.005) | 0.29 (±0.026) | 0.06 (±0.006) |
| | Branch | 0.11 (±0.006) | 0.27 (±0.010) | 0.06 (±0.003) |
| **SS** | Stem | 0.06 (±0.008) | 0.33 (±0.022) | 0.06 (±0.009) |
| | Root | 0.06 (±0.005) | 0.30 (±0.009) | 0.08 (±0.006) |
| | Branch | 0.06 (±0.014) | 0.23 (±0.012) | 0.08 (±0.009) |

The stated initial mass loss temperatures show a difference between the two species, indicating that birch is more reactive than the Sitka spruce – apparent for the different tree sections. As a result, the most reactive set of samples were the birch branch wood, initiating decomposition at 233°C (±0.9°C), while the least reactive are the Sitka spruce stem wood, which didn’t begin thermal degradation until 246°C (±1.5°C). Although the temperatures differ, there is a comparable pattern between the different tree sections – the stem wood is the least reactive, while the branch wood is the most. Considering the burnout temperatures of the samples, there is again a clear difference in the reactivity of the two species; the birch achieved burnout at lower temperatures than the Sitka spruce. Burnout for the birch occurs from 471-473°C – dependent on the tree section – while for the Sitka spruce this range was determined as 478-481°C.

While the birch displays greater reactivity than the Sitka spruce for both its initial decomposition and burnout temperatures, this is not the case for the hemicellulose ‘shoulder’, which occurs where the decomposition of structural components overlap [27]. The derived reactivity data in Table 5.7 indicates that the Sitka spruce hemicellulose is more reactive. Indeed, the peak reactivity of the shoulder, for the birch stem wood, occurred at 288°C (±2.1°C), while for the Sitka spruce the temperature was 273°C (±2.7°C). These are comparable to previously published results [27, 32, 34]. Peak decomposition reactivity rates, occurring at the stated temperatures, can be found in Table 5.8. The hemicellulose shoulder of the Sitka spruce occurs at a lower temperature, coinciding with its reduced peak rate of reaction when compared to the birch; these are established as 0.06 and 0.12 Wt.% s$^{-1}$ for the Sitka spruce and birch stem wood, respectively. The difference between the two species is given in Figures 5.15 and 5.16, with a pronounced shoulder clearly evident for the birch when compared to the Sitka spruce. These results imply that the temperature difference, existing between the two samples, are dictated by the combination of polysaccharides classified within the hemicellulose.

The peak rates of thermal degradation associated with the volatile component – and the temperatures these occur at – are similar for both the birch and the Sitka spruce samples. For the birch, this occurred between the temperatures of 324-326°C while, for the Sitka spruce, this was determined as 325-328°C. Again, these are comparable to previously published temperature results [27, 32], and the peak temperature of the cellulose in Figure 5.14. The reactivity rates, detailed in Table 5.8, are significantly larger than those of the hemicellulose shoulder. Additionally, the calculated mean results indicate that there is little species-based variation between the stem and root wood. There is however, intra-species variation; this is most evident with the birch root samples, which have a large relative error associated with their peak volatile reactivity, calculated as 9%. The increased heterogeneity of the birch root wood as a fuel is visible in Figure 5.15, especially when compared to the mass loss plots of the other sections and species. Finally, the char combustion phase – observed as the second peak in Figures 5.15 and 5.16 – takes place at temperatures in excess of 400°C. The validity of the stated temperatures, located in Table 5.7, are in agreement with previously published char combustion results [52, 53]. Moving away from the relatively homogenous nature of the volatile combustion, the species variance reappears with the peak rates of char degradation. This is visible in both the mass loss and derivative plots, specifically those of the birch stem and Sitka spruce branch wood. The results indicate that the birch root char is the most reactive, with peak reactivity achieved at 445°C (±4.9°C), while the Sitka spruce stem wood is again the least reactive, occurring at 463°C (±4.2°C).

### 5.3.4. Potassium & Combustion Relationship

As previously discussed, potassium is a highly mobile nutrient which, once taken up through the roots, distributes itself around the tree and aids in its growth.

Further to its role in cell expansion – supporting key functions, such as water and nutrient transportation – its impact on the combustion process is well documented; the existence of potassium salts and other catalytic metals within biomass affect its reactivity. Some of the potassium contained within wood is in a more mobile state, resulting in its release during combustion [29, 54, 55]. The completed potassium results – completed on all 36 samples – can be found in Table 5.6, however their calculated mean values have also been included in Table 5.7.

In addition to increasing the fuel's reactivity, potassium can also cause issues with corrosion. The partitioning of K between the vapour and solid phase, during combustion, depends on the salts and other minerals that are present. Some of the potassium is bound to organic structures, such as the hemicellulose, while detectable levels of potassium have been established within the secondary walls of cells, which are directly linked to a tree's lignin content [39, 55]. Since the thermal degradation of hemicellulose occurs at lower temperatures than the other structural components, the relationship with potassium content and the temperature of initial mass loss can be investigated.

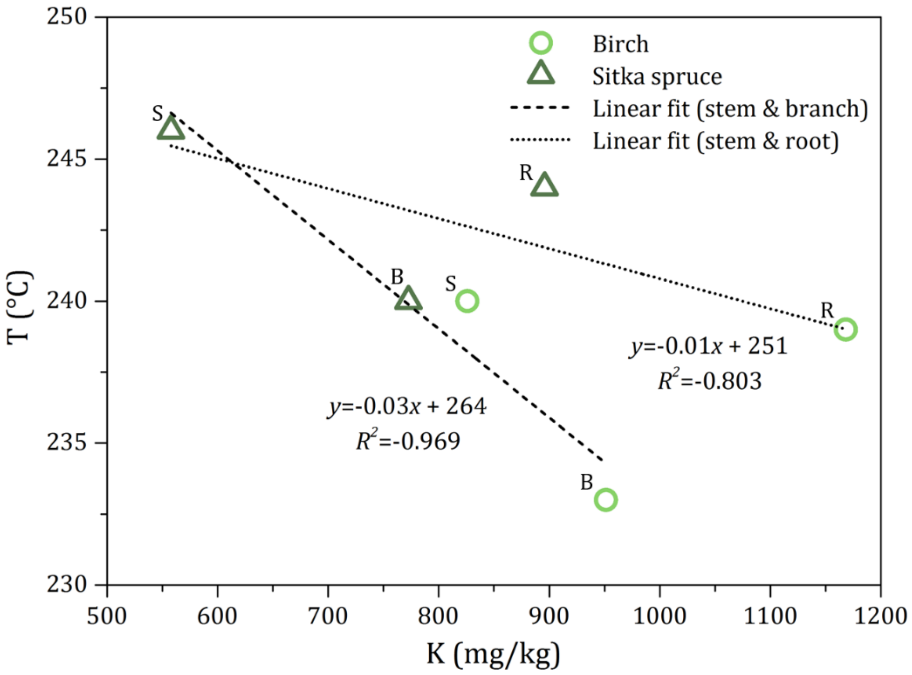


Figure 5.17 – **Relationship between mean potassium and initial mass loss temperature results for birch and Sitka spruce; differences in root (R) and branch (B), including the stem (S)**

Considering the propensity of potassium to increase reactivity, Figure 5.17 plots the mean potassium contents and initial mass loss temperature for the different tree sections. Firstly, interspecies variation is evident; the birch has an increased potassium content and is more reactive than the Sitka spruce, visible throughout the entirety of the tree. Since no single relationship is observed in Figure 5.17, it suggests that although potassium clearly impacts reactivity, the severity of this impact differs for different tree sections.

Observable for both species, the roots contain more potassium than the branches, but are subsequently less reactive – this is supported by the differences in the two produced linear regressions. The results suggest that potential fundamental differences exist in the catalytic availability of potassium within the lignocellulosic components, specifically in relation to the roots and branches. Effectively, the decreased reactivity witnessed in the roots, when compared to the branch wood, may be a result of lower potassium within its hemicellulose. The bulk of the potassium would instead be located elsewhere, particularly the lignin. Tree roots play a vital role in accessing the essential nutrients and water contained within soil; accordingly, to support transportation, their cells will likely experience increased lignification. Indeed, the results in Section 5.3.2.1 demonstrate a relationship between ash – of which potassium is a key constituent – and lignin content. This, coupled with previously published research – which shows the existence of potassium within lignin-rich secondary cell walls – adds weight to the inferred conclusions on potassium and how it differs in different tree sections [15, 39, 55].

Although the use of calculated means allow for the identification of general correlations, their use can prompt other, more detailed, relationships to be overlooked. Consequently, Figure 5.18 plots the potassium and initial mass loss temperature results for each individual sample, allowing for a more thorough analysis of the species, specific to tree sections. Again, as with Figure 5.17, the grouping of birch and Sitka spruce results show a clear interspecies variation, with the inclusion of individual results amplifying this. Although the relationship between increased potassium and reactivity is clearly evident, the results highlight that the species and tree sections have a much greater influence on reactivity. The potential for other species-specific factors to impact reactivity is

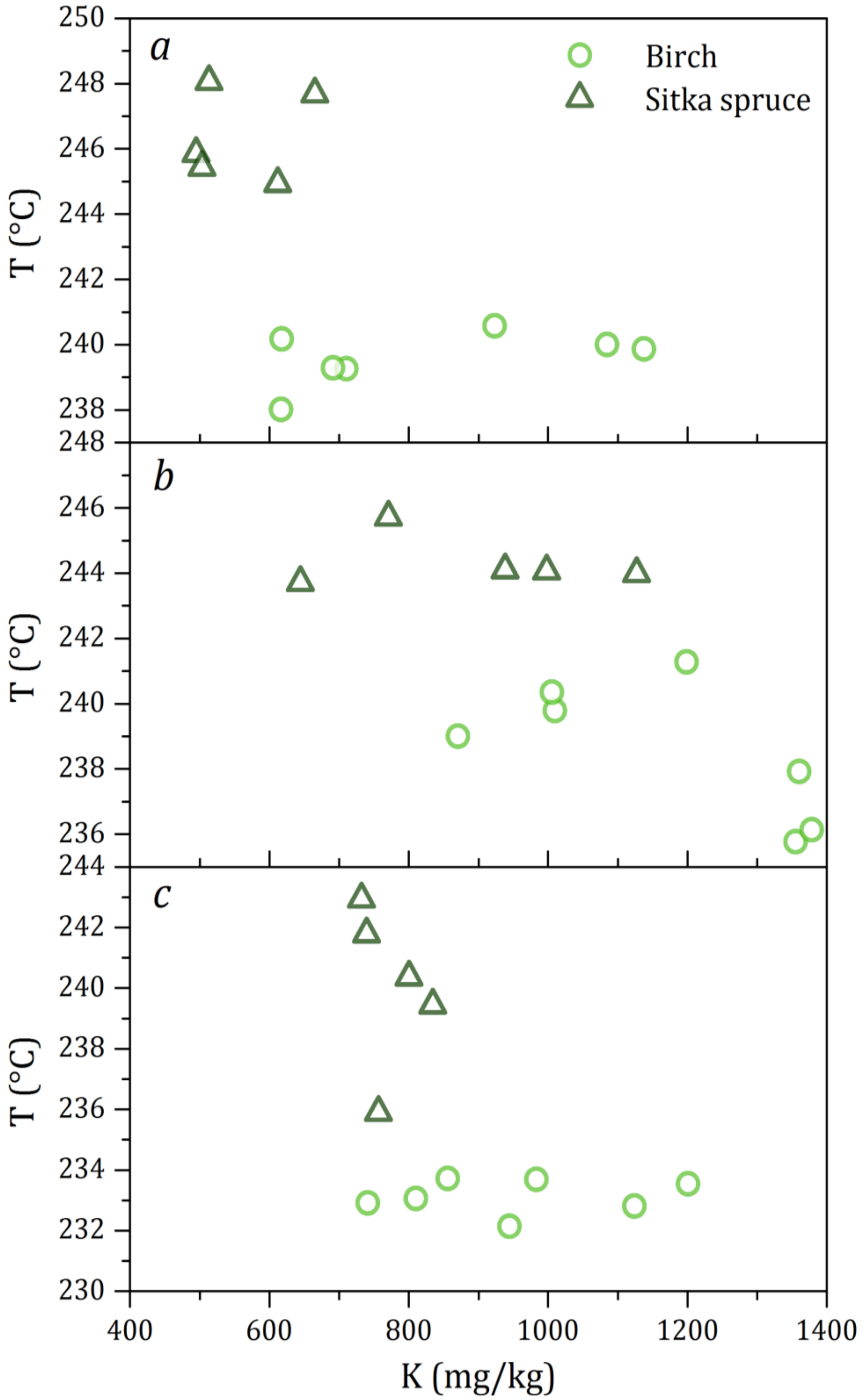


Figure 5.18 – **Relationship between potassium content (on a dry basis) and initial mass loss temperature for birch and Sitka spruce; comparison between stem (a), root (b) and branch (c) wood**

best highlighted in the branch wood of the birch and Sitka spruce. The potassium contents of the Sitka spruce branch wood varies only slightly, but their initial reactivity differs markedly. Inversely, the determined initial mass loss temperatures of the birch are contained to a difference of just 2°C, while its potassium range is more than 4 times that of the Sitka spruce.

Although their mean values form part of a strong negative correlation, shown by the linear regression in Figure 5.17, the data points in Figure 5.18 suggest there are other relationships at work. The results of the birch branch samples – which are the most reactive group – indicate that the increased potassium content has little impact upon the reactivity. Although spanning a larger temperature range, this is also evident for the birch stem wood suggesting potential species-based heterogeneity, with regards to reactivity. Accepting that the existence of potassium – in the form of salts, located within the cells – increases reactivity, it's possible to infer the following conclusion; that the amount of catalytically active potassium associated with the hemicellulose component of wood is limited by species and tree section. This can be supported by previous research on the release of potassium for a range of different biomasses, which have shown that the mobility of potassium is dictated by the species [16, 55].

### 5.3.5. Kinetic Modelling

The kinetic parameters produced as part of this combustion chapter – modelling both the devolatilisation and char combustion process – are based upon the combustion data produced in Section 5.3.3, using a modified version of the *Reaction Rate Constant Method*.

Table 5.9 – **Determined kinetic parameters and weightings used for modelling the combustion of hemicellulose (He), cellulose (Ce) and lignin (Li)**

| | | Parallel Reactions | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| **He** | $E$ | *130.9* | *59.3* | *87.1* |
| | $\ln A$ | *28.1* | *7.1* | *8.3* |
| | $n_x$ | *0.19* | *0.61* | *0.2* |
| **Ce** | $E$ | *179.5* | - | - |
| | $\ln A$ | *32.9* | - | - |
| | $n_x$ | *1* | - | - |
| **Li** | $E$ | *62.4* | *260.6* | - |
| | $\ln A$ | *7.2* | *40.2* | - |
| | $n_x$ | *0.68* | *0.32* | - |

*E=activation energy (kJ mol$^{-1}$), A=pre-exponential factor (1/s), $n_x$=mass fraction*

The model assumes a set of parallel reactions – occurring for each of the structural components – which, when combined, give the overall mass loss rate of the given lignocellulosic fuel [35]. Accordingly, the mechanism used to determine the kinetic differences between birch and Sitka spruce, given in Equation 5.7, utilises their determined hemicellulose, cellulose and lignin values – each parallel reaction is attributed an equivalent mass fraction value, given by $n_x$. The experimental combustion results given in Figure 5.14, highlight a total of six peak rates of reactivity that occur during the combustion of the lignocellulosic components; three are associated with the hemicellulose, two with the lignin and one with the cellulose. In addition to identifying peaks, the derived burning profiles can be used to measure the areas under each peak, establishing values for their mass fraction. Utilising this, Figure 5.19 plots the modelled reactivity rates of the hemicellulose, cellulose and lignin, while their associated kinetic parameters are located in Table 5.9.

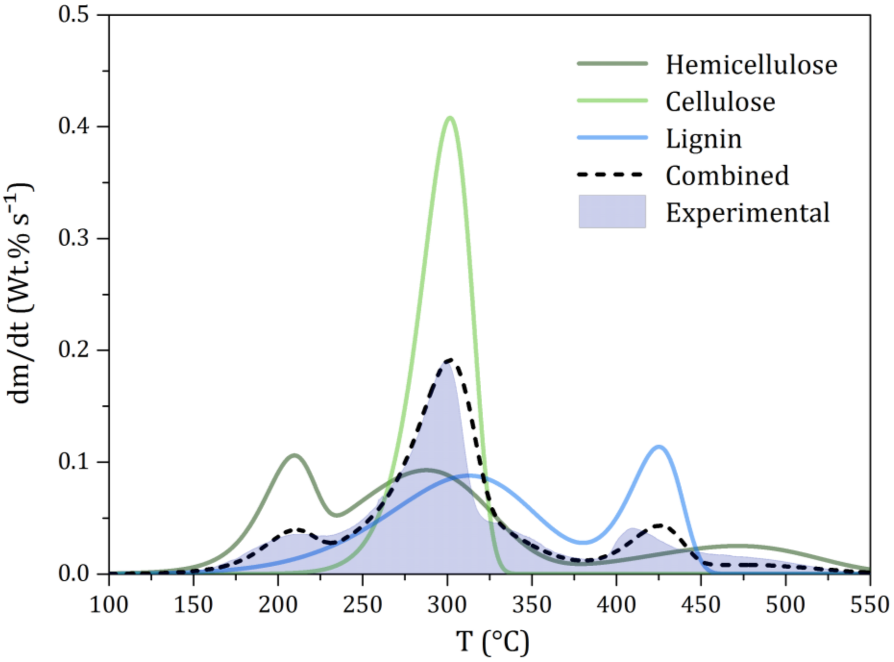


Figure 5.19 – **Modelled reactivity rates (Wt.% s$^{-1}$) of hemicellulose, cellulose and lignin; comparison between combined model data and experimental data**

Similarly to the experimental results in Figure 5.14, an even weighting has been applied to each of the structural components, producing a combined plot that represents the combustion rates of reactivity for a generic lignocellulosic fuel. The peaks associated with the devolatilisation and char combustion phase are clearly evident, as is the initial hemicellulose shoulder. Figure 5.19 details the combined plots for both the experimental and modelled data – the model, based upon a total of 6 parallel reactions, clearly represents a good fit. Indeed, the modelled combustion data has a calculated relative error of 3.9% for its rate of reactivity plot.

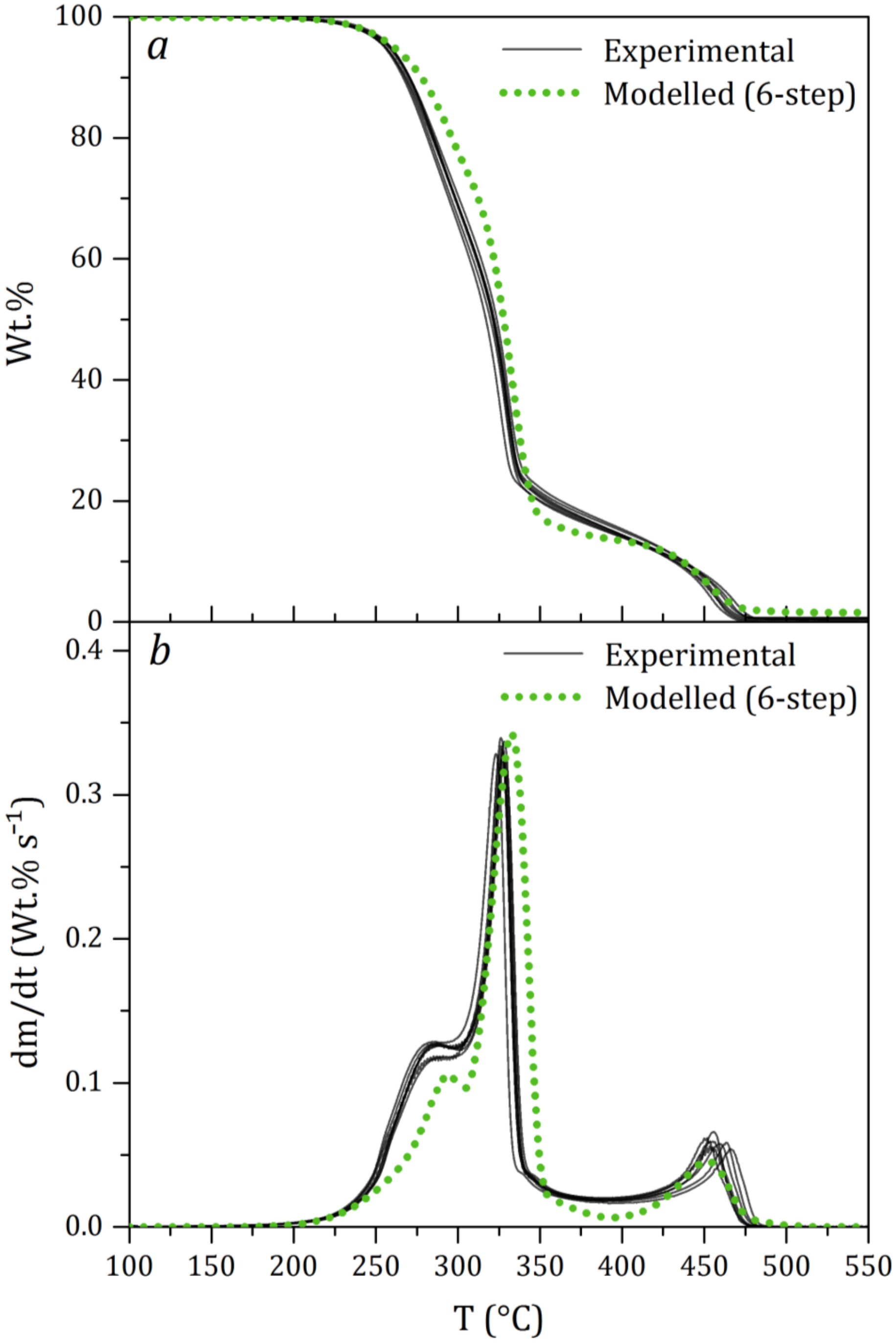


Figure 5.20 – **Modelled mass loss (a) and rate of reactivity (b) plots for birch stem wood; using a 6-step kinetic model, based on lignocellulosic contents**

Table 5.10 – **Kinetic parameters, weightings and calculated errors for the modelled combustion of birch (BI) and Sitka spruce (SI); determined using a 6-step kinetic model, based on lignocellulosic mass fractions**

| | | **Hemicellulose** | | | **Cellulose** | **Lignin** | | | **Error (%)** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | $m_{\infty}$ | Mass loss | dm/dt |
| **BI** | $E$ | *129.7* | *215.0* | *120.2* | *274.2* | *87.6* | *308.7* | *1.58* | *1.35 - 2.20* | *3.61 - 5.69* |
| | $\ln A$ | *24.8* | *41.6* | *14.7* | *50.3* | *12.0* | *46.8* | | | |
| | $n_x$ | *0.048* | *0.145* | *0.048* | *0.554* | *0.123* | *0.082* | | | |
| **SS** | $E$ | *146.2* | *147.2* | *109.5* | *251.1* | *75.7* | *253.9* | *0.62* | *1.41 - 2.49* | *3.14 – 5.55* |
| | $\ln A$ | *28.6* | *26.7* | *12.6* | *45.4* | *9.3* | *37.0* | | | |
| | $n_x$ | *0.032* | *0.095* | *0.032* | *0.555* | *0.172* | *0.114* | | | |

*E=activation energy (kJ mol$^{-1}$), A=pre-exponential factor (s$^{-1}$), $n_x$=mass fraction, $m_{\infty}$=terminal mass (Wt.%)*

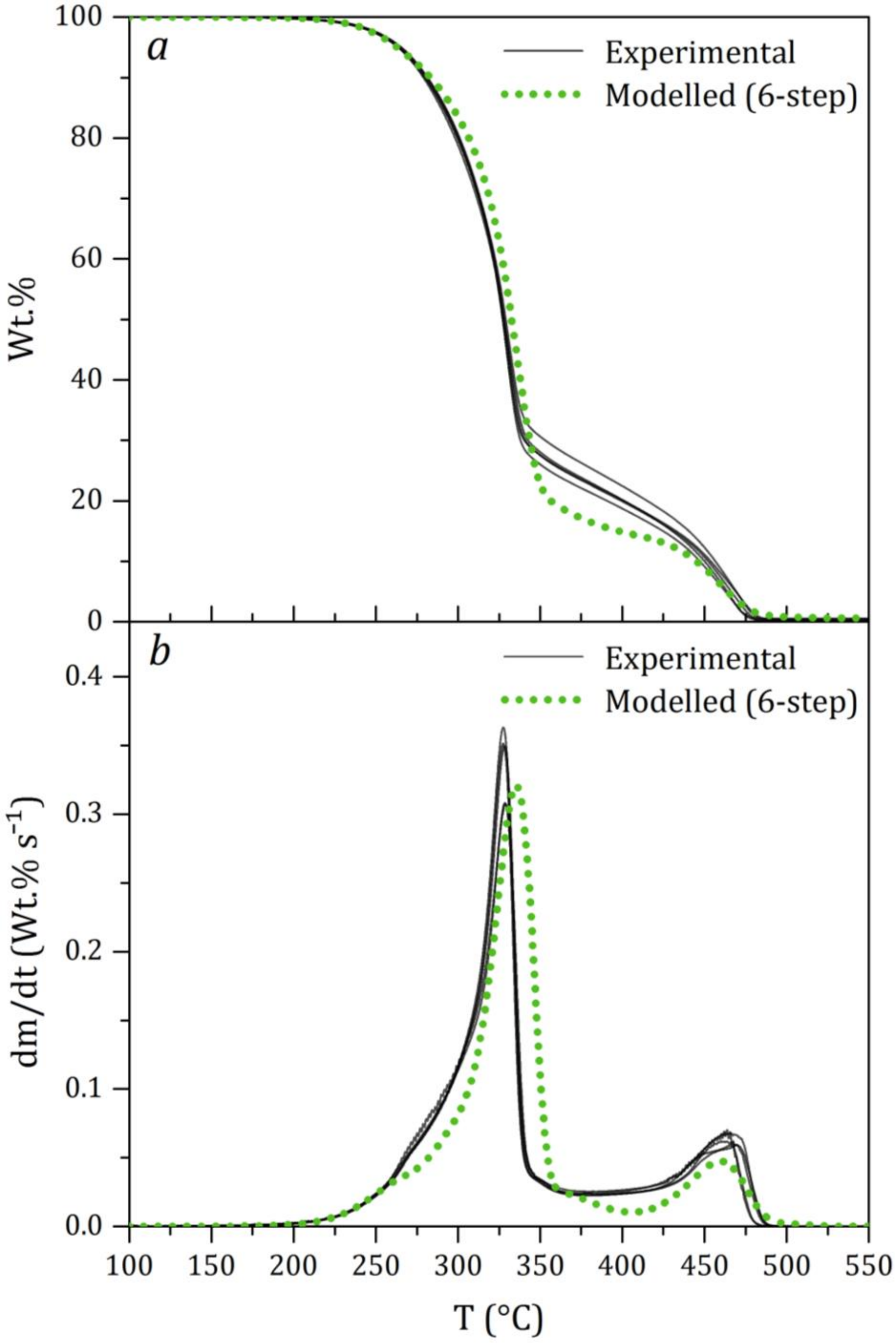


Figure 5.21 – **Modelled mass loss (a) and rate of reactivity (b) plots for Sitka spruce stem wood; using a 6-step kinetic model, based on lignocellulosic contents**

Assuming the occurrence of six key parallel reactions, the kinetic parameters of the birch and Sitka spruce stem wood have been established, utilising these to model their mass loss profiles and rates of reactivity during the combustion process. Consequently, the results of the models – and their comparison to the experimental data – are shown for the birch and Sitka spruce in Figures 5.20 and 5.21, respectively. The established parameters and associated weightings of the two models can be found in Table 5.10. The profiles produced using the 6-step model achieve a good fit with the experimental data, supported by the calculated errors. For the birch model, the relative errors – when compared to the seven birch samples – range between 1.35% and 2.2% for the mass loss curves. The modelled Sitka spruce data – which was compared to five samples – produce relative errors within the range of 1.41% and 2.49%.

The profiles of the rates of reactivity are derived from the modelled mass loss data, therefore any existing error is exacerbated. Indeed, the relative errors increase for both the birch and Sitka spruce range between 3.61% - 5.69% and 3.14% - 5.55%, respectively. The errors of the kinetic models are apparent for both species – in Figures 5.20 and 5.21 – and can be associated with two specific regions. The first relates to the early stages of devolatilisation, which link directly to the thermal degradation of the hemicellulose contained within the fuel. As discussed previously, the hemicellulose content of wood is heterogeneous, and differs significantly in its composition between species [39, 51]. These differences will impact on the reactivity and combustion behaviour of the wood; this is supported by the results in Figure 5.14. To allow for a suitable comparison of the kinetic parameters of birch and Sitka spruce, the allocation of their known lignocellulosic contents between the 6 modelled reactions have been established using the weightings in Table 5.9, determined from the experimental data of the lignocellulosic components.

Further influences that could contribute to the existing error may relate to the extractive contents of the wood. As evidenced previously in Chapter 4, the stem wood contains only a small extractive content. As a result, the model is based purely on the known structural components of the samples, calculated on an extractive free basis. The existence of pectin, resins and inorganic components – such as potassium – may impact upon the rates of reactivity, however their influence has not been specifically included. Errors are also incurred in the region where the devolatilisation phase ends and char combustion begins. This is particularly evident for the modelling of Sitka spruce; however – since the kinetic parameters model the degradation of the structural components across both combustion phases – the extent of the error is acceptable. The incorporation of heterogeneity into a model is a difficult process, one which could ultimately impact upon the quality of the output. Although the produced models are flawed, the use of 6 parallel points of reactivity has successfully replicated both the devolatilisation and char combustion peaks, as well as the hemicellulose shoulder. Consequently, the combination of their strong fit to data and the supporting errors give validity and confidence to the stated activation energy ($E$) and pre-exponential factor ($A$) results, located in Table 5.10. The determined values for the $E$ and $A$ help quantify that birch stem wood is more reactive than Sitka spruce stem wood, throughout the devolatilisation and char combustion phases. However, the increased initial reactivity evident for the Sitka spruce is potentially a result of its hemicellulose composition; Figure 5.14 identifies arabinose as the most reactive monosaccharide, in terms of its initial mass loss. The presence of arabinose is species dependent, specifically associated with the xylan contained within softwood [39, 51]. Although this research is unable to verify the existence of arabinose within the Sitka spruce stem wood, when considering its reduced potassium content compared to the birch, the composition of the woods polysaccharides could help explain the initial increased hemicellulose reactivity.

## 5.4. Discussion

Trees differ; this is evident from simple observations relating to their visual appearance and the places they grow, to more complex variables relating to their fundamental composition – such as those highlighted in the previous chapter – or their genetic history. Given that these differences exist, the work in this chapter has attempted to establish how this variation, between birch and Sitka spruce, impacts upon their potential combustion properties. Understanding wood combustion – and the differences that may arise due to species choice – first requires a detailed comprehension of the composition. Building upon the previous work contained within this thesis, the results produced in this chapter show that the two species fundamentally differ in their elemental, chemical and structural compositions. This is not just apparent between the birch and Sitka spruce, but also individually, between their different tree sections. The increased homogeneity of the coniferous Sitka spruce is evident in its determined fundamental characteristics. This is clearly an important trait when considering the suitability of a biomass feedstock as a fuel, however there are additional behaviours that can be inferred from the produced elemental, chemical and structural components.

Firstly, the results from the ultimate and lignocellulosic analysis indicate that the growth focus differs between the two species. While the carbon accumulation of the Sitka spruce is similar throughout the tree, this is not the case for the UK-grown birch; its root and branch wood contain more carbon, indicating that the focal point of growth is focused away from the stem. The determined lignin results – indicating increased cell lignification, aiding resource transportation – correlates with the stated carbon values. For the birch, the increased lignin content located within the roots adds to our knowledge of the species' growth focus; that, of the individual birch trees analysed in this chapter, their roots are most favoured and the stem the least. As previously indicated in the literature, birch can produce quality timber on favourable sites but, under poor conditions, its growth and form is severely hindered [6, 7]. Of the seven birch trees analysed in this chapter, six were sourced from sites that were typified by acidic, podzol soil – this tends to be deficient in both moisture and nutrients, making it unconducive for growth. These results indicate that birch grown on poor sites will focus their growth towards the roots, in search of the necessary moisture and nutrients. This subsequently reduces the quality of the produced 'above-ground' wood, impacting on its potential as fuel. Comparatively, the lignin contents in Sitka spruce – unlike its evenly distributed carbon – is considerably larger in the branch wood, while both the stem and roots have similar quantities. Therefore, the growth focus of the Sitka spruce is instead on its canopy. This is most likely a direct result of the forest management of the Sitka spruce plantations; an increased planting density – and the competition this invokes for the existing resources – directly effects the trees growth [56]. The relative homogeneity shown in the fundamental characteristics of the analysed Sitka spruce – further reinforced by the difference in the two locations of the sourced samples – implies that increased fuel homogeneity could be assumed when utilising the resource, especially when compared to the birch.

Additional influences affecting tree growth are the presence of nitrogen and potassium – two vital nutrients for increasing productivity and aiding cell expansion. These attained benefits however, have negative implications on the combustion process; this includes increased reactivity, $NO_x$ and $N_2O$ emissions and the occurrence of slagging and fouling. The birch has increased contents of both nitrogen and potassium when compared to the Sitka spruce, evident throughout the different sections of the tree. Although the nitrogen contents of both species are low when compared to other biomass feedstocks, of the two, Sitka spruce would make the most preferable fuel when considering their initial contents. This preference also extends to the partitioning of the nitrogen between the volatile and the char components of the wood. Nitrogen partitioning, occurring during the devolitilisation phase, is impacted by changes in temperature and residence time, with increases in both prompting a reduction in the nitrogen content of the char [23, 24]. By keeping these conditions the same, it is possible to ascertain the differences that occur due to species variation. The partitioning results indicate that the carbonisation of Sitka spruce would deplete the nitrogen content of the produced char – this is evident for its stem, root and branch wood. Conversely, the carbonisation of birch stem and branch wood concentrates the nitrogen in the char; particularly in the stem wood, where its char would potentially contain twice the nitrogen content of the fuel. The determined species variation in nitrogen partitioning ultimately impacts the end-use suitability of the wood. Of the two species in question, the increased theoretical char yields and the reduced nitrogen content would make Sitka spruce the preferable species for fuel-based carbonisation. Although the increased nitrogen content of the birch stem's theoretical char yield makes it inferior as a fuel, when compared to the spruce, it would potentially make a better feedstock for producing soil-improving biochar.

In addition to the differences in the fundamental characteristics of birch and Sitka spruce, the variation extends to the individual relationships that exist between characteristics. For example, within the literature a link between potassium – a key inorganic constituent – and lignin has previously been established [39]. Utilising the extensive experimental work completed in this chapter, species-specific relationships between the ash and lignin contents have been derived, for both the birch and Sitka spruce, establishing a defined link between the chemical and structural components of wood. The ash content of biomass, and the inorganics associated with it, cause an array of issues, such as those relating to corrosion and slag formation. There are benefits associated with an increased lignin content; lignin is less reactive than hemicellulose, demonstrating a slower rate of thermal decomposition over a much larger temperature range. In addition to this, as discussed in previous chapters, lignin has an inherently higher energy content than the carbohydrate-based cellulose and hemicellulose. Consequently, a fuel with a larger lignin content should be a better fuel for heating. Both the ash and lignin contents are important when determining the potential of a fuel, therefore establishing a link between the two would be beneficial. The research in this chapter show that an increase in ash content coincides with an increase in lignin, although the amount differs between the two species. Considering the functions produced in Figure 5.11, the Sitka spruce is again shown to be a more preferable fuel; as established, the increases in its ash content correlates with lignin accumulation at a quicker rate than in the birch.

A key inorganic constituent existing within wood is potassium which, in addition to its role in growth, also influences the combustion process. Of the two species, the birch contains the largest potassium content and variability found between individual specimens. This is evident for its stem, root and branch wood. Indeed, in keeping with the previously displayed homogeneity of the Sitka spruce, there is very little variation in the potassium contents of its stem and branch wood, even when sourced from two separate sites. Although the stem and branch wood of Sitka spruce appears to be less susceptible to site conditions, this is not the case for its root wood; their potassium results show greater variability. Expanding upon this, the stem wood of both species evidence a negative correlation between their potassium and nitrogen contents – as nitrogen decreases, its potassium increases. Utilising birch and Sitka spruce stem wood with higher nitrogen contents, which are still low when compared to other biomass types, results in a reduction in potassium.

The impacts of potassium during combustion are not consigned to just fouling and slagging; the existence of potassium salts and other catalytic metals increase the reactivity of the biomass [29, 54, 55]. When examining the different sections of the tree, there are evident links between the potassium content and the initial mass loss temperature during combustion. Crucially, birch is more reactive than Sitka spruce – this is evident throughout the tree. The results in this chapter indicate that although there is certainly a relationship between potassium and increased reactivity, there are also other factors impacting upon this. For example, while the roots have a larger potassium content than the branch wood, their increased reactivity is less than expected. The distribution of potassium within the structural components, and how this differs between the branch and root wood, could potentially explain this. Hemicellulose is heterogeneous, consisting of a wide array of polysaccharides that differ, not only in their composition, but also in their functionality. Consequently, some of these not only act as structural components but, at times when the plant is lacking the resources required for photosynthesis, the polysaccharides can instead be recycled and utilised [51, 57]. A tree's branch wood – signifying an important part of the canopy – is directly associated with the photosynthesis process. As a result the composition and functionality of its hemicellulose, coupled with its associated potassium content, may differ to the other parts of the tree. This could therefore be the cause of the increased reactivity, evident within both the birch and Sitka spruce branch wood. In addition to this, it's important to note that of the total potassium contained within biomass, some is bound with the other inorganic constituents – making part of it catalytically inaccessible. Looking closer at the intra-species relationships between initial mass loss and potassium content, the birch stem and branch results indicate that their reactivity isn't directly dictated by increases in the determined potassium content. This suggests that there is potentially a species-based limit on potassium, impacting the effect it can have on reactivity.

The in-depth analysis of the elemental, chemical and structural characteristics of the two species, completed within this chapter, highlight the differences that exist in their fuel properties. Unsurprisingly, this variability continues when considering their combustion characteristics. Of the two species, birch is the most reactive; both its initial mass loss and burnout temperatures are less than those of the Sitka spruce, evident for the different tree sections. This, coupled with the increased GCV's of its stem wood, indicates that higher temperatures can be produced from the combustion of Sitka spruce, making it again, a more preferable fuel than the birch. Additionally, the mass loss profiles – and the consequent derived rates of reactivity – of the two species differ. This is most evident during the thermal decomposition of hemicellulose, where the 'shoulder' is more pronounced for the birch and is present during the combustion of its stem, root and branch wood. The results suggest that the polysaccharide composition is vital, dictating the decomposition temperature of hemicellulose. The importance of the structural components found within wood, are further highlighted by the results of the kinetic modelling. Using the known hemicellulose, cellulose and lignin mass contents – combined with kinetic parameters that assume six parallel reactions – the reactivity differences between the birch and Sitka spruce stem wood have been demonstrated. The results indicate that, for the majority of the combustion process, the birch is more reactive than the Sitka spruce. However, this is not the case for the initial thermal degradation of the hemicellulose, where the Sitka spruce hemicellulose is more reactive than that found within birch. Arabinose – a monosaccharide, specifically associated with the xylan found in softwood – is more reactive than other sugars associated with hemicellulose. Therefore the increased initial reactivity of the Sitka spruce hemicellulose decomposition, potentially indicates that arabinose features in the composition of its polysaccharides.

## 5.5. Conclusions

Nearly 100 years ago *The Firewood Poem* identified the properties of firewood for a number of species, using simple visual observations made during their combustion. Of these, the poem proposes that birch burns too fast, that it blazes up bright and doesn't last. Using extensive experimental and modelling methods, this chapter has shown this account to be correct; that the increased reactivity of the birch's thermal degradation is directly linked to its composition. One of the major benefits of birch is its resilience and propensity to grow on poor sites. However, this adaptability comes at a price when considering its potential as a fuel; the growth focus favours the roots on poor sites, resulting in stem wood that contains less fixed carbon and lignin. Consequently, the tendency of birch to burn fast and not last – making it a less than ideal fuel – can be exacerbated by utilising wood sourced from poor sites.

Of the two species, Sitka spruce has been shown to be the better option for use as a fuel. This is dictated by its more preferable fundamental fuel properties, its decreased reactivity and, perhaps most importantly, its increased homogeneity – apparent for a number of key factors impacting combustion. Considering the dominance of Sitka spruce in UK forestry – representing around a quarter of the nation's existing resource – it is important to establish the accessibility of the feedstock if its potential is to be fully realised. As a result, Chapter 6 will focus on the UKs forest and woodland feedstocks, determining how the location and physical geography of the nation's wood resource directly impacts upon the viability of the harvesting and extraction processes.

## 5.6. References

[1]. Nussbaumer T. 2003. Combustion and co-combustion of biomass: fundamentals, technologies and primary measures for emission reduction. *Energy & Fuels*, 17, pp1510-1521

[2]. Poletto M., Zattera A. J. and Santana R. M. C. 2012. Thermal decomposition of wood: kinetics and degradation mechanisms. *Bioresource Technology*, 126, pp7-12

[3]. Williams A., Jones J. M., Ma L. and Pourkashanian M. 2012. Pollutants from the combustion of solid biomass fuels. *Progress in Energy and Combustion Science*, 38, pp113-137

[4]. DUKES. 2016. *Digest of United Kingdom Energy Statistics (DUKES) 2016*. Department for Business, Energy and Industrial Strategy, HMSO, London

[5]. Koski V. and Rousi M. 2005. A review of the promises and constraints of breeding silver birch (*Betula pendula* Roth) in Finland. *Forestry*, 78(2), pp187-198

[6]. Cameron A. D. 1996. Managing birch woodlands for the production of quality timber. *Forestry*, 69(4), pp103-119

[7]. Hynynen J., Niemisto P., Viherä-aarnio A., Brunner A., Hein S. and Velling P. 2010. Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in Northern Europe. *Forestry*, 83(1), pp103-119

[8]. Ward S. 2017. *Forest Statistics 2017*. IFOS-Statistics, Forest Research, 231 Corstorphine Road, Edinburgh

[9]. Mason W. L. 2007. Silviculture of Scottish forests at a time of change. *Journal of Sustainable Forestry*, 24(1), pp41-57

[10]. Gardiner B., Leban J-M., Auty D. and Simpson H. 2011. Models for predicting wood density of British-grown Sitka spruce. *Forestry*, 84(2), pp119-132

[11]. Macdonald E. and Hubert J. 2002. A review of the effects of silviculture on timber quality of Sitka spruce. *Forestry*, 75(2), pp107-138

[12]. Congreve C. 1930. *The firewood poem*. Online: allpoetry.com/The-Firewood-Poem

[13]. Bridgeman T. G., Darvell L. L., Jones J. M., Williams P. T., Fahmi R., Bridgewater A. V., Barraclough T., Shield I., Yates N., Thain S. C. and Donnison I. S. 2007. Influence of particle size on the analytical and chemical properties of two energy crops. *Fuel*, 86, pp60-77

[14]. Fromm J. 2010. Wood formation of trees in relation to potassium and calcium nutrition. *Tree Physiology*, 30, pp1140-1147

[15]. van Loo S. and Koppejan J. 2008. *The handbook of biomass combustion and co-firing*. Earthscan Ltd, Dunstan House, London

[16]. Mason P. E., Darvell L. I., Jones J. M. and Williams A. 2016. Observations on the release of gas-phase potassium during the combustion of single particles of biomass. *Fuel*, 182, pp110-117

[17]. C. E. N. Standard. 2015. *Solid biofuels. Determination of major elements. Al, Ca, Fe, Mg, P, K, Si, Na and Ti*, BS EN ISO 16967:2015. BSI

[18]. García R. and Báez A. P. 2012. Atomic Absorption Spectrometry (AAS). In: *Atomic Absorption Spectroscopy* [Farrukh M. A. (eds)], InTech Europe, Rijeka

[19]. Vitousek P. M. and Howarth R. W. 1991. Nitrogen limitation on land and in the sea: How can it occur? *Biogeochemistry*, 13, pp87-115

[20]. Millard P. and Grelet G-A. 2010. Nitrogen storage and remobilization by trees: ecophysiological relevance in a changing world. *Tree Physiology*, 30, pp1083-1095

[21]. Hayhurst A. N. and Lawrence A. D. 1992. Emissions of nitrous oxide from combustion sources. *Progress in Energy and Combustion Science*, 18(6), pp529-552

[22]. Ren X., Sun R., Meng X., Vorobiev N., Schiemann M. and Levendis Y. A. 2017. Carbon, sulfur and nitrogen oxide emissions from combustion of pulverised raw and torrefied biomass. *Fuel*, 188, pp310-323

[23]. Glarborg P., Jensen A. D. and Johnsson J. E. 2003. Fuel nitrogen conversion in solid fuel fired systems. *Progress in Energy and Combustion Science*, 29, pp89-113

[24]. Darvell L. I., Jones J. M., Gudka B., Baxter X. C., Saddawi A., Williams A. and Malmgren A. 2010. Combustion properties of some power station biomass fuels. *Fuel*, pp2881-2890

[25]. Morgan P. A., Robertson S. D. and Unsworth J. F. 1986. Combustion studies by thermogravimetric analysis. 1. Coal oxidation. *Fuel*, 65, pp1546-1551

[26]. Biagini E., Lippi F., Petarca L. and Tognotti L. 2002. Devolatilization rate of biomasses and coal-biomass blends: an experimental investigation. *Fuel*, 81, pp1041-1050

[27]. Grønli M. G., Várhegyi G. and Di Blasi C. 2002. Thermogravimetric analysis and devolatilization kinetics of wood. *Industrial and Engineering Chemistry Research*, 41(17), pp4201-4208

[28]. Carpenter A. M. and Skorupska N. M. 1993. *Coal combustion – analysis and testing*. IEA Coal Research, IEACR/64, London

[29]. Jones J. M., Saddawi A., Dooley B., Mitchell E. J., Werner J., Waldron D. J., Weatherstone S. and Williams A. 2015. Low temperature ignition of biomass. *Fuel Processing Technology*, 134, pp372-377

[30]. Bridgeman T. G., Jones J. M., Shield I. and Williams P. T. 2008. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. *Fuel*, 87, pp844-856

[31]. McNamee P., Darvell L. I., Jones J. M. and Williams A. 2015. The combustion characteristics of high-heating-rate chars from untreated and torrefied biomass fuels. *Biomass and Bioenergy*, 82, pp63-72

[32]. Di Blasi C. 1993. Modeling and simulation of combustion processes of charring and non-charring solid fuels. *Progress in Energy and Combustion Science*, 19, pp71-104

[33]. Saddawi A., Jones J. M., Williams A. and Wójtowicz M. A. 2010. Kinetics of the thermal decomposition of biomass. *Energy Fuels*, 24, pp1274-1282

[34]. Branca C., Albano A. and Di Blasi C. 2005. Critical evaluation of global mechanisms of wood devolatilization. *Thermochimica Acta*, 429, pp133-141

[35]. Branca C., Iannace A. and Di Blasi C. 2007. Devolatilization and combustion kinetics of Quercus cerris bark. *Energy & Fuels*, 21, pp1078-1084

[36]. Yang H., Yan R., Chen H., Lee D. H. and Zheng C. 2007. Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel*, 86, pp1781-1788

[37]. Bruun E. W., Hauggaard-Nielsen H., Ibrahim N., Egsgaard H., Ambus P., Jensen P. A. and Dam-Johansen K. 2011. Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil. *Biomass and Bioenergy*, 35, pp1182-1189

[38]. Oasmaa A., Solantausta Y., Arpiainen V., Kuoppala E. and Sipilä K. 2010. Fast pyrolysis bio-oils from wood and agricultural residues. *Energy Fuels*, 24, pp1380-1388

[39]. Hon D. N-S. and Shiraishi N. 2001. *Wood and cellulosic chemistry*, 2nd Edition. Marcel Dekker, Inc. New York

[40]. Déjardin A., Laurans F., Arnaud D., Breton C., Pilate G. and Leplé J-C. 2010. Wood formation in Angiosperms. *Comptes Rendus Biologies*, 333, pp325-334

[41]. Russell S. H., Turrion-Gomez J. L., Meredith W., Langston P. and Snape C. E. 2017. Increased charcoal yield and production of lighter oils from the slow pyrolysis of biomass. *Journal of Analytical and Applied Pyrolysis*, 124, pp536-541

[42]. Glaser B., Lehmann J. and Zech W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. *Biology and Fertility of Soils*, 35(4), pp219-230

[43]. Rogers L. A. and Campbell M. M. 2004. The genetic control of lignin deposition during plant growth and development. *New Phytologist*, 164, pp17-30

[44]. Drew M. C. 1975. Comparison of the effects of a localized supply of phosphate, nitrate, ammonium and potassium on the growth of the seminal root system, and the shoot, in Barley. *New Phytologist*, 75, pp17-30

[45]. Comerford N. B., Smethurst P. J. and Escamilla J. A. 1994. Nutrient uptake by woody root systems. *New Zealand Journal of Forestry Science*, 24(2/3), pp195-212

[46]. García R., Pizarro C., Lavín A. G. and Bueno J. L. 2013. Biomass proximate analysis using thermogravimetry. *Bioresource Technology*, 139, pp1-4

[47]. Demirbaş A. 2003. Relationships between lignin contents and fixed carbon contents of biomass samples. *Energy Conversion and Management*, 44, pp1481-1486

[48]. Sharma R. K., Wooten J. B., Baliga V. L., Lin X., Chan W. G. and Hajaligol M. R. 2004. Characterization of chars from pyrolysis of lignin. *Fuel*, 83, pp1469-1482

[49]. Nowakowski D. J. and Jones J. M. 2008. Uncatalysed and potassium-catalysed pyrolysis of the cell-wall constituents of biomass and their model compounds. *Journal of Analytical and Applied Pyrolysis*, 83, pp12-25

[50]. Mitchell E. J. S., Lea-Langton A. R., Jones J. M., Williams A., Layden P. and Johnson R. 2016. The impact of fuel properties on the emissions from the combustion of biomass and other solid fuels in a fixed bed domestic stove. *Fuel Processing Technology*, 142, pp115-123

[51]. Scheller H. V. and Ulvskov P. 2010. Hemicelluloses. *Annual Review of Plant Biology*, 61, pp263-289

[52]. López-González D., Fernandez-Lopez M., Valverde J. L. and Sanchez-Silva L. 2013. Thermogravimetric-mass spectrometric analysis on combustion of lignocellulosic biomass. *Bioresource Technology*, 143, pp562-574

[53]. Pereira S., Martins P. C. R. and Costa M. 2016. Kinetics of poplar short rotation coppices obtained from thermogravimetric and drop tube furnace experiments. *Energy Fuels*, 30, pp6525-6536

[54]. Jones J. M., Darvell L. I., Bridgeman T. G., Pourkashanian M. and Williams A. 2007. An investigation of the thermal and catalytic behaviour of potassium in biomass combustion. *Proceedings of the Combustion Institute*, 31, pp1955-1963

[55]. Clery D. S., Mason P. E., Rayner C. M. and Jones J. M. 2018. The effects of an additive on the release of potassium in biomass combustion. *Fuel*, 214, pp647-655

[56]. Deans J. D. and Milne R. 1999. Effects of respacing on young Sitka spruce crops. *Forestry*, 72(1), pp47-57

[57]. Hoch G. 2007. Cell wall hemicelluloses as mobile carbon stores in non-reproductive plant tissues. *Functional Ecology*, 21, pp823-834

# Chapter 6. The cost of utilising UK-grown wood for bioenergy

*"When we use the tree respectfully and economically, we have one of the greatest resources on the earth" – Frank Lloyd Wright*

## 6.1. Introduction

Wood biomass forms two thirds of the global renewable resource for energy generation, representing ~9% of the world's primary energy consumption in 2010. This reliance on biomass, to meet domestic renewable targets, extends to the UK; however – as a nation – its current biomass feedstock supply depends heavily upon imported wood resource. In 2016, the UK's wood pellet imports totalled 6.8 million tonnes, with nearly 80% sourced from the United States and Canada [1, 2]. To supplement these imports, the interest in utilising the UK's local forest resource for use in energy generation has continued to increase. Indeed, since 2007 the delivery of UK-grown wood to woodfuel industries has increased by 290%, reaching 1.95 million green tonnes of wood in 2017 alone. Of this figure, 79.5% was attributed to conifer species, emphasising the UK's current reliance on its softwood feedstocks and its well-established timber markets [2].

The reported forest cover in the UK – reviewed in Chapter 3 – totals more than 3 million hectares (ha) of tree cover, distributed fairly evenly between conifer (softwood) and broadleaved (hardwood) species. Assuming the UK's current total wood deliveries for use in energy generation is maintained, its annual extraction rate equates to approximately 1.22 t ha$^{-1}$ yr$^{-1}$ of wood removals. This is detailed in Figure 6.1, which shows the current woodfuel arisings – sourced from the UK's forest feedstocks – and how these distribute between hardwood and softwood species. In addition to the known removals, the estimated rates of net growth for the UK's hardwoods and softwoods (also established in Chapter 3) are included; as is the calculated potential volume of surplus stump wood, left following current felling activities. Consequently, the current published forest data indicates a potential for increasing the extraction of UK-grown wood resource for bioenergy production, without impacting other timber industries or invoking deforestation.

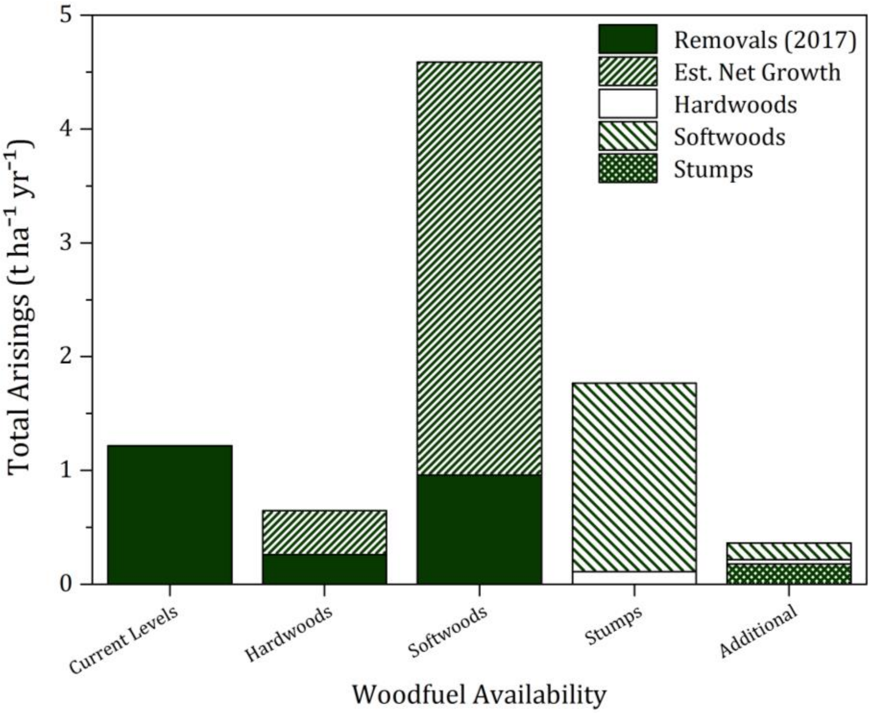


Figure 6.1 – **Current and potential arisings of woodfuel in the UK, based upon published statistics [2]**

Forests represent an important resource, containing an array of social, ecological and economic benefits which – through sustainable forest management practices – can be maintained and protected [3]. This thesis has, so far, focused on the properties of the UK's current wood resource, utilising a large sample set and extensive laboratory techniques to establish the suitability of different species for use in bioenergy production. However, the viability of UK-grown wood is not dictated just by its physical properties; the accessibility of wood feedstocks – and the associated felling, extraction and comminution costs – represent a key barrier in its increased utilisation. Achieving the respectful and economic utilisation of forest resource for bioenergy production – while successfully preserving the associated benefits – first requires a thorough understanding of the costs associated with accessing the resource. This chapter will therefore focus on the UK's existing forest feedstocks, establishing the costs related to the felling and extraction processes and how the UK's natural geography and existing infrastructure impacts upon its economic feasibility.

Within the UK, the sale of wood resource occurs across two main formats; sold either as standing wood – where the purchaser is responsible for the felling and extraction of the purchased wood – or at the roadside, where the harvesting processes are instead completed by the landowner [4]. The resulting prices – which are highly susceptible to change – differ between the two, with an increased average price for roadside logs representative of the additional costs required for felling and extracting. Consequently, the Forestry Commission produce national statistics for two indices – the Coniferous Standing Sales Price Index and the Softwood Sawlog Price Index – which detail updated average prices, following the sales of overbark timber. The 5-year average for Coniferous Standing Sales is 17.14 £ $m^{-3}$, while for the roadside Sawlogs this is significantly larger at 36.78 £ $m^{-3}$. The value of standing timber is dictated by the intended end-use of the wood, with high value solid timber products achieving a much greater price than wood intended for energy production. However, during the last decade – coinciding with the increased utilisation of wood biomass for bioenergy – these prices have continue to increase; for 2017, these have reached highs of 20.74 £ $m^{-3}$ and 43.35 £ $m^{-3}$ for the sale of standing and roadside timber prices, respectively. These increases, forecast by Bolkesjø *et al* (2006), are partially attributed to the intensified use of low-quality roundwood for bioenergy, driving up the demand and consequent prices [4-6].

In addition to fluctuating market prices and the demand for specific natural resources, the location and associated terrain of forest feedstocks have a major impact upon the economic viability of wood biomass. The quantification of these impacts can be completed using geographical information system (GIS) tools – as part of a decision support system (DSS) – which can combine different spatial, economic and process data [7, 8]. The varied use of GIS tools to identify, assess and value different geographic influences on forest resources has continued to grow; this includes analysis of factors such as bioenergy production, alternative forest functions – such as ecosystem services – and the impact of terrain on the management and associated costs of harvesting [8-11]. Considering the previously stated aims of this chapter, the next section will detail the literature-sourced harvesting data and spatial datasets – specific to the UK's terrain, infrastructure and forest resource – used to establish the costs of accessing UK forest resource for bioenergy production. Incorporating these with the known energy contents of UK-grown wood – determined previously in this thesis – the chapter will use this as a foundation to determine the potential energy costs associated with UK forest wood harvesting.

## 6.2. Methodology

Establishing accurate costs of accessing forest resource – in this case for use in bioenergy production – depends upon first defining the felling and harvesting process. Figure 6.2 therefore details the process route for obtaining forest wood for bioenergy – spanning from its natural state as standing timber, through to its end use. The chosen felling process relates directly to the intended management of the selected forest, which in turn will impact the amount of biomass that is produced. Clearfelling – a highly mechanised practise – involves the felling of all standing timber within a forest stand. This is established as the most cost effective process, however there are associated environmental and societal implications with the clearfelling operation [2]. Shelterwood systems are also heavily mechanised, involving the removal of a large proportion of the standing timber, leaving a certain number of trees to help moderate the physical impacts to the site. Thinning operations form a key silvicultural practice, promoting better tree health, growth and stand structure. This process includes pre-commercial thinning, selective harvesting and salvage operations, resulting in the removal of a reduced volume of timber than other felling options [12-16]. An additional benefit to utilising mechanised felling operations is that the debrashing and cross-cutting of the tree are often incorporated into the process, occurring within the stand.

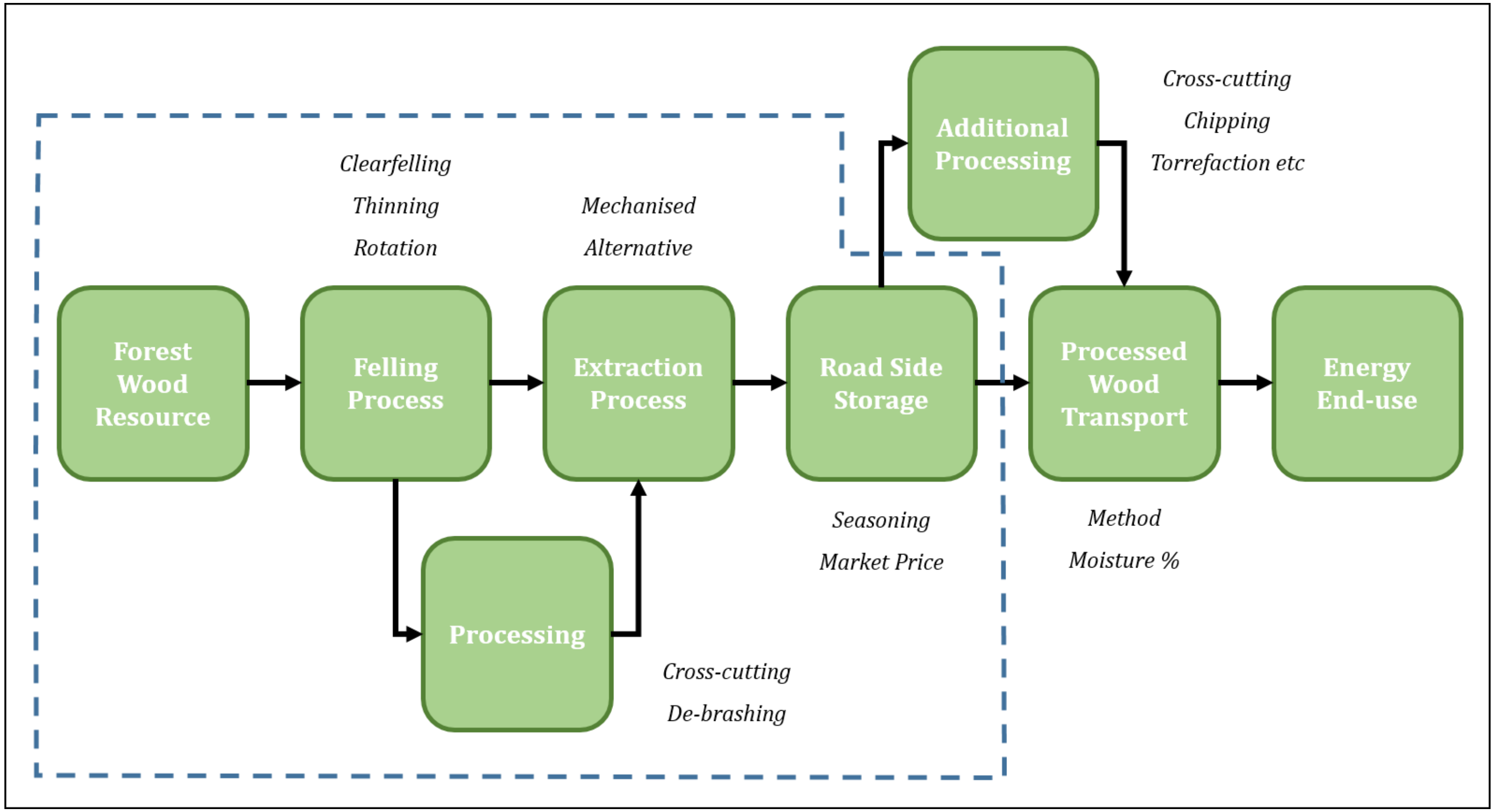


Figure 6.2 – **Harvesting system and additional process influencing factors; the felling and extraction of forest wood resource for use in bioenergy production**

Following the felling of the standing timber, the wood must then be extracted to the roadside. The extraction process is one of the most important phases in the forest wood supply chain; historically this was achieved using man and animal power, however this has undergone significant mechanisation. Often the most expensive phase in forest harvesting, there are three main factors which have the greatest influence on the final cost; the choice of extraction technology, the sites terrain and the extraction distance [8, 17, 18]. If debrashing and cross-cutting has not been completed within the stand – usually due to an identified market for the brash – then additional processing can occur at the roadside.

Once extracted, the felled logs are stacked and left to season; this is effectively an air drying process that reduces the moisture content of the timber, improves its quality and, perhaps most importantly, decreases transportation costs. Indeed, transporting wood biomass – especially for use in energy generation – represents a large proportion of the total delivered costs [19, 20]. The seasoning of the wood is an important element, directly impacting its market value – this is relevant, regardless of whether the timbers end use is construction- or energy generation-based. Further processing, such as comminution, can also occur at the roadside. The emergence of mobile roadside chippers – influenced by the increased demand for woodfuel – has improved the access of land owners to alternative forest product markets [21].

### 6.2.1. Machine & Labour Costs

Although the transportation represents an important part of biomass costs, accurate calculations are dependent upon the known end destination for the wood resource – the distance, biomass volume and transportation mode will heavily influence the associated costs [20]. With these undefined, this research is instead focused on understanding the costs incurred during the felling and extraction phases of the forest wood supply chain – in keeping with the current structure for timber pricing – as discussed previously. Estimating the supply costs of forest biomass can be achieved by utilising two forms of data; the first, exploiting the machine and labour costs associated with the chosen felling and extraction processes and the second, establishing their productivity [22].

Table 6.1 – **Adjusted labour and machine costs attributed to the felling, extraction and comminution processes of wood biomass [22]**

| **Labour Costs**[a] | **£ hr$^{-1}$** | **Machine Costs**[b] | **£ hr$^{-1}$** |
|---|---|---|---|
| Felling | *20.53* | Single-grip Harvester | *79.83* |
| Manual Cutting (Chainsaw) | *20.53* | Chainsaw | *23.51* |
| Stump Lifting | *20.53* | Stump Harvester | *54.12* |
| Forwarding | *20.05* | Forwarder | *56.83* |
| Skidding | *20.05* | Skidder | *53.59* |
| Skidding (Mini-skidder[c]) | *20.05* | Mini-skidder[c] | *30.50* |
| Cable Yarding | *20.05* | Cable Yarder | *127.79* |
| Chipping | *20.53* | Chipper | *129.71* |

[a]*adjusted for wage increases,* [b]*adjusted for inflation,* [c]or mini-forwarder

The data contained in Table 6.1 details the hourly labour and machine costs for an array of key forest machinery and apparatus, typically utilised during the felling and extraction phases. These figures have been sourced from an INFRES report – produced by Natural Resources Institute Finland – yielding country-specific labour and machine costs. This utilises elements corresponding with the capital and operational costs throughout the machinery's working lifetime – such as the initial financial outlay and fuel consumption – to estimate an hourly monetary figure, specific to individual countries [22]. This report was published in 2015, expressing the estimated figures for costs – specific to the UK – in EUR (€), therefore these have first been adjusted before being converted to GBP (£); as stated in Table 6.1, the labour costs have been adapted using the UK's annual earnings growth rate, while the machine costs have been adjusted for inflation. These were then converted to GBP, using an exchange rate of 0.88, helping to form the basis of the economic analysis completed in this chapter.

### 6.2.2. Felling & Extraction

The hourly labour and machine costs, given in Table 6.1, can be combined with details on their productivity to estimate the financial requirements for felling and extracting timber. Productivity can be affected by an array of topographical and distance related features, which should be incorporated into the analysis to ensure an accurate portrayal of costs [8, 22]. Consequently, the following section details the productivity differences associated with the alternative felling and extraction methods, sourced extensively from the literature.

#### 6.2.2.1. Productivity

The productivity of different forest harvesting methods – and how these differ from one another – has been reviewed extensively in Section 3.4, outlining the differences in technologies that have previously been published. This data has been collated in Table 6.2, detailing specific productivities of individual felling, extraction and comminution processes. In addition to productivity, Table 6.2 also includes details such as the diameter at breast height (DBH), the payload and the extraction distance, where appropriate. It's important to note that the utilised data has been attained from a number of international field trials, from nations with more established forest industries; these are representative of the productivities that could be achieved in the UKs forests, however they are still estimations and should not be considered as definitive values.

Using the assembled data, mean productivities were produced for chainsaw felling and the use of single-grip harvesters. Previous field tests have shown that increases in DBH coincide with an increase in productivity [14, 16, 25], therefore to ensure the calculated means are comparable, they have been standardised to a DBH of 25cm, using the following equation;

$$\bar{X}_s = \bar{X}_p + \left[(V - \bar{X}_d) \times \left(\frac{SE_p}{SE_d}\right)\right] \tag{6.1}$$

where;

| | |
|---|---|
| $\bar{X}_s$ | is the standardised mean for productivity (m$^3$ h$^{-1}$) |
| $\bar{X}_{p,d}$ | is the calculated means for productivity ($p$) and DBH ($d$) |
| $V$ | is the chosen standardised DBH value |
| $SE_{p,d}$ | is the calculated standard error for productivity and DBH |

By using Equation 6.1, the standardisation of the results incorporates the distribution of the productivity and DBH values, utilising how they interact with one another. The productivity of stump harvesting is influenced by different stump diameters, however the number of stumps (ha$^{-1}$) affects productivity – no

Table 6.2 – **Productivity and additional key factors related to different felling, extraction and comminution processes, sourced from literature**

| **Process** | **Productivity (m$^3$ h$^{-1}$)** | **Distance (m)** | **DBH/PL$^a$ (cm/m$^3$)** | **Additional Details** | **Ref.** |
|---|---|---|---|---|---|
| | | | *Felling* | | |
| Chainsaw | *9.41, 11.71* | - | *18.0, 14.1* | Selective Thinning (SW) | [15] |
| Chainsaw | *33.63* | *9.9* | *40.2* | Selective Thinning (HW) | [23] |
| Chainsaw | *20.6* | *35.63* | *87.62* | Selective Thinning (HW) | [16] |
| Chainsaw | *10, 9.6, 13.2, 5.2* | - | - | Delimbing/Bucking | [24] |
| SG Harvester | *47.7* | - | *26.0* | Shelterwood (retain 400 trees ha$^{-1}$) | [12] |
| SG Harvester | *25.4* | - | *18.8* | Shelterwood (retain 300 trees ha$^{-1}$) | [13] |
| SG Harvester | *9.2* | *10.0* | *20.0* | Selective Thinning (HW) | [14] |
| SG Harvester | *23.1* | - | *27.0* | Selective Thinning (MW) | [25] |
| Stump | *7.9-10.8* | - | *577*$^b$ | Stump Harvesting | [26] |
| Stump | *5.5, 5.1, 2.9* | - | *237, 270, 245*$^b$ | Stump Harvesting | [27] |
| | | | *Extraction* | | |
| Skidder | *22.39* | - | - | Conventional Logging (skid trails) | [28] |
| Skidder | *20.51* | *288.9* | *2.71*$^a$ | Downhill extraction (HW) | [29] |
| Skidder | *14.51* | *211.56* | *2.78*$^a$ | Continuous time study Model | [30] |
| Forwarder | *15.9* | *250* | *8.0*$^a$ | Whole Tree Harvesting | [31] |
| Forwarder | *17.2* | *121* | *5.74*$^a$ | Cut-to-Length (MW) | [17] |
| Forwarder | *17, 9* | *50, 450* | - | Whole Tree Harvesting | [32] |
| Tractor | *6.24 (5.25)* | *100* | - | Log Skidding (Haulage) | [17] |
| Tractor | *3.2-5.3* | *103-736* | *4.1-5.4*$^a$ | Tractor Haulage (Whole Tree) | [31] |
| Mini-skidder | *4.33 (2.47)* | *320* | *2.1*$^a$ | Selective Thinning (HW) | [33] |
| Cable Yarder | *7.03, 10.7* | *198, 440* | *21.5, 30.8* | Two Yarder types & three sites | [34] |
| Skyline | *10.09* | *100* | - | Requires Corridors | [17] |
| | | | *Comminution* | | |
| Grinding | *48.8, 31.8* | - | - | Log and stump grinding | [35] |
| Chipping | *35, 30.1, 16.9, 15.3* | - | - | Differing mesh sizes and chippers | [36] |
| Chipping | *18.7, 22.6, 18.3* | - | - | Small-scale chippers | [21] |

$^a$*Payload,* $^b$*Stems ha*$^{-1}$*, DBH=diameter at breast height, SW=Softwood, HW=Hardwood, MW=Mixedwood* matter the stump size – with increased numbers positively affecting productivity [26]. Using a modified version of Equation 6.1 – incorporating stumps ha$^{-1}$ in place of DBH – the calculated mean productivity for stump harvesting was adjusted, assuming 400 stumps ha$^{-1}$.

In essence, the extraction of felled wood involves its transportation from one point to another. The productivity is therefore dictated by the time it takes to load, extract and unload the desired resource. Site specific factors such as roughness and slope will impact the travel speed and load size, however the extraction distance is the major influence on productivity – at greater distances, productivity will reduce [17, 25, 31]. Using the collated data in Table 6.2, mean productivity values (m$^{3}$ h$^{-1}$) were calculated for four alternative extraction methods; 1) skidding, 2) forwarding, 3) mini-skidding/forwarding (small-scale extraction), and 4) cable yarding, or skyline extraction as it's also referred to. Again, as the published data is from an array of different field experiments, the calculated productivities have been adjusted over a standard extraction distance of 250m. This utilised Equation 6.1, replacing the DBH data with that of the extraction distances. In addition to calculating mean extraction productivities at 250m, regression functions – depicting the relationship between productivity and extraction distance – have been derived for the four methods, based upon the published data.

#### 6.2.2.2. Scenario Development

Combining the labour and machine costs (£ hr$^{-1}$) with the calculated productivity values (m$^{3}$ hr$^{-1}$) – specific to each individual felling and extraction method – results in the creation of comparable system costs (£ m$^{3}$). These are important for understanding the costs of individual procedures, however the resource accessibility requires a combination of both the felling and extraction processes. As a result, a number of scenarios have been produced to represent the different routes for accessing wood biomass and the costs associated with them. These include examples of the most economic options – a result of the mechanisation of the harvesting phases – and how these differ when considering the impact of extraction distance and the existence of steep slopes. In comparison, additional scenarios reviewing supply routes that reduce the environmental impact, resulting in a reduced productivity, have also been created; this is important when considering vulnerable sites and specific management objectives. Finally, stump harvesting – specifically for use in energy generation – continues to be a divisive process for extracting wood resource from forest systems. This is mainly a result of the environmental and ecological impacts associated with the practice. The UK has previously explored the viability of stump harvesting, however the practice is best associated with Scandinavian nations, specifically Finland and Sweden [37, 38]. Although the UK's interest in stump harvesting has waned, scenarios depicting their potential role in wood supply routes have also been explored; this will help determine the volume of wood biomass, from different feedstocks, that can be sourced from the UK's forests and at what cost.

### 6.2.3. Geographic Variance

This chapter has two main focuses; the first in establishing the costs attributed to the processes of wood felling and extraction, and secondly, to apply these in the context of UK forestry. The achievement of this second objective requires appropriate data, relating specifically to the UK's terrain, forest resource and existing infrastructure. As previously discussed, spatial data can be exploited with geographical information system (GIS) software, combining economic and process data to produce results specific to an individual area.

#### 6.2.3.1. Data Sources

The UK spans approximately 243,000 km$^2$, across four constituent nations; England, Scotland, Wales and Northern Ireland. Its terrain is a mixture of lowland areas, particularly in the south of England, and mountainous regions which can be found predominantly in Scotland, Wales and the north of England. Up-to-date forest cover data is recorded as part of the National Forest Inventory (NFI), which is a continuous nationwide woodland survey undertaken by the Forestry Commission. The NFI provides data in the form of an ESRI Shapefile that covers the entirety of Great Britain, detailing the size, distribution and composition of its forested areas [39]. The management of Northern Ireland's forest resource –

and the consequent dissemination of data – is performed by the Northern Ireland Forest Service (NIFS). Similarly to the produced NFI data, the NIFS have collated an inventory dataset – again in the form of an ESRI Shapefile – which details the forest cover, specific to Northern Ireland [40].

In addition to the forest resource data, an array of terrain and infrastructure datasets have been utilised. These have been sourced from Ordnance Survey (OS), a government agency responsible for the mapping and surveying of Great Britain, and Ordnance Survey of Northern Ireland (OSNI) [41, 42]. Consequently, the terrain related datasets used within this research – again in the form of ESRI Shapefiles – were the Great Britain *OS Terrain 50* vector dataset and the *OSNI 50m DTM* point dataset. The infrastructure data relates to the UK's current road system, utilising three datasets to best cover the whole road network; this included the *OS Open Roads* dataset, covering the British road network as of 10/2017, the *National Forest Estate Roads GB 2016* Dataset and the *OSNI Open Data 2015 Road Network*, which details Northern Ireland's road network.

The above data sources are all necessary for helping to establish the supply and the associated impacts of accessing the UK's forest wood resource. However, to offer appropriate context for the research, data relating to the potential demand for woodfuel have also been included. This includes 2011 *Census* data – specifically related to population distribution – sourced from the Office for National Statistics (ONS), the National Records of Scotland and the Northern Ireland Statistics and Research Agency [43-45]. The spatial boundaries of the data differ between the constituent nations; for England and Wales this is given as 2011 Lower Layer Super Output Areas (LSOAs), for Scotland as 2011 *Census* Output Areas and for Northern Ireland as 2011 Super Output Areas. The correct digitalised spatial boundaries – as ESRI Shapefiles, specific to the given data – have been sourced from the UK Data Service [46]. Finally the accurate visualisation of the data is important – the produced maps must represent the recognisable profile of the UK's coastal outline. As a result, an outline of the entire UK – at an extent of 50.10319° to 60.15456° latitude and -7.64133° to 1.75158° longitude – has been sourced from GADM maps [47]. The details regarding the licensing of the data sources – utilised extensively in this research – are located in Appendix D.

#### 6.2.3.2. Framework Development

The size and shape of LSOAs and other output areas, are dictated by population concentrations and not the physical area of land. This is appropriate for data sources such as the 2011 Census, however this is not the case for forest resource, which is characterised predominantly by its area size. The forest coverage in the UK is mainly located away from densely populated residential areas, therefore using spatial boundaries with uneven areas would result in a biased comparison.

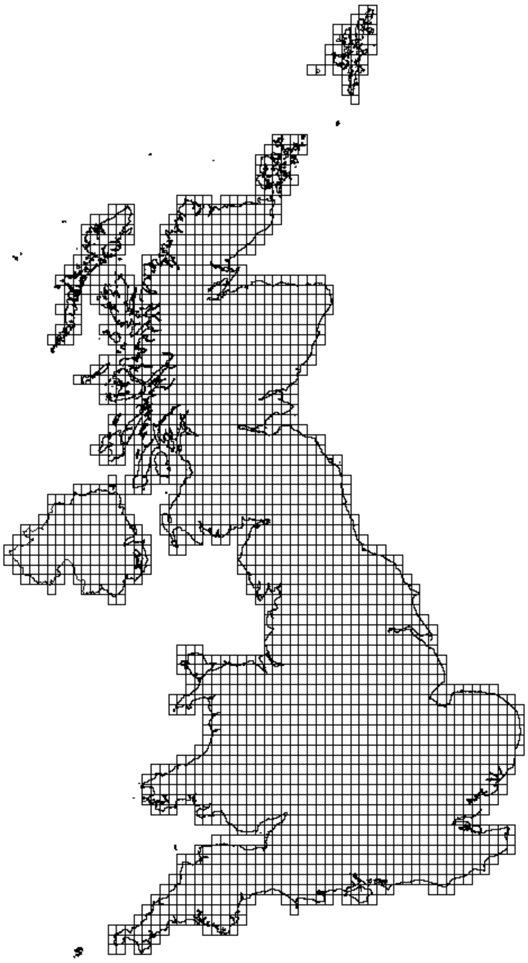


Figure 6.3 – **Grid framework created for spatial analysis and visualisation of UK forest resource**

To ensure the appropriate analysis and visualisation of the different data sources, a gridded framework has been created – shown in Figure 6.3 – covering the full extent of the UK. The framework consists of 2159 identical cells, each with an area of 55 square miles.

#### 6.2.3.3. Spatial Data Manipulation

The spatial analysis contained within this chapter has been conducted using ESRI's *ArcGIS* – a widely-used piece of geographical information system (GIS) software. Although the software is extensively supported, containing a wide array of uses and extensions, its main component is a geospatial processing tool, ArcMap; its use allows for existing raw spatial data to be edited and manipulated. This research has been completed using *ArcMap, v.10.2.2.*

The NFI and NIFS forest datasets form the basis of the spatial analysis, however they contain redundant data which must first be removed. The data, given as individual polygons within the shapefile, is classified into a set of interpreted forest types (IFT), categorised as; Conifer, Broadleaved, Mixed (Predominantly Conifer), Mixed (Predominantly Broadleaved), Coppice, Coppice with Standards, Shrub Land, Young Trees, Felled, Ground Prepared for New Planting and Assumed Woodland. Combined, the areas of the different IFTs equate to the stated total forest cover in the UK, estimated at 3.17 million ha in 2017 [2, 48]. The IFTs aren't all directly related to physical forest wood resource; therefore – using the inbuilt tools within *ArcMap* – the Conifer, Broadleaved and Mixed categories have been extracted from the initial dataset, producing individual shapefiles. The specific distribution of softwood (conifer) and hardwood (broadleaved) species, between the two mixed datasets, is unknown. Therefore, to avoid making unquantifiable assumptions, the Predominantly Conifer category has been merged with the Conifer dataset, while the Predominantly Broadleaved category has been merged with the initial Broadleaved category. The merged Conifer and Broadleaved data shapefiles, forming the basis of the spatial analysis, can be found in *Appendix E*.

One of the key factors affecting the harvesting process within forests is the terrain – particularly the slope – which can be a limiting factor for certain felling and extraction processes. Slope classification relates to steepness; a slope is classed as steep when ranging between 14-24° (25-45%), with anything above 24° considered very steep [18]. An increase in slope severity results in reduced stability during the use of forest felling and extraction machinery. Therefore, by establishing the forest areas that exist on steep and very steep slopes, it is possible to attribute the correct harvesting supply route and the associated costs of harvesting the wood resource. Mechanised felling can operate on a maximum slope of 14°, with manual felling – using a chainsaw – required on steeper slopes. For extraction processes, forwarding and skidding are only effective on slope gradients up to 17°; on steeper sites, methods like the labour intensive gravity sliding or cable yarding is utilised [9, 18, 49].

The *OS Terrain 50* and the *OSNI 50m DTM* datasets represent two different classes of elevation data; the first is contour based, while the latter represents surface-specific point data. These can both be manipulated in *ArcMap* to produce slope data for the entirety of the UK. The digital terrain model (DTM) data is first used to interpolate the elevation values into a raster format, using an inbuilt tool that is based upon the ANUDEM method [50]. Employing the *Ordnance Survey National Grid* coordinate system as a framework, individual raster maps were interpolated – at a resolution of 100 $km^2$ – ensuring a high-degree of precision for the produced elevation models. Within *ArcMap's* 3D Analyst Tools, the *Slope* function is then applied to the produced raster maps, identifying the specific gradients. As the spatial analysis of different factors requires the data sources to be in the same format, the raster maps need converting into polygons. The successful conversion from raster to polygon first requires the individual pixel values to be turned into integers, achieved by truncation; this process removes the decimal points, always rounding the number towards zero (for an example of truncated raster data, see *Appendix E*). The raster datasets can then be converted to polygons – a process which retains the correct shape, but smooths the edges. As discussed, gradients in excess of 17° require alternative methods of felling and extraction; therefore the converted cells with a value of ≥17° are extracted into a separate shapefile, identifying the specific locations that are too steep (see *Appendix E*). Layering the ≥17° slope shapefile over the two produced forest resource datasets allows for the areas of softwood and hardwood forests, on steep sites, to be calculated.

The extraction distance of wood, from the forest stand to road side, is an important variable – one that can severely affect the final costs, impacting the financial viability of the resource. The *OS Open Roads, National Forest Estate Roads GB 2016* and *OSNI Open Data 2015 Road Network* datasets can be used in combination with inbuilt *ArcMap* tools, helping establish the distance of the forest resource from the roadside. This is achieved using the *Buffer* analysis, producing Euclidean buffers – that assume the distance on a two-dimensional Cartesian plane – around the linear road data. For use in this analysis, two individual buffers have been produced; these detail 250m and 750m buffer zones around the UK's road (see *Appendix E*). Similarly to the slope data, the produced buffers can be used in combination with the resource databases to identify the areas of forest that exists ≤250m, ≥750m and between 250m-750m.

LSOAs are the lowest geographical spatial boundary that official, national-level statistics are released – such as those related to *Census* data. Their designated area size relates to population and residential households, with approximately equal numbers attributed to each defined area. Consequently, in densely populated areas the boundaries are much smaller than rural areas [51]. Using *ArcMap* it is possible to convert the output areas – relating to the population data, sourced from the 2011 *Census* – into the spatial framework illustrated in Figure 6.3. Firstly, the geographic centre for each individual output area – assumed as a representative location for the feature in question – are generated into points. These are then overlayed with the grid framework, allowing each individual point to be allocated to an appropriate cell – dictated by their spatial orientation. The value associated with each individual point is then attributed to its newly determined cell.

#### 6.2.3.4. Scenarios & Spatial Data Combination

The spatial datasets can be combined with the previously produced felling and extraction scenarios, allowing for the identification of costs that are specific to the UK's forest resource. Consequently, five unique spatial datasets – generated for both the hardwood and softwood resource – are available for combination with the produced scenarios. These are detailed in Table 6.3. Utilising the same feature to point method described in the previous section – converting LSOA boundaries into the produced grid framework – the data in each unique spatial dataset is attributed to its geographically appropriate cell (see Appendix E).

The established felling and extraction routes – and their associated costs – differ in their suitability when considering the five spatial datasets, outlined in Table

6.3. The calculated areas of forest resource, attributed to each individual spatial condition, can be used to create terrain- and road infrastructure-based weightings that can be applied to the estimated costs of felling and extracting the resource. The method for achieving this is detailed in Equations 6.2 and 6.3.

Table 6.3 – **UK forest resource spatial datasets and their different conditions**

| | | **Spatial Datasets** | | |
|---|---|---|---|---|
| | | DS | Hardwood | Softwood |
| <17° | <250m | *1* | + | + |
| | 250-750m | *2* | + | + |
| | ≥750m | *3* | + | + |
| ≥17° | <750m | *4* | + | + |
| | ≥750m | *5* | + | + |

$$w_i = \frac{Ar_i}{\sum_{i=1}^{n} Ar_i} \tag{6.2}$$

and:

$$\bar{X}_c = \sum_{i=1}^{n} w_i c_i \tag{6.3}$$

where:

| | |
|---|---|
| $w_i$ | is the normalised weighting of the $i^{th}$ group ($i$=1, 2, 3, …, $n$) |
| $Ar_i$ | is the calculated area of the $i^{th}$ group ($i$=1, 2, 3, …, $n$) |
| $\bar{X}_c$ | is the calculated mean cost of wood harvesting (£ $m^3$) |
| $c_i$ | is the supply route costs of the $i^{th}$ group ($i$=1, 2, 3, …, $n$) |

The above equations allow for the combination of produced spatial and process data; this results in the calculation of mean extraction and felling costs – dependent upon the chosen supply route – for each individual cell within the grid framework. In addition to highlighting how the UK's existing terrain and infrastructure impact the costs of extraction, the geographic variance can also be demonstrated.

## 6.3. Results

Due to the diverse nature of the produced results, the following section will be broken down into three main areas; 1) the differences in productivity and costs associated with different felling and extraction methods, 2) their application to the UK's existing forest resource – considering the impact of the nation's geography on accessing UK-grown wood, and 3) how the produced data, within the grid framework, can be best utilised for forest resource decision making.

### 6.3.1. Forest Resource Harvesting Productivity

Establishing the felling and extraction expenditure requires a combination of the known labour and machine costs, with the expected productivity of the method. As a result, the calculated productivities of chainsaw and single-grip harvester felling – produced using data from published literature – can be found in Table 6.4. Additionally, the productivity of the different extraction methods, which includes the impact of distance, is located in Table 6.5.

#### 6.3.1.1. Felling Productivity & Costs

Within forestry, there are two main methods for tree felling; either chainsaw felling or by a more mechanised process using harvesters – in this case, single-grip harvesters. Utilising an array of published data, the felling productivities for chainsaw and single-grip harvester use have been calculated as 14.0 $m^3$ $h^{-1}$ and 34.2 $m^3$ $h^{-1}$, respectively. These have been standardised at a 25cm DBH, both ensuring the comparability of the two methods while being representative of the UK's current stock [52]. It should be noted that the estimated harvester productivity is based upon two different harvesting methods, combining results from shelterwood and selective thinning systems. On forest sites – typified specifically by poor stand accessibility – a selective thinning system could result in a greatly reduced productivity when using heavy machinery for felling [14]. An additional benefit to using a single-grip harvester – further to the increased productivity – is that the felling process includes the debrashing and cross-cutting of the felled trees. Chainsaw felling therefore requires the incorporation of additional processing, detailed in Table 6.4 – the resulting productivity has been calculated as 9.5 $m^3$ $h^{-1}$.

Although the felling productivity of a chainsaw is considerably lower than that of the single-grip harvester – when assuming a 25cm DBH – the literature

Table 6.4 – **Calculated productivity and mean costs for felling and processing techniques**

| | **Productivity ($m^3$ $h^{-1}$)** | **Mean Cost (£ $m^{-3}$)** |
|---|---|---|
| Chainsaw[a] | 14.0 | 3.15 (±0.80) |
| Single-grip Harvester[a] | 34.2 | 2.93 (±0.77) |
| Stump Harvester[b] | 7.4 | 10.04 (±1.88) |
| Chainsaw Processing | 9.5 | 4.64 (±0.70) |
| Chipping | 26.4 | 5.69 (±0.75) |

*[a]standardised (25cm DBH) & [b]standardised (400 stems $ha^{-1}$)*

Table 6.5 – **Calculated productivity and mean costs for different extraction process over long and short distances**

| | **Short Distance[a]** | | **Long Distance[b]** | |
|---|---|---|---|---|
| | Productivity ($m^3$ $h^{-1}$) | Mean Cost (£ $m^{-3}$) | Productivity ($m^3$ $h^{-1}$) | Mean Cost (£ $m^{-3}$) |
| Forwarder | *14.1* | *5.47 (±0.62)* | *9.8* | *7.77 (±0.89)* |
| Skidder | *19.2* | *3.85 (±0.39)* | *5.2* | *10.52 (±1.07)* |
| Mini-skidder[c] | *4.7* | *10.69 (±1.27)* | *3.5* | *14.04 (±1.66)* |
| Cable Yarder | *9.2* | *16.01 (±1.60)* | *6.7* | *22.07 (±2.21)* |

[a]standardised at a distance of 250m, [b]calculated at 750m, using the functions in Figure 6.5, [c]or mini-forwarder

indicates that it greatly increases when felling much larger trees. Although the UK's broadleaved resource is typified by trees with larger DBH values – a result of the shift to high forest regimes – the smaller diameter value has been used, acknowledging the likelihood that smaller trees would be utilised for woodfuel [16, 23, 52, 53]. Combining the calculated productivities with the labour and machine costs, found in Table 6.1, results in the production of felling costs; for the chainsaw and harvester methods, these are 3.15 £ $m^{-3}$ (±0.80) and 2.93 £ $m^{-3}$ (±0.77), respectfully. There is little difference in the initial calculated costs, however – when including the costs associated with the required additional processing – the chainsaw felling increases to 7.79 £ $m^{-3}$ (±1.50), which is more than twice that of using a single-grip harvester.

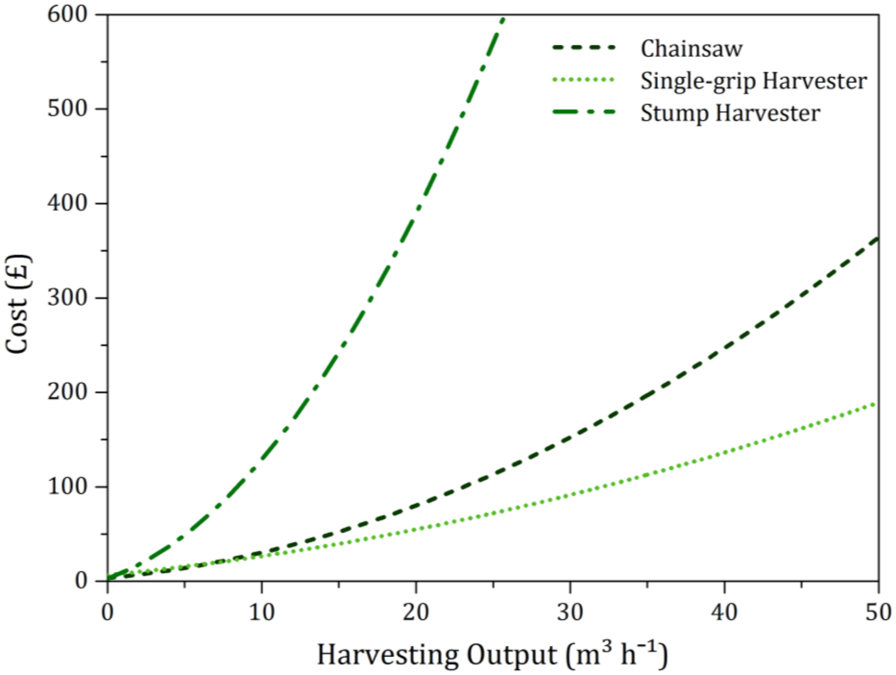


Figure 6.4 – **Changes in costs of felling and stump harvesting methods, relating to an increased hourly output ($m^3$ $h^{-1}$) derived from data in Tables 6.4 and 6.5**

In comparison to the felling process – which involves the clearing of 'above-ground' wood – stump harvesting instead utilises heavily mechanised processes to breakup and remove the stump and roots [38]. The increased work rate required to harvest stumps, when compared to felling, results in a smaller calculated productivity, determined as 7.4 $m^3$ $h^{-1}$. This poor productivity, coupled with the expensive nature of the required machinery, results in a calculated cost of 10.04 £ $m^{-3}$ (±1.88) – clearly making it the most expensive route for amassing wood resource from forest stands.

Although there are differences between the accrued costs (£ $m^{-3}$) of chainsaws, single-grip harvesters and stump harvesters, these are further exacerbated when the scale of operation is increased. Figure 6.4 shows that the application of a time element to the harvesting output, impacts the three wood supply processes differently. The chainsaw felling costs – not including the additional processing – closely mirror those of the single-grip harvester up to an output of 10 $m^3$ $h^{-1}$, however at higher felling rates this begins to decouple. This highlights that as the woodfuel industry continues to grow – coinciding with an increased demand for wood resource – reductions in felling costs are best achieved by the mechanisation of forestry processes, as supported by previous literature [2, 14]. The results in Figure 6.4 also indicate that the already high costs of stump harvesting are worsened when increasing the scale of operation. This suggests that any use of stump residues should be kept at a minimum – supplementing 'above-ground' wood resource – and that scaling up the operation isn't viable.

#### 6.3.1.2. Extraction Distance – Productivity & Costs

The extraction process of wood resource has experienced a large shift towards mechanisation to increase productivity. Although the terrain roughness and slope influence extraction productivity, one of the key factors – applicable to all forest stands – is the extraction distance. Table 6.5 details the calculated productivities for some of the most frequent methods of extraction; skidding, forwarding, mini-skidding/forwarding and cable yarding, which is also referred to as skyline extraction. Over a standardised distance of 250m, extraction by skidder results in the best productivity, calculated at 19.2 $m^3$ $h^{-1}$, with forwarding the second best, achieving 14.1 $m^3$ $h^{-1}$. Of the four extraction methods, the worst productivity is incurred by mini-skidding, which – as a result of its smaller payload – has an estimated extraction productivity of 4.7 $m^3$ $h^{-1}$. Finally, cable yarder systems are best utilised on sloped sites that are inaccessible for heavy machinery. Although its productivity – calculated as 9.2 $m^3$ $h^{-1}$ – is smaller than forwarding and skidding, it is not completely inhibitory.

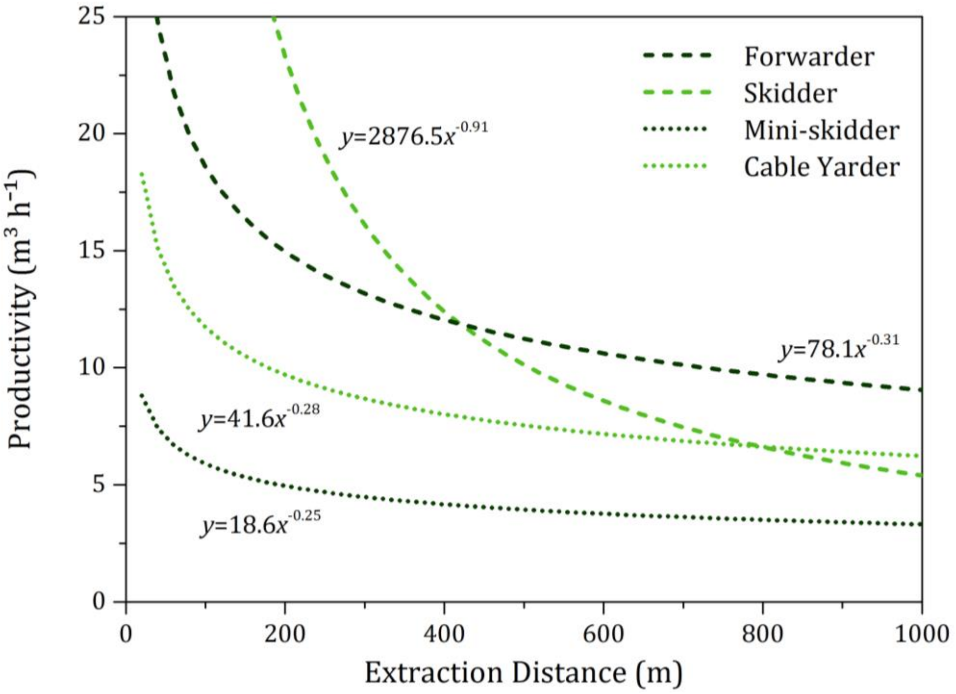


Figure 6.5 – **The impact of distance on the productivity of different extraction methods derived from data in Tables 6.4 and 6.5**

Using data collated from the literature, given in Tables 6.1 and 6.2, relationships between the distance and productivity – specific to the extraction processes – have been inferred; these are detailed in Figure 6.5. Instead of utilising linear functions to depict the relationships between distance and productivity, exponent-based regression has been used, in acknowledgement that neither variable can fall below zero. Consequently, as evidenced in Figure 6.5, of the four considered extraction methods, skidding productivity is impacted the most by distance. Unlike forwarding, which makes use of hydraulic loaders to load wood as it moves throughout a forest stand, skidding requires the wood to be attached and directly dragged to the roadside. This, coupled with the increased payload of a forwarder, results in skidder extraction being the most productive over short distances, while forwarders are more productive over longer distances.

The differences in productivity impact the calculated extraction costs. As shown in Table 6.5, over a short distance – standardised at 250m – the costs of skidder and forwarder extraction are calculated at 3.85 £ m$^{-3}$ (±0.39) and 5.47 £ m$^{-3}$ (±0.62), respectively. Increasing the extraction distance to 750m, forwarding becomes the cheaper option – calculated at 7.77 £ m$^{-3}$ (±0.89) – while skidding increases to 10.52 £ m$^{-3}$ (±1.07). The reduced productivity of small-scale extraction processes result in larger costs; these have been calculated as 10.69 £ $m^{-3}$ (±1.27) over 250m, increasing to 14.04 £ $m^{-3}$ (±1.66) at 750m. Although achieving an acceptable level of productivity, the increased labour and machine costs associated with cable yarding results in high extraction costs – at 250m this has been calculated at 16.01 £ $m^{-3}$ (±1.60).

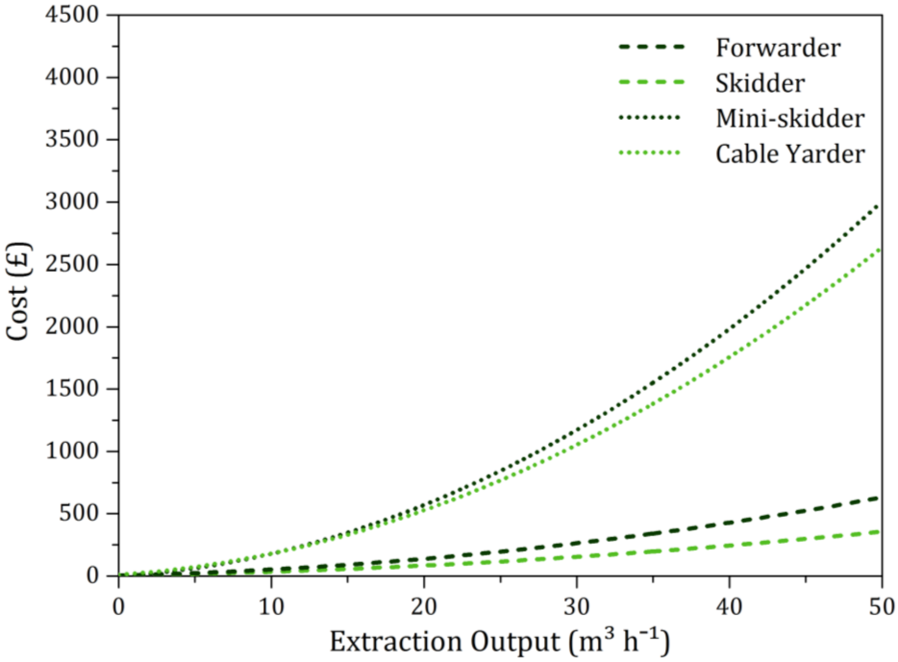


Figure 6.6 – **Changes in costs of extraction methods at 250m, relating to an increased hourly output ($m^3$ $h^{-1}$) derived from data in Tables 6.4 and 6.5**

As with the calculated felling costs, the differences between extraction methods increase when considering the potential growth in the operation scale. Again, the application of a time element – representing an increased requirement for wood supply – has been represented in Figure 6.6. As the required output increases, there is a decoupling between the forwarding and skidding processes, however this is less severe than that displayed by the mini-skidder and cable yarding processes. The results in Figure 6.6 highlight that, when considering an increase in operation scale, a reliance on mini-skidding or cable yarding is not viable.

#### 6.3.1.3. Felling & Extraction Combination

The felling and extraction processes are important components of the forest wood supply routes, therefore the combination of their associated costs – in a number of different scenarios – allows for the estimation of figures for the entire harvesting process. Table 6.6 details a total of eight different forest wood harvesting routes, highlighting the cost differences that are incurred through different scenarios. These have also been illustrated in Figure 6.7, demonstrating how the differences in costs are compounded at larger quantities of wood fuel.

Table 6.6 – **Wood supply scenarios and calculated costs; from standing timber to roadside**

| Scenario | Details | Cost (£ $m^{-3}$) |
|---|---|---|
| **1** | *Mechanical + Skidding (250m)* | *6.78 (±1.16)* |
| **2** | *Mechanical + Skidding (750m)* | *13.45 (±1.83)* |
| **3** | *Mechanical + Forwarding (750m)* | *10.70 (±1.65)* |
| **4** | *Chainsaw + Mini-skidding* | *13.84 (±2.06)* |
| **5** | *Chainsaw + Mini-skidding + Delimbing* | *18.48 (±2.76)* |
| **6** | *Chainsaw + Cable Yarding* | *19.17 (±2.40)* |
| **7** | *Stump harvesting + Forwarding (250m)* | *15.51 (±2.50)* |
| **8** | *Stump harvesting + Forwarding (750m)* | *17.80 (±2.77)* |

Scenarios 1, 2 and 3 represent the mechanisation of the felling and extraction processes, assuming the use of large harvesting machinery. Depending on the location of the forest wood resource, across shorter extraction distances, a combination of single-grip harvesters and skidders provide the most economical supply route for accessing wood resource. However, when considering longer extraction distances, the estimated scenario costs indicate that forwarders should instead be utilised. The mechanisation of forest harvesting is the most cost effective route for accessing wood resource, but this can have severe detrimental impacts on the environment, especially on sensitive sites. The increased weight of the machinery can prompt issues with soil compaction, soil damage and damage to vegetation – reducing the ecological diversity of a forest stand [54, 55]. As a result, Scenarios 4, 5 and 6 contain forest wood supply routes which represent lower impact processes for felling and extracting. Assuming a short extraction distance, the cost of combining chainsaw felling with a small-scale extraction method is more than double the most economical mechanised method. When incorporating the delimbing and cross-cutting processes, the total cost increases – estimated at 18.48 £ $m^{-3}$ (±2.76) – which is a 173% rise on the costs of Scenario 1.

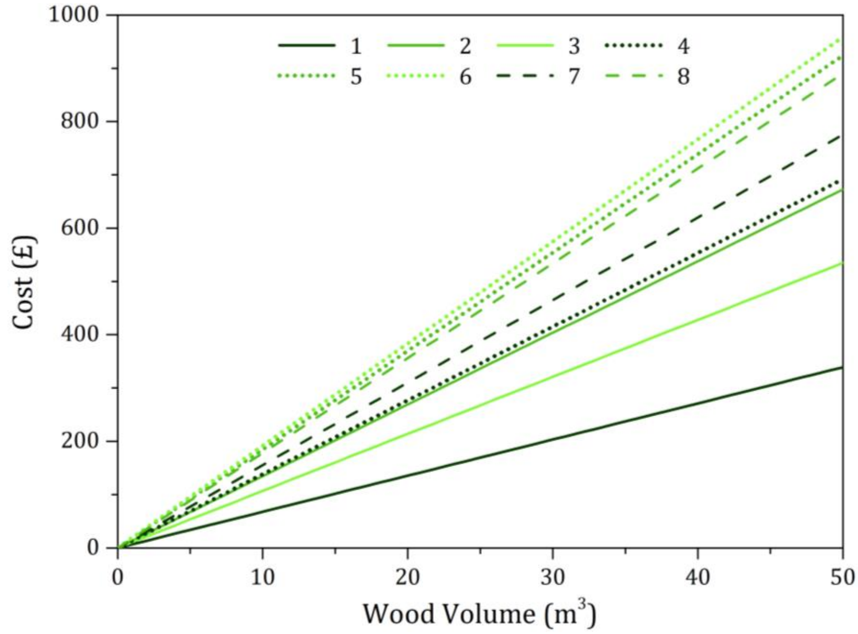


Figure 6.7 – **Comparison of wood supply scenarios; from standing timber to roadside**

Alternatively, Scenario 6 represents the harvesting of forest sites on slopes that are too steep for mechanised access. Combining chainsaw felling with a cable-based extraction system results in the most expensive supply route for wood biomass, calculated at 19.17 £ $m^{-3}$ (±2.40). Assuming a short extraction distance, this value doesn't include the additional processing of the wood – this would increase the costs by a further 4.64 £ $m^{-3}$ (±0.70). The final two scenarios consider the costs associated with accessing and extracting stump wood within a forest site, ready for roadside chipping once removed. The calculated costs of stump harvesting range between 15.51-17.80 £ $m^{-3}$, depending on the extraction distance. Once at the roadside, the additional costs of chipping – given in Table 6.4 – are calculated at 5.69 £ $m^{-3}$ (±0.70). As displayed in Figure 6.7, increases to the volume of harvested wood resource exacerbate the differences in cost. This is important when considering the scale of the operation; if large volumes of wood are required, then the additional costs of obtaining the resource by low-impact methods will increase quickly.

### 6.3.2. Cost Variance in the UK

The calculated costs for alternative felling and extraction scenarios, established previously, can be used to estimate the costs associated with harvesting the UK's forest wood resource. This is achieved by applying the chosen supply scenario costs to the spatial datasets, incorporating the UK's terrain and infrastructure into the final produced results.

#### 6.3.2.1. UK Forest Wood Resource

Before applying the scenario costs, it is important to first understand the location of the UK's hardwood and softwood forest resource; as a result, Figures 6.8 and 6.9 detail the distribution of the UK's broadleaved and conifer woodlands, respectively, across its four constituent nations.

As shown in Figure 6.8, a large proportion of the UK's hardwood resource is located in England, particularly in the south east. The largest concentrations of broadleaved species can be found in the counties of Sussex, Surrey, Kent and Hampshire; these have several cells which contain broadleaved forest areas totalling more than 3000 ha. In Wales the broadleaved woodland cover is spread evenly across the nation, except for within the mountainous regions, which are instead dominated by conifer species. Considering the grid framework, a large proportion of the cells contain total areas of Welsh broadleaved woodland ranging between 500-1500 ha. Unlike England and Wales, both Scotland and Northern Ireland are typified by a smaller coverage of broadleaved species. Other than a few hotspots of broadleaved cover in central Scotland, the majority of the defined areas contain totals that are less than 1000 ha, with a lot of these less than 100 ha. Finally, the majority of the cells within Northern Ireland contain broadleaved forest cover less than 500 ha, although Fermanagh – in the west of the country – contains several cells with a total area of between 500-1000 ha. Based upon the same forest datasets utilised in this research – adjusting for new planting – the Forestry Commission estimate the area of the UK's broadleaved woodlands in 2017 at 1.55 million hectares (ha). However, this includes a range of interpreted forest types (IFTs) that aren't directly related to wood resource; categories such as Felled, Shrub Land and Ground Prepared for New Planting are included within the final estimated woodland totals [2, 48]. Considering the UK's useable wood resource, Figure 6.8 only contains the extracted data that can be directly attributed to broadleaved species; all other unsuitable IFTs have been discounted. As a result, the total areas of broadleaved woodlands – containing standing timber – is greatly reduced from the stated figures, estimated to be 1.18 million ha.

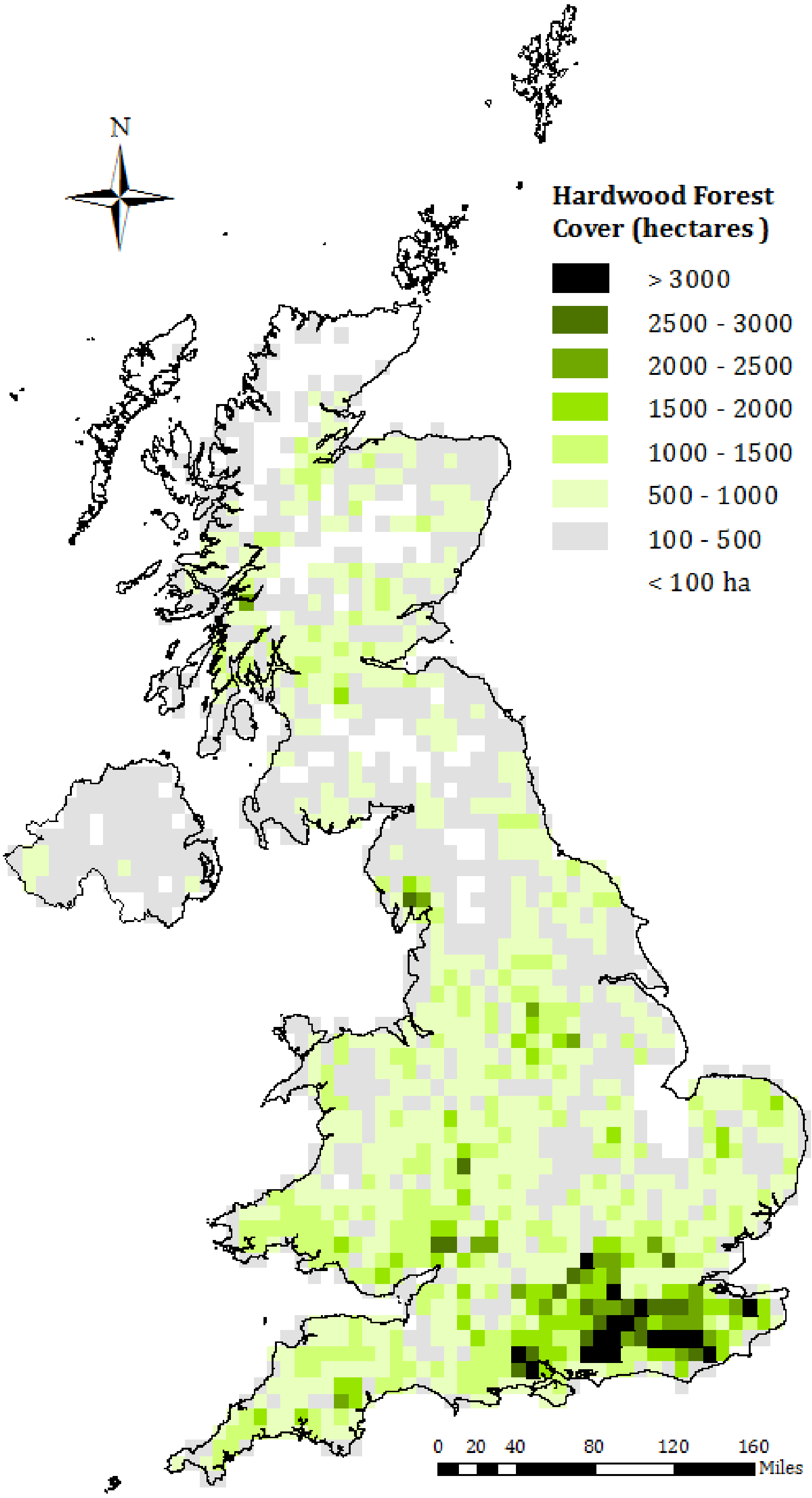


Figure 6.8 – **Distribution of the UK's hardwood woodland resource (hectares)**

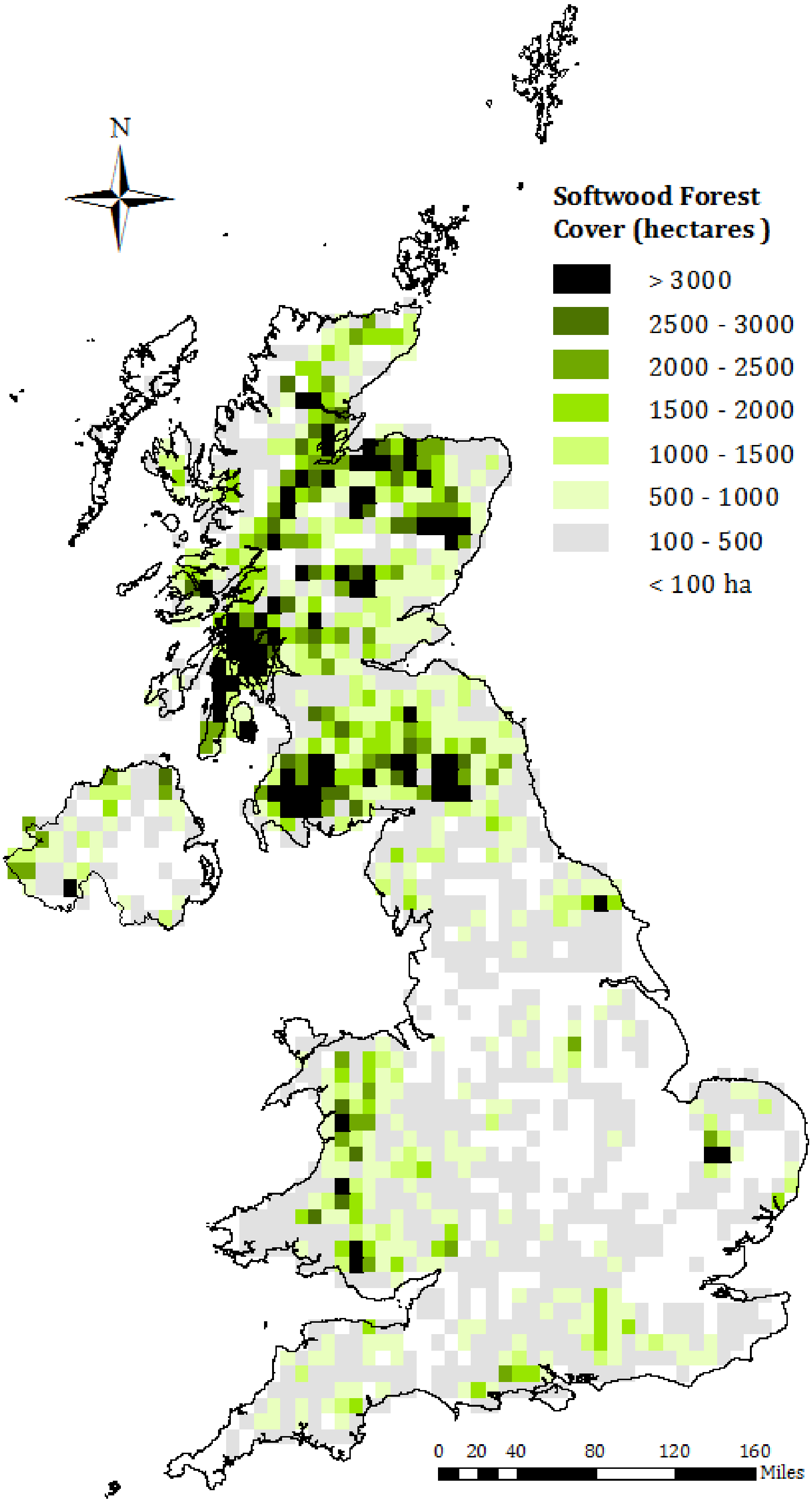


Figure 6.9 – **Distribution of the UK's softwood forest resource (hectares)**

As evidenced in Figure 6.9, the distribution and structure of the UK's softwood species differ greatly to that of its hardwood resource. Firstly, there are considerably more areas with high concentrations of forests; unlike the hardwood map, which contains 18 cells with total forested areas in excess of 3000 ha, the softwood map has 80. The majority of these are found in Scotland – particularly in the Scottish highlands and in the south of the country, away from the densely populated areas of Glasgow and Edinburgh. The large concentration of conifer plantations in upland sites are a direct result of the UK's post-war forest policy, focusing on the afforestation of land with low soil fertility and little agricultural value [56]. By contrast, England's softwood coverage is sparse, containing only a limited number of areas that exceed 500 ha of conifer forest cover. Indeed, the only cells within England that contain large areas of conifer species are situated close to the Scottish border in the north, in the north east, in East Anglia and on the south coast. The majority of the Welsh conifer feedstocks are located in the nation's mountainous regions of Powys and Snowdonia, containing several areas exceeding 2500 ha of conifer forest cover.

Finally, following the 1st World War, Northern Ireland's forest stocks were reduced to ~1%, prompting a concerted effort to increase the forest coverage; achieved predominantly via large scale conifer plantations [57]. Consequently, a large proportion of the conifer resource is based in the west of the country – primarily in Fermanagh, the least populated region of the country. There are also several areas in Antrim and Derry/Londonderry, containing forested conifer areas that total more than 2000 ha. As with the UK's hardwood resource, the Forestry Commission's area estimates of conifer forests – given as 1.62 million ha, in 2017 – include additional IFT categories. The area of the UK's total softwood forest cover, illustrated in Figure 6.9, has subsequently been estimated at 1.23 million ha, when considering the areas containing standing timber.

#### 6.3.2.2. Forest Wood Supply Costs

The associated costs of felling and extracting wood resource from forests differ, dictated by the sites location and conditions. Applying appropriate scenario costs to the different spatial datasets – outlined in Table 6.3 – allows for the weighted mean costs to be estimated, specific to each individual area. As a result, Figure 6.10 details the costs of harvesting wood in the UK, assuming the most economic scenario for each dataset. Within the produced grid framework, a total of 101 individual cells contain felling and extraction mean costs in excess of 12.50 £ $m^{-3}$, representing more than 88,000 ha of hardwood and softwood forests. Of this total forest cover, ~67% is attributed to conifer species; this dominance is predictable, representative of the post-war upland planting policy previously discussed. Although Figure 6.10 portrays the most economic forest harvesting scenarios, certain areas within the UK – due to their specific location – have considerably larger costs. Consequently, the largest calculated mean cost has been determined at 23.59 £ $m^{-3}$.

Considering the four constituent nations, the terrain and infrastructure of Scotland clearly has the largest impact on harvesting its existing forest resource; this is most apparent in its highland regions, specifically in the north west of the country. In southern Scotland – where large swathes of conifer forest cover exist – the factors impacting felling and harvesting are clearly reduced. This area forms an important component of the UK's commercial forest industry, with several major sawmills existing in the south west of the country, close to Dumfries. Although not as severe as the Scottish highlands, a large proportion of Wales is impacted by the location of its resource, particularly in parts of the Brecon Beacons and Snowdonia. In England, the affected areas are greatly reduced; these include the Lake District, several locations across the Pennines and the coastal regions of Exmoor National Park. Finally, although representing a much smaller area of wood resource – when compared to the rest of the UK – Northern Ireland's favourable conditions mean that its determined harvesting costs are lower across the entire country. Within the framework, 2000 of the individual cells contain some form of tree cover, indicating that the majority of the UK has a semblance of forest representation, even if only small. Of these, broadleaved cover is dominate in more than 65% of the cells, highlighting its wider distribution across the UK when compared to conifer species. The spatial distribution of the UK's hardwoods and softwoods can be found in *Appendix E*.

Table 6.7 contains the calculated means and standard deviations for the produced felling and extraction costs, presented in Figure 6.10. Combined, the mean felling and extraction costs have been calculated as 8.63 £ $m^{-3}$, however this changes when apportioning the areas by either hardwood or softwood dominance. Indeed, the costs of harvesting wood from areas dominated by

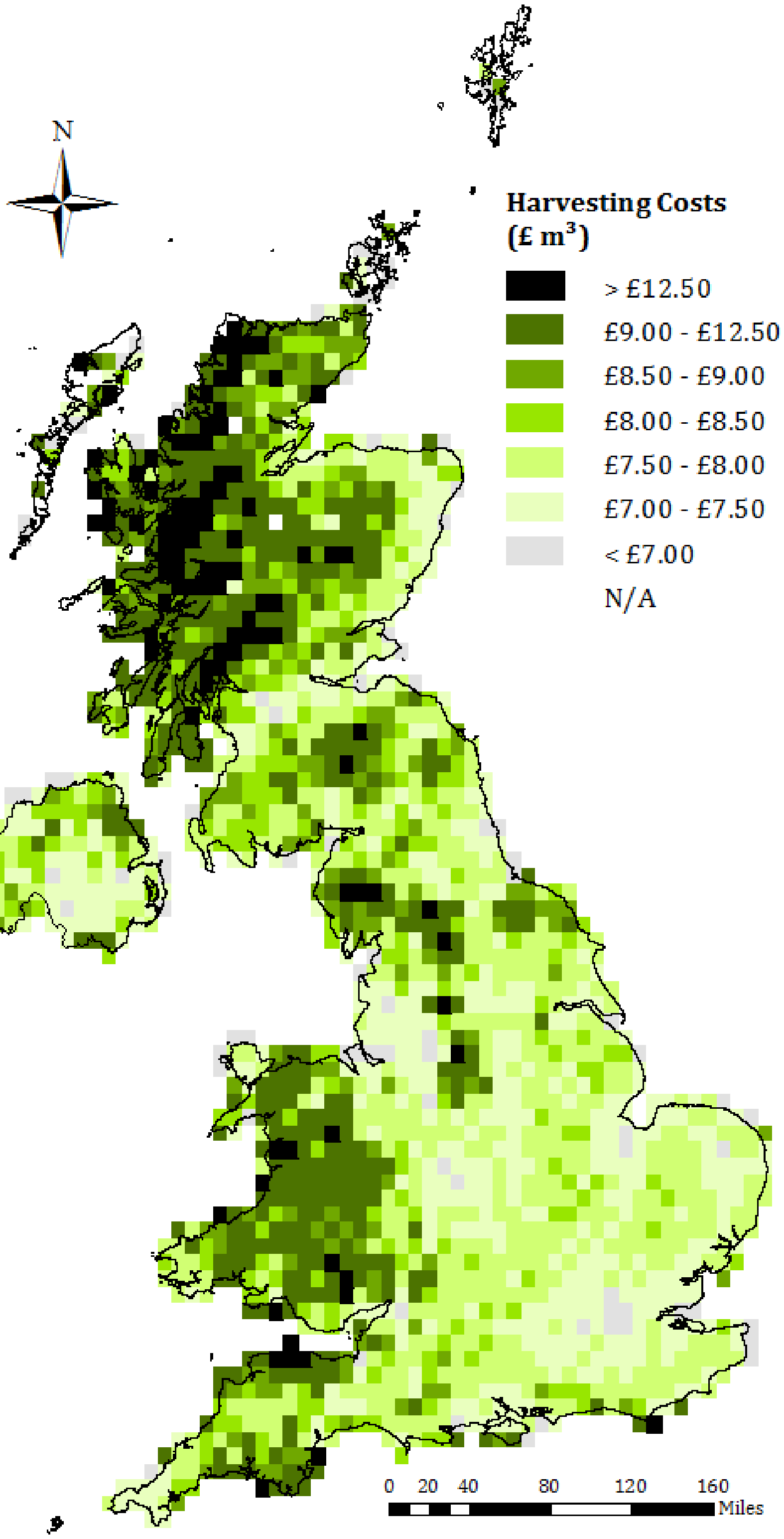


Figure 6.10 – **Costs of felling and extracting wood resource (£ m$^3$) from UK forests; impact of slope and extraction distance**

broadleaved forests (M=8.29, SD=1.92) are statistically significantly less than those dominated by conifer cover (M=9.27, SD=1.89); $t(10.868)=1998$, $p<0.001$.

This indicates that the UK's broadleaved resource is located in more accessible locations than its conifer feedstocks.

Table 6.7 – **Descriptive statistics for the estimated felling and extraction costs of the UK's hardwood- and softwood- dominated areas**

| Forest Harvesting Costs (£ $m^{-3}$) | n | Mean | Std. Dev. |
|---|---|---|---|
| **Hardwood** | *1309* | *8.29* | *1.92* |
| **Softwood** | *691* | *9.27* | *1.89* |
| **Total** | *2000* | *8.63* | *1.96* |

The results in Figure 6.10 are clearly important for understanding the UK's existing forest resource – and how best to utilise it – however, the data can also be useful when identifying preferable areas for tree planting. Mentioned previously in this thesis, the UK governments recent *Clean Growth Strategy* has proposed the creation of 130,000 ha of new woodland cover across England. This would include the newly proposed 'Northern Forest', which is set to span coast-to-coast – from Liverpool to Hull [58]. The long-term nature of tree growth and forest establishment means that any decision-making process should be as best informed as possible. Therefore any planting of new woodland cover in England, and other proposed national-level afforestation schemes, would benefit from utilising the data produced in this chapter.

### 6.3.2.3. Energy Costs

The wood bioenergy market – which continues to grow in the UK – forms an important income component for forest owners. However, there are several obstacles that impact the received product price, namely inconstant demand, high operating costs and long transportation distances. Estimated delivered market prices of refined woodfuel products, such as woodchips and pellets, have previously been published; given as £0.034 $kWh^{-1}$ and £0.05 $kWh^{-1}$, respectively [59, 60]. The comminution and transportation of wood biomass contributes to a large proportion of the final costs of wood biomass, therefore understanding the costs of the felling and extraction processes – in the context of energy potential – is important for determining the feedstocks viability. The previous section

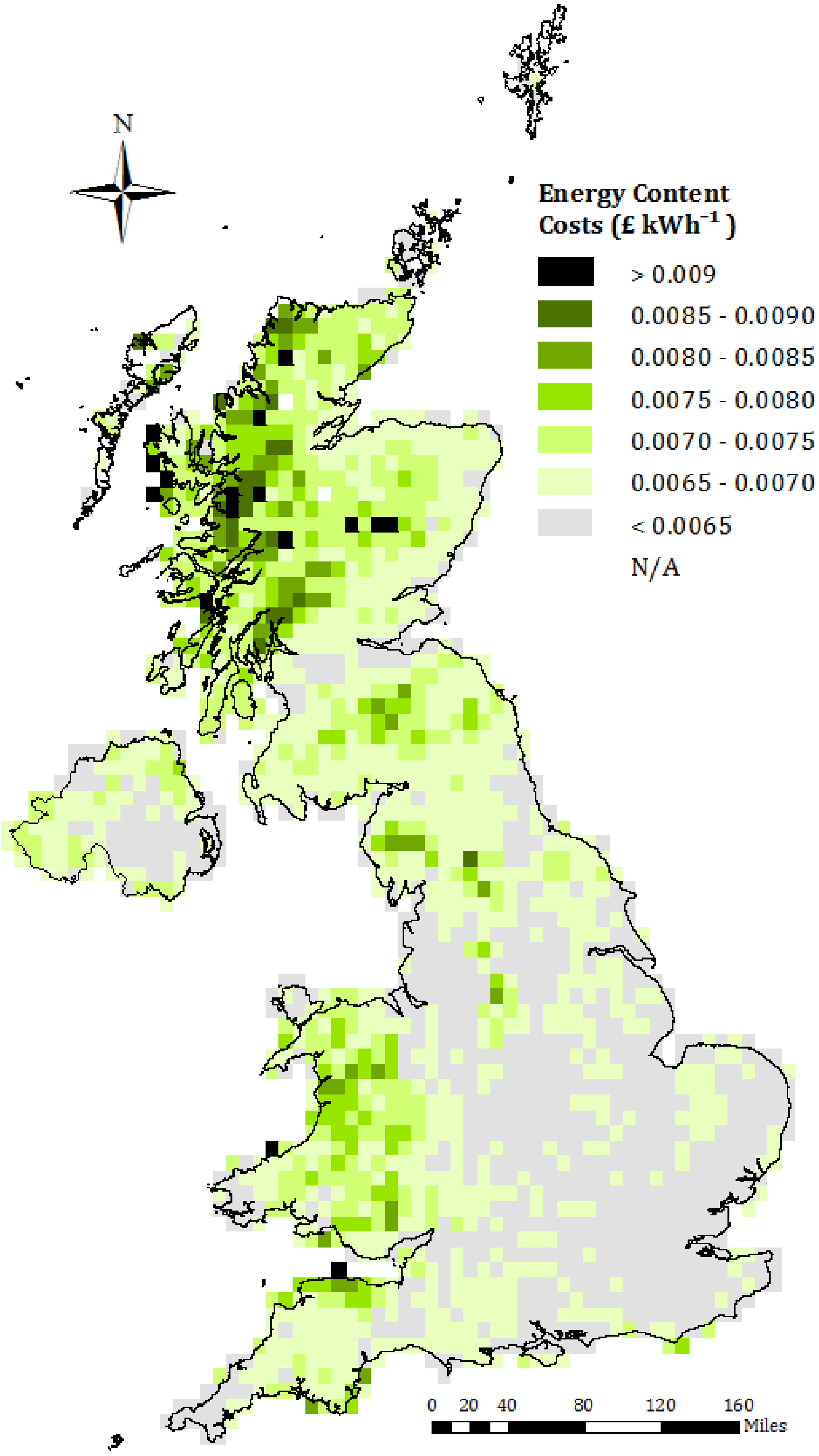


Figure 6.11 – **Estimated energy costs (£ kWh$^{-1}$) of wood biomass at the roadside; including the felling, extraction and stumpage price**

established the UK's felling and extraction costs associated with the most economic harvesting routes. Using this as its basis, Figure 6.11 details the calculated costs as a unit of energy (£ kWh$^{-1}$), utilising the calorific values established previously in Chapter 4. Exploiting both the experimentally determined species energy contents and characteristics – and those determined from the reviewed literature – general hardwood and softwood calorific values have been calculated. Assuming a moisture content of 30%, values of 11.44 and 11.76 MJ/kg have been calculated – for use with the hardwood and softwood resource, respectively. Combining these with the felling and extraction data allows for the determination of the energy costs (£ $kWh^{-1}$), appropriate for the wood resource located by the roadside.

As previously stated in this chapter, the UK's average 5-year Sawlog Price is 36.78 £ $m^{-3}$ [4]. Applying the above calorific values to the calculated Sawlog Price allows for the production of a roadside baseline energy cost; estimated at £0.01 $kWh^{-1}$ (±0.001), this represents approximately a third of the total delivered woodchip cost. In comparison, the UK's calculated mean energy costs – incorporating both the incurred harvesting costs and an average standing price of £17.14 $m^3$ – is £0.007 $kWh^{-1}$ (±0.001), with the majority of the resource falling below the baseline cost. This indicates that at current timber prices, when using the most economic mechanised felling and extraction methods, there is value in UK forest timber for use in bioenergy. It's important to note that these costs are based on advantageous conditions, using the productivity and scenario values contained in Tables 6.4, 6.5 and 6.6. By reducing the mechanised productivities by 50% – representing more difficult site conditions – the costs increase across the UK. The resulting mean is calculated at £0.009 $kWh^{-1}$ (±0.001). Although this prompts an increase in the number of areas elevated above the baseline – making them unviable – the majority of the UK sites still offer value, even with severely reduced felling and extraction productivities.

#### 6.3.2.4. Alternative Scenarios

In addition to the more economic forest wood supply routes, the scenarios in Table 6.6 also detail alternative methods of accessing wood resource. This includes the use of small-scale harvesting processes – utilising chainsaw felling with smaller extraction technologies – and the controversial practice of stump harvesting. At the beginning of this chapter, Figure 6.1 detailed the UK's current arisings, highlighting the potential for increasing the 2017 woodfuel removal volume by ~30%. Indeed, an additional 0.361 t $ha^{-1}$ $yr^{-1}$ could be potentially sourced from the UK's forests, achieved by utilising just a small proportion of the estimated net growth and some of the remaining conifer stumps. This figure assumes the removal of 10% of the conifer stumps left following felling, 10% of the hardwood net growth – acknowledging the need to increase the management of hardwood forests – and 4% of the softwood net growth.

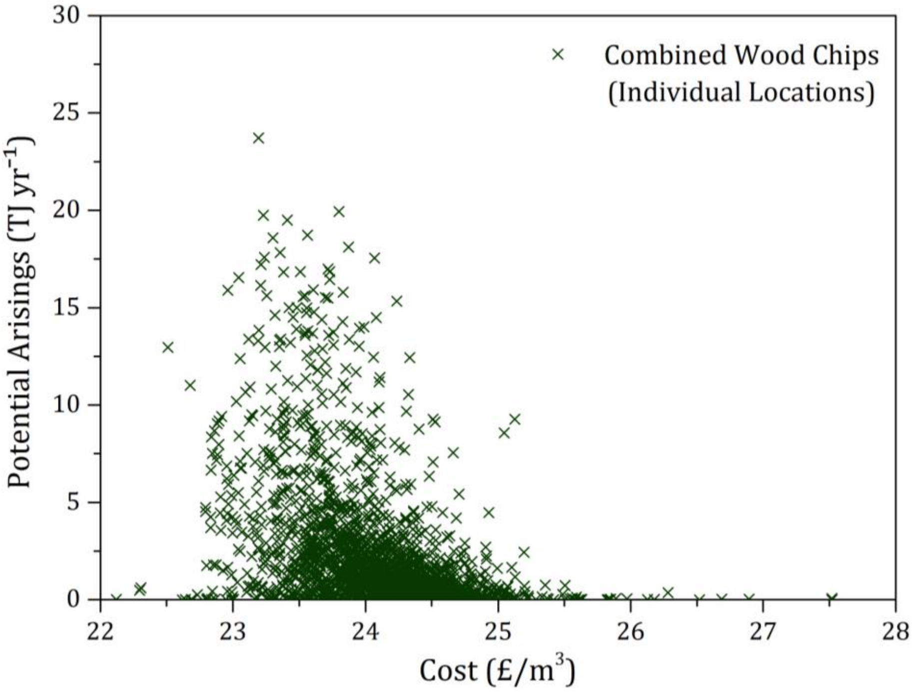


Figure 6.12 – **Estimated costs and energy content of potential arisings; produced from small-scale thinnings and conifer stump harvesting**

By applying the estimated arising figures to the produced calorific contents, the potential energy content (TJ $yr^{-1}$) for each cell can be estimated – representative of realistic increases in wood extractions that don't invoke deforestation. Figure 6.12 plots these calculated energy contents against their roadside costs, including the felling, extraction and chipping of the wood resource. Additionally, the geographical locations of the estimated energy contents can be found in Figure 6.13. As evidenced in Figure 6.12, a large proportion of the estimated woodchip arisings fall below 5 TJ $yr^{-1}$; a figure amounting to ~140 MWh, which is equivalent to the annual volume required for three medium scale 40kW boilers [61]. Using this as a minimum value, Figure 6.13 details a total of 280 locations

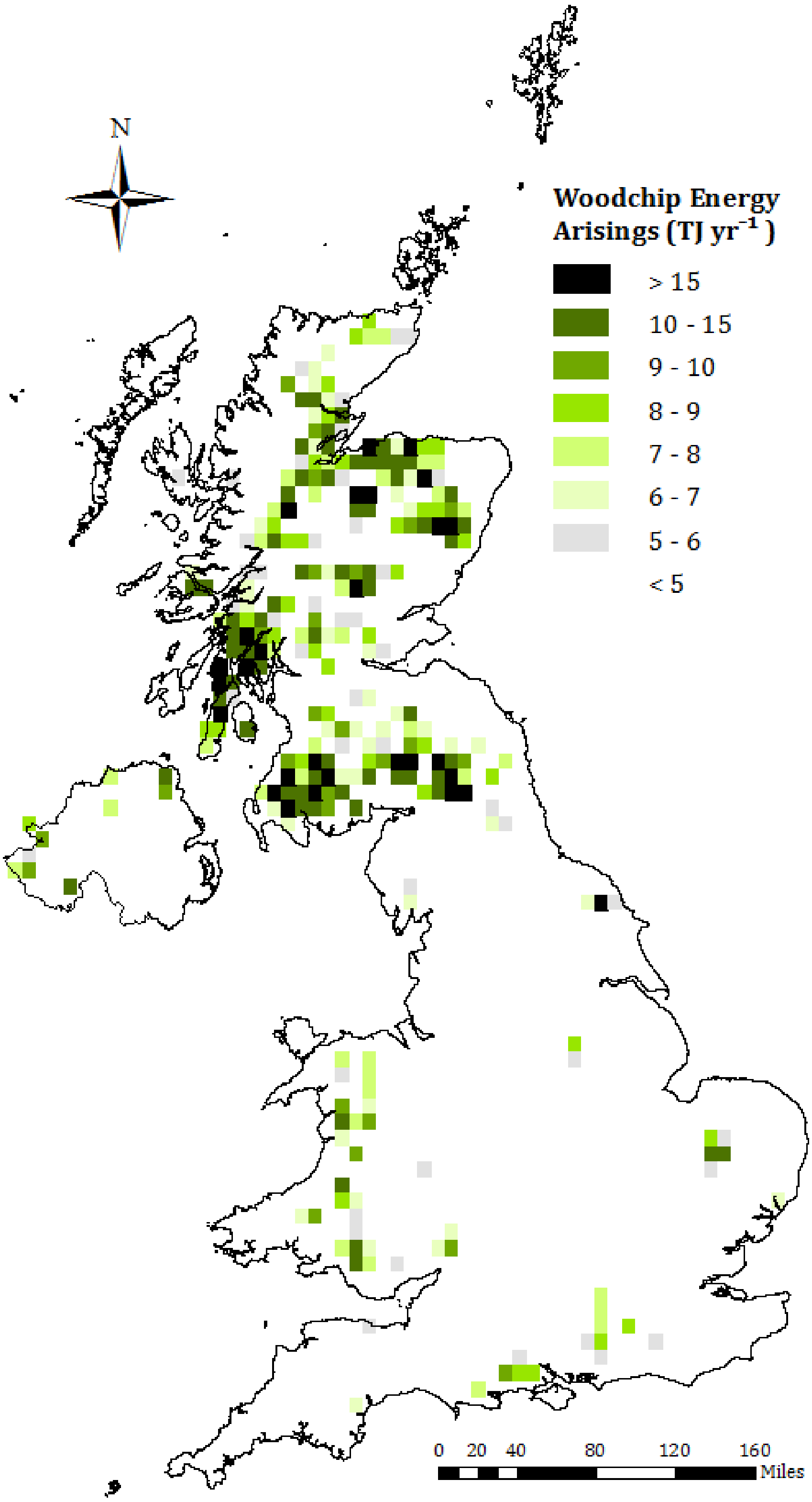


Figure 6.13 – **Location of potential arising (TJ yr$^{-1}$) from woodchips; produced from small-scale thinnings and softwood stump harvesting**

containing woodchip arisings that amount to more than 5 TJ yr$^{-1}$. These account for a combined 2,645 TJ yr$^{-1}$, representing a 3.2% increase on the 2016 figures for wood use in domestic energy consumption [62]. Although this is a relatively small volume, it still represents a substantial amount of energy and highlights that the UK's forests and woodlands are currently underutilised for sourcing local wood biomass for domestic use.

When considering the specified 280 cells, the calculated mean cost is 23.62 £ $m^{-3}$ (±0.41); this incorporates the felling, extraction and chipping of the wood feedstocks at the roadside. However, it doesn't include the stumpage price – an attempt to represent the costs expected for forest owners, opting to produce woodchips from their own woodlands using small-scale harvesting equipment. The calculated woodchip costs fall within the Forestry Commissions stated range – given as 21.51 £ $m^{-3}$ to 26.91 £ $m^{-3}$ – giving validity to the results contained within this chapter. Additionally, the Forestry Commissions suggested wood chip price, containing a 30% moisture content, equates to 74.32 £ $m^{-3}$. This therefore represents an excellent opportunity for forest owners to profit [63]. There are other important site-specific factors which may impact upon productivity, however the calculated costs – and those of the Forestry Commission – demonstrate the potential for forest owners to produce woodchips economically, utilising alternative sources of wood fuel. As the woodfuel market continues to grow, the opportunities for forest owners to profit from their wood products – particularly via domestic bioenergy production – may act as an incentive to improve the active management of their woodlands; principally private broadleaved woodlands, which have been recently underutilised [53].

#### 6.3.2.5. Identifying Optimal Locations

The final part of this chapter focuses on how best to utilise the previously produced results, helping inform the decision making process; this relates specifically to increasing the use of home-grown wood feedstocks for domestic bioenergy use. As previously discussed, the transportation of wood biomass – both the method and distance – has a major impact on the final costs [59]. Identifying potential areas of demand that overlay with the existing forest resource can help establish preferable locations for increased domestic woodfuel use. This would in turn reduce the costs – and resulting $CO_{2e}$ emissions – that are attributed to the transportation process, increasing the viability and benefits of utilising locally sourced wood. This final section therefore focuses on the development of a simple decision-making tool, combining some of the key results from this chapter and others within this thesis.

Establishing areas that may have a demand for woodfuel can be a complicated process, especially when tailoring this for an array of specific factors. These are determined by the final desired outcomes; however, a principle component – forming the core of any demand-based data – is the UK's population and its geographical distribution. As a result, using the same grid framework as the other datasets, Figure 6.14 details the UK's population distribution. To remove any potential bias, dictated by the large range of values, the data has been standardised using the feature scaling method – detailed in Eq. 6.4;

$$x_s = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{6.4}$$

where;

$x_s$ is the standardised value

$x_{min}$ is the smallest value within the given dataset

$x_{max}$ is the largest value within the given dataset

Instead of displaying specific numbers of UK inhabitants, the standardised data in Figure 6.14 depicts the locations of high- and low-concentration areas, within the uniform spatial regions of the grid framework. Converting the UK population data into this format results in a dataset which can be combined with the costs and energy contents, previously produced in this chapter. The data in Figure 6.14 – clearly depicting population hotspots over the UK's major cities and towns – will form a key part of the proposed decision-making tool. Although basic in its premise, the assumption that an increased concentration of people within a defined area will result in increased demand is a logical notion – if there are no people then there can be no demand. Additional factors – including societal issues, such as levels of deprivation, environmental concerns or political preferences – could affect the demand for wood-based bioenergy, however these all relate to population, highlighting that it is indeed at the core [64].

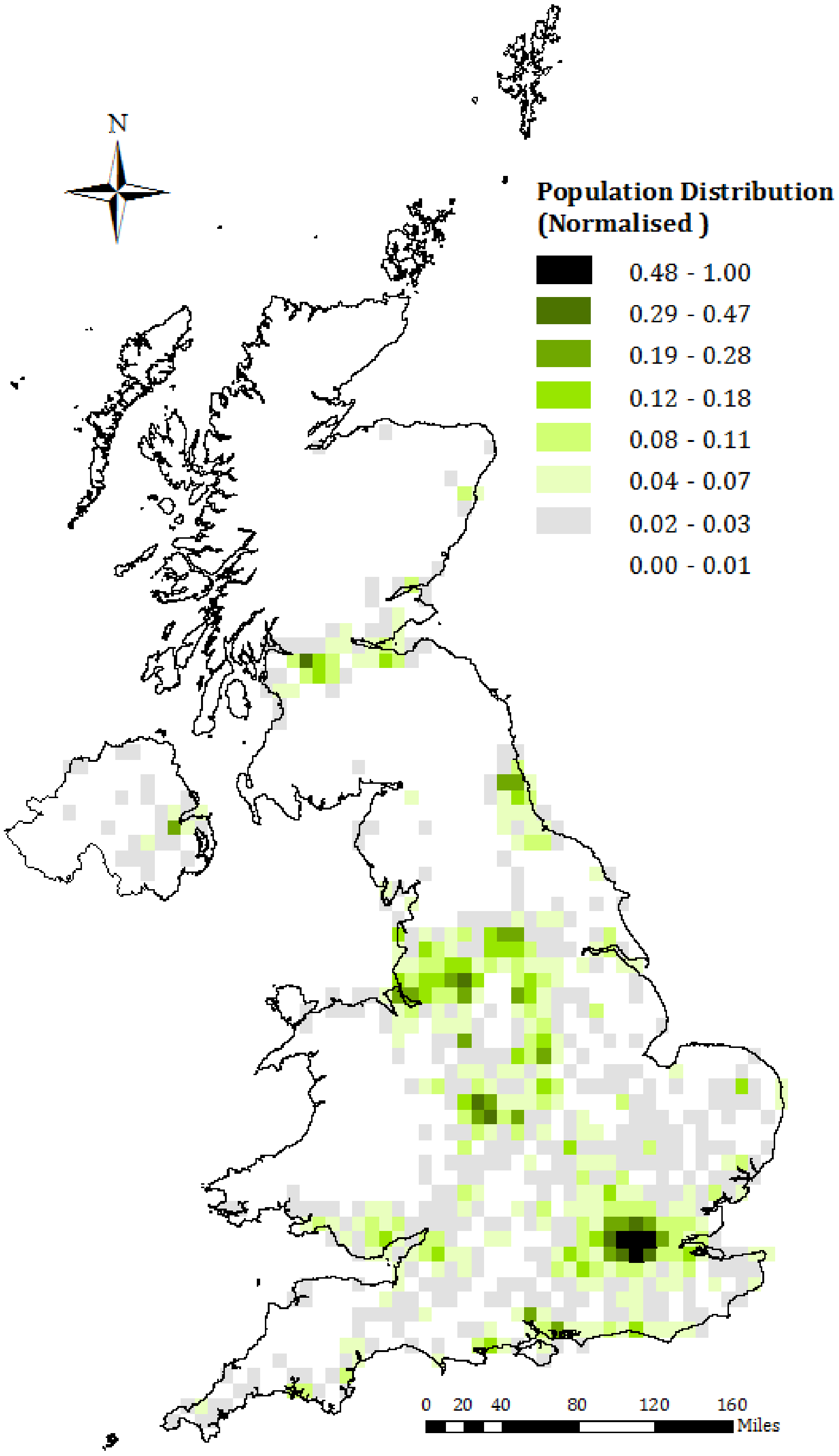


Figure 6.14 – **Normalised UK population distribution depicting areas of high- and low-concentrations**

Besides the potential consumers, the price of a commodity is also important when establishing demand [64]. In the context of woodchip production for domestic consumption, the cost data contained in Figure 6.12 details the range in the production costs, dictated by differences in the UK's terrain and infrastructure. Increased production costs – as well as other factors such as quality or moisture content – would impact the final price, therefore the data in Figure 6.12 would also form an important part in the decision-making process. Again, this must be standardised, using an amended version of feature scaling. This swaps the minimum and maximum values around in Equation 6.4, resulting in the lower calculated costs receiving the larger standardised values. The final dataset used is a standardised version of the woodchip energy arisings, found in Figure 6.13, again using the rescaling method detailed in Eq. 6.4.

Table 6.8 – **Simple designation of weightings, used within decision-making framework for establishing domestic woodchip use**

| Wood Biomass Decision Support | | |
|---|---|---|
| | **Datasets** | **Weightings (%)** |
| **Demand** | *Costs* | *25* |
| | *Population* | *25* |
| **Supply** | *Energy Arisings* | *50* |

Although only utilising three datasets, these represent a substantial amount of detailed data contained within a framework that allows for their integration. The simple combination of the values – applying appropriate weightings, as detailed in Table 6.8 – allows for calculated scores to be determined for each individual cell within the grid framework. Evidently, a wide array of data sources can be combined to identify optimal locations, within the UK, helping to increase the uptake of domestic woodchip combustion. These results are presented in Figure 6.15, detailing the top 1%, 5% and 10% of sites across the UK, specific to the increased woodchip use. The majority of the calculated optimal sites can be found in the rural areas of Scotland, spanning a wide range of locations across the nation. Considering that a large proportion of the UK's current forest industry exists in Scotland – in 2017 more than 63% of the softwood removals were from Scottish forests [2] – the infrastructure for increasing the production and delivery of woodfuel should already be in place. Similarly to Scotland, the determined optimal locations within the UK's remaining constituent nations are also situated predominantly away from urban hotspots. This includes several locations across mid Wales and in the northern and western regions of Northern Ireland, typified by their small towns and rural communities.

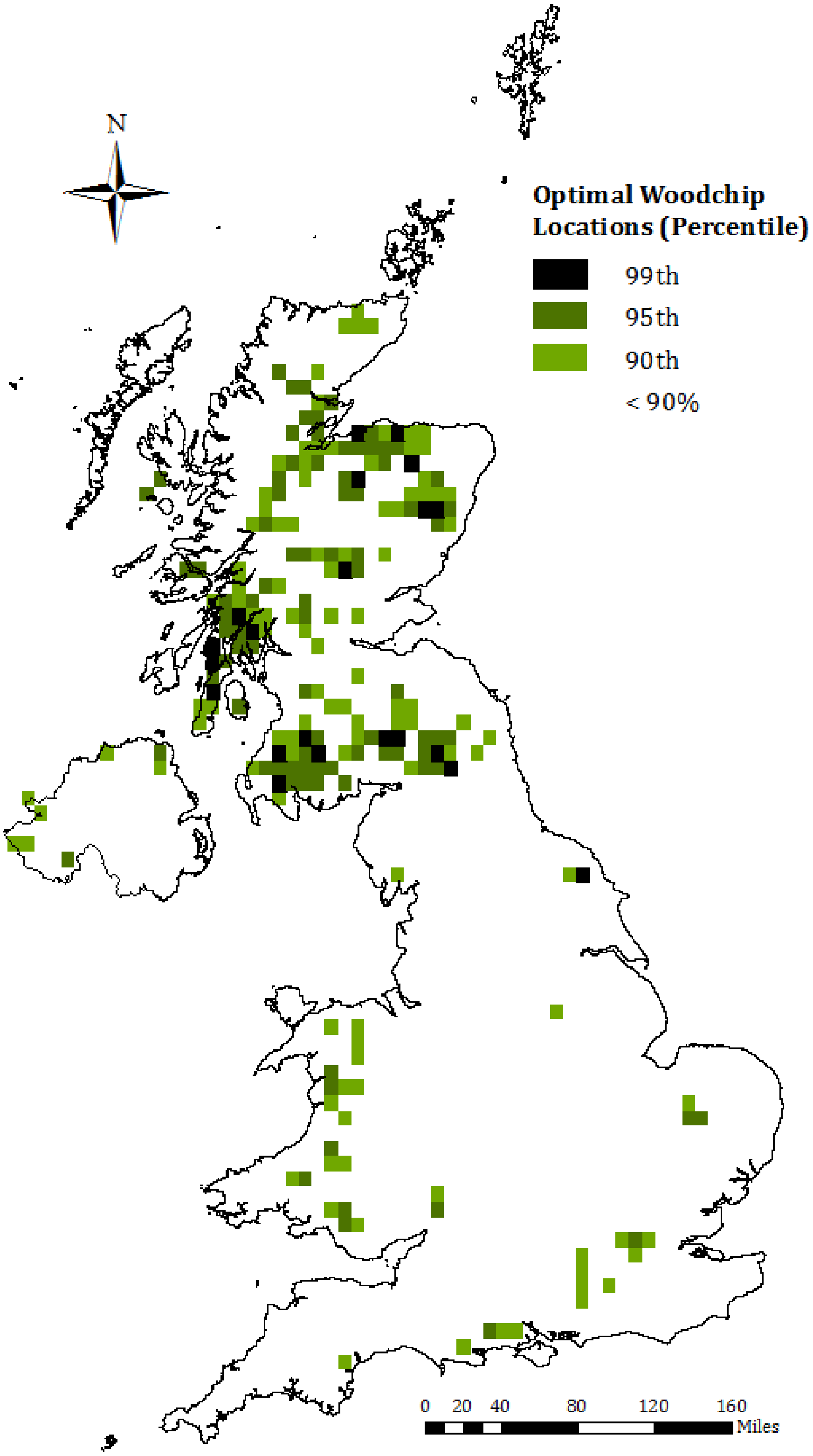


Figure 6.15 – **Optimal locations for increasing the uptake of woodchip combustion within the UK; calculated 99th, 95th and 90th percentiles**

These results show that by utilising different data sources – converting them into a comparable format – it is possible to help inform the decision making process,

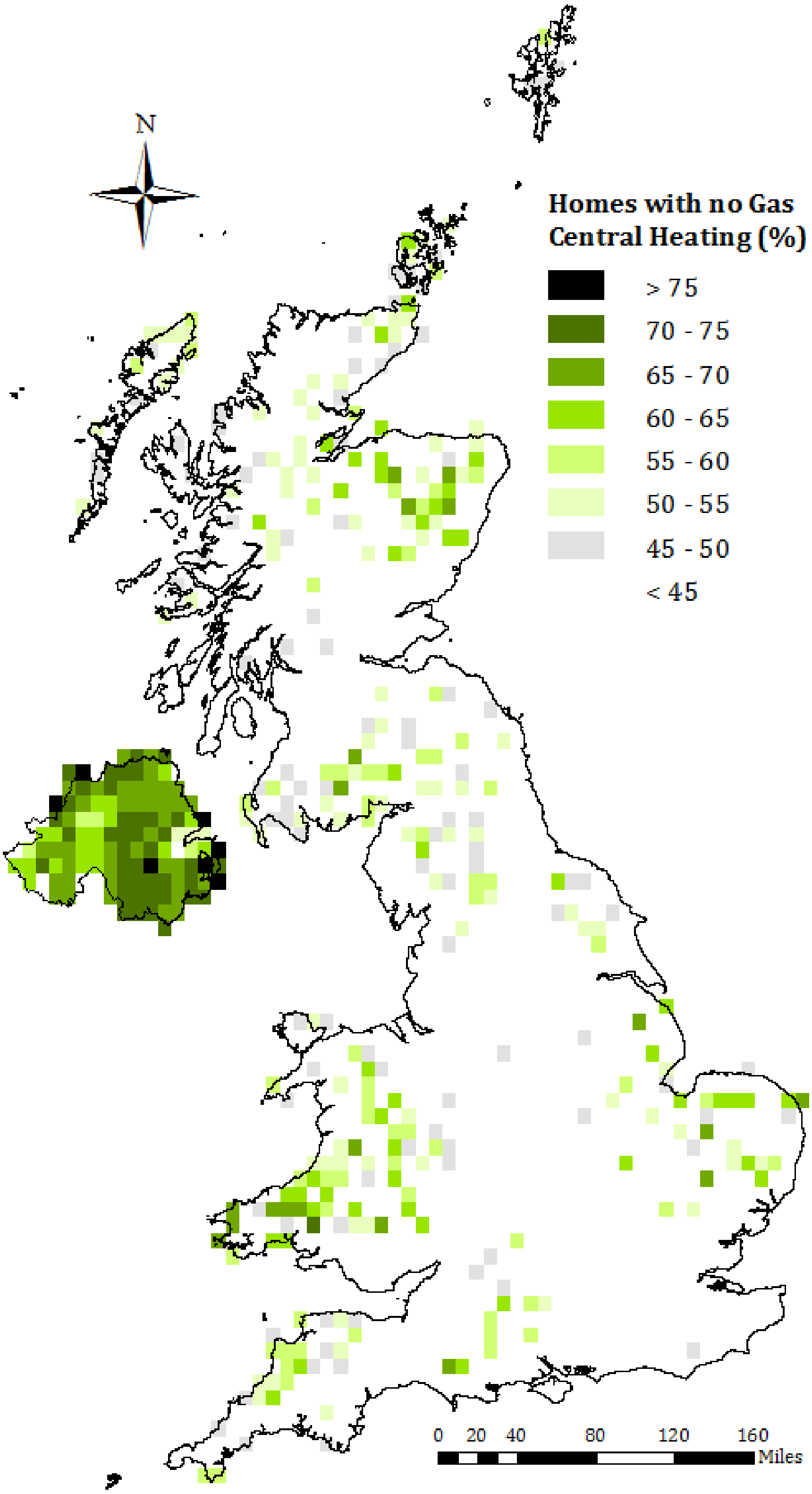


Figure 6.16 – **Geospatial areas of UK homes with high concentrations of no gas central heating, produced using 2011 *Census* data [43-45]**

establishing specific areas that are best for increasing the uptake of locally sourced woodfuel. Although simple in its application, Figure 6.15 clearly details the location of the small individual optimal areas – measuring just 55 square miles – that are situated in the UK. Considering these results, the map in Figure 6.16 – identifying high concentration areas within the UK where the existing domestic properties have no gas central heating – highlights the potential decision-making benefits of utilising a system such as the one in this chapter. As evidenced by Figure 6.16, there are still a large number of rural communities that depend upon alternative forms of heating. This includes areas across all of the UK's constituent nations – in particular Northern Ireland – which has a large proportion of its housing stock with no access to gas central heating.

As a result, both Figures 6.15 and 6.16 demonstrably show that the UK's rural areas offer an excellent opportunity for increasing the use of local wood fuel resource, reducing the reliance of small communities on fossil fuels such as coal and oil. This in turn would help reduce the emissions of $CO_2$ attributed to domestic heating, and – in the case of oil deliveries, which can be prohibitively expensive – it would help combat fuel poverty and other issues related to energy access. Indeed, a defined sustainable forest management plan – making use of local forest resources for bioenergy generation, in the locations that need it the most – could result in array benefits that are in keeping with the UK's current forest resource policy objectives [3].

## 6.4. Discussion

Trees represent one of the greatest natural resources we have on earth. Whether sustaining human life – through the air that we breathe – or by sequestering carbon, helping negate the potential impacts of climate change; the importance of our forests and woodlands is undeniable. This extends to their utilisation as a feedstock for energy generation – although, it's accepted that the increased deployment of woodfuel should be achieved both respectfully and sustainably. To accomplish this – while further avoiding negative environmental and social impacts, such as deforestation, a loss of diversity or reduced public access [3] – the sustainability of the woodfuel market also requires its economic viability.

Understanding the costs associated with accessing forest biomass – and how these change, depending upon the location and terrain – is important for establishing if, and by how much, the local wood resource can be used for energy generation.

Determining the economic variation of accessing forest resource first requires the alternate methods of felling and extracting timber to be defined, highlighting how their calculated productivity and costs differ. The mechanisation of forest practices – as with other industries, such as agriculture – is driven by the desire to reduce costs, especially when considering anticipated increases to the scale of operation. Indeed, the emergence of the bioenergy market has placed additional demand on the forest wood industry to produce more low-quality timber resource, prompting the necessary use of large-scale mechanised harvesting options to achieve this [6, 14]. As expected, the results produced within this chapter highlight the financial benefits of mechanisation; the increased productivity of felling and wood extraction from forest stands, using mechanised processes, reduces the associated costs. However, this economic success can come at the expense of the environment and ecology of a forested site; as discussed in Chapter 3, the size and weight of the utilised felling and extraction machinery – producing excessive ground pressures – can cause significant degradation to the forest floor. This is exacerbated on sensitive sites, prompting major disturbances and compaction to the soil that are detrimental to its structure and the carbon stored within it [37, 54]. To combat this, alternative low-impact methods of extraction have been developed, sacrificing productivity for reduced ground pressures. As a result of the reduced productivity, the environmentally sensitive methods of felling and extraction tend to incur larger costs for their extracted wood; this is a concern, potentially impacting the financial viability of the feedstock's use in energy generation.

An additional benefit to defining the different methods of felling and extraction – and their subsequently calculated productivities – relates to their potential use in life cycle analysis (LCA). Currently, a number of uncertainties exist when calculating the $CO_2$ emissions associated with bioenergy production from forest wood; in particular, these concern a range of environmental conditions and silvicultural practices [7, 65, 66]. Determining the productivity of specific felling, extraction and comminution processes – using a large number of referenceable sources – can help reduce the uncertainty surrounding them, resulting in universal values that assumptions can be based upon. Although these sources are predominantly from international field trials – a result of other nations being more invested in forest research than the UK – their use is important to estimate the expected productivity in UK forests; although these figures are not definitive, they are important for helping forest owners, local authorities and governmental organisations understand the potential costs associated with accessing the UK's existing forest resource. Further to the discussed environmental degradation – associated with the mechanised processes of forest harvesting – there are individual site-features that directly hinder the productivity of felling and timber extraction. Of the potential individual constraints, access within a forest stand is hugely important, with reductions in productivity a result of the machinery's decreased ability to move [54]. Access within the stand is worsened by site-specific factors, including the density of the standing timber, the density of other vegetation – such as the invasive species rhododendron, discussed in the literature review – or existing watercourses, which often require the creation of designated crossing points. The soil type and moisture content are also key; saturated clays and brown soils can increase the likelihood of rutting and slipping which, in turn, reduces productivity and damages the site [54, 55]. This chapter has identified the negative effects of increased extraction distance upon productivity, however quantifying the impacts of site-specific features, especially at a national level, is inherently difficult. This requires large quantities of detailed data – including intricate knowledge of individual forest stands that is not readily available – resulting in the use of basic assumptions instead. Indeed, when assuming a 50% reduction in productivity for the most economical mechanised processes, most of the UK's wood resource remains viable for use within the woodfuel market.

Evidently, the UK's forest managers are left with difficult decisions to make, weighing the environmental impacts of harvesting processes against their costs. Considering the currently high prices for roadside sawlogs and wood chips in the UK [5, 63], the woodfuel market will continue to be a key source of accessible income for forest owners. The results indicate that producing woodchip from thinnings and residues – utilising the low impact harvesting methods – can still be financially viable at current market prices, although it should be remembered that this is not a guarantee and is susceptible to change. Considering the basic supply chain detailed previously in this chapter (Figure 6.2), the assumed wood chip energy contents and costs produced within this chapter are representative of UK wood resources that have undergone additional processing, following its road side storage. With the transportation distance and method representing crucial components of the final costs of wood biomass [59], identifying potential areas that could utilise their local wood feedstocks could help support the expansion of bioenergy generation, even if the market price was to reduce. Advancements in chipping technology have resulted in the development of portable roadside chippers; these can chip logs, logging residues and stumps directly into vehicles, ready for transportation to the end user. In the UK, this would most likely be combined with a truck and trailer system – this is versatile, often offering the most cost effective route for wood transportation over shorter distances [20]. The premise of the research completed in this chapter is based on utilising small amounts of the additional net growth of forests in small-scale, rural energy installations. This however should not be to the detriment of a forest's environmental, ecological and societal benefits which themselves have associated values; considering the desired sustainable use of our forest resource, these should not be ignored [3, 67].

The analysis completed in this chapter is therefore important for understanding the potential amounts of energy that could be sustainably produced from UK-sourced woodchips and at what cost. As a result, these estimations and the data contained within this chapter would be of great value to a number of different stakeholders within the woodfuel sector, ranging from national government agencies through to individual forest owners – particularly those that do not actively manage their woodlands. Local authorities, government agencies and NGO's could utilise this research to help inform policy decisions and support for increased use of local wood resources, coupled with a defined planting regime. Applying a top down approach, the work completed in this chapter would allow policy makers and organisations to identify preferable areas for increased localised woodfuel use, allowing for a greater focus on additional investigations.

The UK’s post-war planting regime focused on unpopulated upland areas, such as the Scottish highlands, producing large homogenous forest stands situated in remote locations [56]. Effectively, land with little value – particularly for use in agriculture or home building – was instead planted with quick growing softwood species, such as the non-native Sitka spruce. Although this successfully increased the UK’s forest cover, the location of the newly established resource has caused potential implications in the economics of harvesting; specifically the stands planted on steep slopes or away from the existing road infrastructure. Unlike the site-specific features – which influence the productivity of the chosen felling and extraction processes – the slope directly influences the methods that can be employed [9, 18, 49]. As a result, by utilising data collated for the UK’s forests and woodlands, this chapter has demonstrated the impacts of geographical location and the known terrain on the costs of felling and extracting wood resource. With the UK governments’ desire to plant 130,000 ha of new woodland cover in England – as part of their *Clean Growth Strategy* [58] – knowledge of the financial implications associated with establishing forests on inaccessible sites, specific to the UK, should prove to be highly beneficial.

## 6.5. Conclusions

Humans represent a truly resourceful species – our ability to solve problems, designing innovative methods to overcome specific issues, has seen mankind flourish. This is certainly apparent within the context of forestry, especially when considering the mechanised processes of felling and extracting trees. As the demand for timber increased, large-scale felling and extraction machinery was produced, achieving higher levels of productivity; fittingly, once it became apparent that these machines caused environmental damage, when used on sensitive sites, alternative low-impact methods were instead designed.

As identified throughout this chapter, there are an assortment of complexities associated with the harvesting processes, often impacting upon the productivity and, ultimately, the final costs of obtaining biomass from forests. Indeed, utilising wood resource – particularly within the bioenergy sector – represents a fine balance between the respectful preservation of the forest environment and the production of an economically viable product. Quantifying the additional costs and benefits attributed to woodfuel use – of which large amounts of uncertainty exist, often with regards to the $CO_2$ emissions produced from timber felling and extraction – necessitates an in-depth knowledge of the individual processes. As a result, the defined productivity assumptions produced within this chapter – tailored specifically to the UK's forest resource – could be of great benefit, to NGO's and government agencies, helping to remove potential uncertainties relating to forest management.

The price of commodities are susceptible to change, however – when considering the current high prices for timber and woodchip – the felling and extraction of wood for use in energy generation is currently economically viable, within the UK. Indeed, even when utilising small-scale felling and extraction methods – reducing the subsequent impact upon the local environment – there is still potential for forest owners to benefit financially, by increasing their production of woodfuel. Profiting from the large amounts of data produced throughout the thesis, this chapter has identified potential areas in the UK that could benefit from utilising local sources of wood biomass. Although the data and estimations produced are by no means definitive, there are a number of environmental and process variables that could impact the results; these could still prove important for policy makers and wood fuel producers, helping to determine the economic viability of increasing local woodfuel use in the UK. Although simple in its premise, the use of different available datasets – manipulated within a defined framework – can help specify locations for further, more extensive analysis.

Bioenergy will continue to form a key component of the UK's energy generation strategy across the short- to mid-term, therefore any opportunity to support this – by best utilising our existing forest resource – must certainly be investigated. Large scale, biomass-based electricity generation will likely be dominated by imported wood pellets during the next decade, however the installation of small-scale biomass boilers – for domestic heating or combined heat and power – could help support the generation of energy within rural areas. This would not only help reduce reliance on fossil fuels, it would also help empower communities, combat fuel poverty and support local forest and land owners.

## 6.6. References

[1]. Lauri P., Havlík P., Kindermann G., Forsell N., Böttcher H. and Obersteiner M. 2014. Woody biomass energy potential in 2050. *Energy Policy*, 66, pp19-31

[2]. Ward S. 2017. *Forest Statistics 2017.* IFOS-Statistics, Forest Research, 231 Corstorphine Road, Edinburgh

[3]. Forestry Commission. 2017. *The UK Forestry Standard – The governments' approach to sustainable forestry*. Forestry Commission, Edinburgh

[4]. Ward S. 2017. *Timber Price Indices – Data to September 2017*. IFOS-Statistics, Forest Research, 231 Corstorphine Road, Edinburgh

[5]. Leefers L. A. and Ghani A. N. A. 2014. Timber Pricing, In: *Handbook of Forest Resource Economics* [Kant S. and Alavalapati J. R. R. (eds)]. Routledge, Taylor and Francis Group, London, UK

[6]. Bolkesjø T. F., Trømborg E. and Solberg B. 2006. Bioenergy from the forest sector: Economic potential and interactions with timber and forest products markets in Norway. *Scandinavian Journal of Forest Research*, 21(2), pp175-185

[7]. Hiloidhari M., Baruah D. C., Singh A., Kataki S., Medhi K., Kumari S., Ramachandra T. V., Jenkins B. M. and Thakur I. S. 2017. Emerging role of geographic information systems (GIS), life cycle assessment (LCA) and spatial LCA (GIS-LCA) in sustainable bioenergy planning. *Bioresource Technology*, 242, pp218-226

[8]. Accastello C., Brun F. and Borgogno-Mondino E. 2017. A spatial-based decision support system for wood harvesting management in mountain areas. *Land Use Policy*, 67, pp277-287

[9]. Sacchelli S., De Meo I. and Paletto A. 2013. Bioenergy production and forest multifunctionality: A trade-off analysis using multiscale GIS model in a case study in Italy. *Applied Energy*, 104, pp10-20

[10]. Nakahata C., Uemura R. and Saito M. 2014. Estimating harvest costs and projecting quantities of logging residues for small-scale forestry in Nasushiobara, Tochigi Prefecture, Japan. *Journal of Forestry Research*, 25(4), pp965-974

[11]. Häyha T., Franzese P. P., Paletto A. and Fath B. D. 2015. Assessing, valuing, and mapping ecosystem services in Alpine forests. *Ecosystem Services*, 14, pp12-23

[12]. Elliasson L., Bengtsson J., Cedergren J. and Lageson H. 1999. Comparison of single-grip harvester productivity in clear- and shelterwood cutting. *Journal of Forest Engineering*, 10(1), pp43-48

[13]. Hånell B., Nordfjell T. and Eliasson L. 2000. Productivity and costs in shelterwood harvesting. *Scandinavian Journal of Forest Research*, 15(5), pp561-569

[14]. Nakagawa M., Hamatsu J., Saitou T. and Ishida H. 2007. Effect of tree size on productivity and time requirements for work elements in selective thinning by a harvester. *International Journal of Forest Engineering*, 18(2), pp24-28

[15]. Mederski P. S. 2006. A comparison of harvesting productivity and costs in thinning operations with and without midfield. *Forest Ecology and Management*, 224, pp286-296

[16]. Behjou F. K., Majnounian B., Dvořák J., Namiranian M., Saeed A. and Feghhi J. 2009. Productivity and cost of manual felling with a chainsaw in Caspian forests. *Journal of Forest Science*, 55(2), pp96-100

[17]. Melemez K., Tunay M. and Emir T. 2014. A comparison of productivity in five small-scale harvesting systems. *Small-scale Forestry*, 13, pp35-45

[18]. Davis C. J. and Reisinger T. W. 1990. Evaluating terrain for harvesting equipment selection. *Journal of Forest Engineering*, 2(1), pp9-16

[19]. Stillwell S. T. C. 1930. The seasoning of timber. *Forestry: An International Journal of Forest Research*, 4(1), pp34-39

[20]. Wolfsmayr U. J. and Rauch P. 2014. The primary forest fuel supply chain: A literature review. *Biomass and Bioenergy*, 60, pp203-221

[21]. Yoshida M., Berg S., Sakurai R. and Sakai H. 2016. Evaluation of chipping productivity with five different mobile chippers at different forest sites by a stochastic model. *Croatian Journal of Forest Engineering*, 37(2), pp309-318

[22]. Prinz R., Anttila P. and Asikainen A. 2015. *Biomass from forests – cost estimation of complete supply chains*. INFRES, Natural Resource Institute Finland

[23]. Wang J., Long C., McNeel J. and Baumgras J. 2004. Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. *Forest Products Journal*, 54(12), pp45-51

[24]. Gałęzia T. 2014. Analysis of the duration of basic logging operations performed using a chainsaw. *Leśne Prace Badawcze* (Forest Research Papers), 75(1), pp25-30

[25]. Puttock D., Spinelli R. and Hartsough B. R. 2005. Operational trails of cut-to-length harvesting of poplar in a mixed wood stand. *International Journal of Forest Engineering*, 16(1), pp39-49

[26]. Laitila J., Ranta T. and Asikainen A. 2008. Productivity of stump harvesting for fuel. *International Journal of Forest Engineering*, 19(2), pp37-47

[27]. Athanassiadis D., Lindroos O. and Nordfjell T. 2011. Pine and spruce stump harvesting productivity and costs using a Pallari KH 160 stump-lifting tool. *Scandinavian Journal of Forest Research*, 26(5), pp437-445

[28]. Holmes T. P., Blate G. M., Zweede J. C., Pereira Jr. R., Barreto P., Boltz F. and Bauch R. 2002. Financial and ecological indicators of reduced impact logging performance in the eastern Amazon. *Forest Ecology and Management*, 163, pp93-110

[29]. Behjou F. K., Majnounian B., Namiranian M. and Dvořák J. 2008. Time study and skidding capacity of the wheeled skidder Timberjack 450C in Caspian forests. *Journal of Forest Science*, 54(4), 183-188

[30]. Ghaffariyan M. R., Naghdi R., Ghajar I. and Nikooy M. 2013. Time prediction models and cost evaluation of cut-to-length (CTL) harvesting method in a mountainous forest. *Small-scale Forestry*, 12(2), pp181-192

[31]. Laitila J., Asikainen A. and Nuutinen Y. 2007. Forwarding of whole trees after manual and mechanised felling bunching in pre-commercial thinning. *International Journal of Forest Engineering*, 18(2), pp29-39

[32]. Laitila J. 2008. Harvesting technology and the cost of fuel chips from early thinnings. *Silva Fennica*, 42(2), pp267-283

[33]. Gallis C. 2004. Comparative cost estimation for forwarding small-sized beech wood with horses and mini-skidder in northern Greece. *Forest Products Journal*, 54(11), pp84-90

[34]. Ghaffariyan M. R., Stampfer K. and Sessions J. 2009. Production equations for tower yarders in Austria. *International Journal of Forest Engineering*, 20(1), pp17-21

[35]. Nuutinen Y., Laitila J. and Rytkönen E. 2014. Grinding of stumps, logging residues and small diameter wood using a CBI 5800 Grinder with a truck as a base machine (Brief report). *Baltic Forestry*, 20(1), pp176-188

[36]. Eliasson L., von Hofsten H., Johannesson T., Spinelli R. and Thierfelder T. 2015. Effects of sieve size on chipper productivity, fuel consumption and chip size distribution for open drum chippers. *Croatian Journal of Forest Engineering*, 36, pp11-17

[37]. Walmsley J. D. and Godbold D. L. 2010. Stump harvesting for bioenergy – A review of the environmental impacts. *Forestry*, 83(1), pp17-38

[38]. Persson T., Egnell G. and Lithell C. 2017. *Stump harvesting – Impact on climate and environment*. IEA Bioenergy, Task43, TR2017:02

[39]. Forestry Commission. 2017. *National Forest Inventory Woodland GB 2016*. Online: https://www.forestry.gov.uk/datadownload

[40]. Forest Service. 2015. *Northern Ireland Woodland Basemap, April 2015*. Online: https://www.daera-ni.gov.uk/dard-publication-scheme

[41]. Ordnance Survey. 2017. *OS OpenData – mapping data and geographic information*. Online: https://www.ordnancesurvey.co.uk/opendatadownload/products.html

[42]. Ordnance Survey of Northern Ireland. 2017. *OS MapShop – Digital products*. Online: https://mapshop.nidirect.gov.uk/

[43]. Office for National Statistics. 2011. *Population and household estimates for Wards and Output Areas in England and Wales (2011 Census).* Online: https://www.ons.gov.uk/census

[44]. National Records of Scotland. 2013. *Census Release 2A*. Online: http://www.scotlandscensus.gov.uk/census-releases

[45]. Northern Ireland Statistics and Research Agency. 2011. *Usual resident population: KS101NI (statistical geographies).* Online: www.nisra.gov.uk/ninis

[46]. UK Data Service. 2012. *Census boundary data.* Online: https://borders.ukdataservice.ac.uk

[47]. GADM. 2015. *United Kingdom administrative area (v2.8, November 2015).* Online: https://gadm.org/data.html

[48]. Forestry Commission. 2016. *NFI description of attributes – Woodland map supporting documents*. Online: https://www.forestry.gov.uk/fr/beeh-a2ugyr

[49]. Spinelli R., Magagnotti N. and Lombardini C. 2010. Performance, capability and costs of small-scale cable yarding technology. *Small-scale Forestry*, 9, pp123-135

[50]. Hutchinson M. F. 2011. *ANUDEM version 5.3 – user guide*. Fenner School of Environment and Society, Australian National University, Canberra

[51]. Tait A. 2012. *Changes to output areas and super output areas in England and Wales, 2001 to 2011*. Office for National Statistics, Newport

[52]. Comeau P. G., White M., Kerr G. and Hale S. E. 2010. Maximum density-size relationships for Sitka spruce and coastal Douglas-fir in Britain and Canada. *Forestry*, 83(5), pp461-468

[53]. Hopkins J. J. and Kirby K. J. 2007. Ecological change in British broadleaved woodland since 1947. *IBIS*, 149, pp29-40

[54]. Hall A. 2005. *Small-scale systems for harvesting woodfuel products*. Technical Note, FCTN009, Forest Research, 231 Corstorphine Road, Edinburgh

[55]. Murgatroyd I. and Saunders C. 2005. *Protecting the environment during mechanised harvesting operations*. Technical Note, FCTN011, Forest Research, 231 Corstorphine Road, Edinburgh

[56]. Malcolm D. C. 1997. The silviculture of conifers in Great Britain. *Forestry*, 70(4), pp293-307

[57]. Kilpatrick C. S. 1985. *Northern Ireland Forest Service – a history*. Department of Agriculture, Environment and Rural Affairs, Belfast

[58]. Department for Business, Energy and Industrial Strategy. 2017. *The clean growth strategy – leading the way to a low carbon future*. Victoria Street, London

[59]. Dirkswager A. L., Kilgare M. A., Becker D. R., Blinn C. and Ek A. 2011. Logging business practices and perspectives on harvesting forest residues for energy: a Minnesota case study. *Northern Journal of Applied Forestry*, 28, pp41-46

[60]. Durusut E., Tahir F., Foster S., Dineen D. and Clancy M. 2018. BioHEAT: a policy decision support tool in Ireland's bioenergy and heat sectors. *Applied Energy*, 213, pp306-321

[61]. Forestry Commission. 2011. *Biomass heating: a guide to medium scale wood chip and wood pellet systems*. Biomass Energy Centre, Farnham, Surrey

[62]. Department for Business, Energy and Industrial Strategy. 2017. *Digest of United Kingdom energy statistics (DUKES) 2017*. Victoria Street, London

[63]. Forestry Commission England. 2017. *Wood as a fuel – comparison with other fuels*. Online: https://www.forestry.gov.uk/forestry/infd-9peg3u

[64]. Sorensen B. 2010. *Renewable Energy – Physics, Engineering, Environmental Impacts*, Economics and Planning (4th Ed.). Academic Press, Elsevier, Oxford

[65]. Klein D., Wolf C., Schulz C. and Weber-Blaschke G. 2015. 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production. *International Journal of Life Cycle Assessment*, 20, pp556-575

[66]. Bösch M., Elsasser P., Rock J., Rüter S., Weimar H. and Dieter M. 2017. Costs and carbon sequestration potential of alternative forest management measures in Germany. *Forest Policy and Economics*, 78, pp88-97

[67]. Price C. 2018. Declining discount rate and the social costs of carbon: Forestry consequences. *Journal of Forest Economics*, 31, pp39-45

# Chapter 7. Conclusions & future work

*"If you really want to eat, keep climbing. The fruits are on the top of the tree" – Israelmore Ayivor*

## 7.1. Introduction

Mankind's ability to survive, to develop and then, ultimately, to thrive, is evident throughout our everyday lives. From the buildings we have constructed to the generation of the energy that's required to power them – since the Industrial Revolution, the human race has truly established itself as the dominate species. However, with great power comes great responsibility; indeed, we are explicitly accountable for the environment we live in and the finite natural resources that we exploit. Of these, forests are globally significant, representing an important terrestrial sink for atmospheric carbon and an established feedstock for industries such as construction, manufacturing and energy generation. As the dependence on bioenergy – as a key transitional fuel source – continues to grow, particularly within the UK, it is imperative that our existing wood feedstocks are preserved and maintained, helping to ensure their sustainable use and existence.

The UK government, as part of their proposed solutions for mitigating climate change, have recently stated their desire to increase the nation's forest cover; this would help support the forest industry and increase the amount of available timber resource, while also sequestering carbon. However, before commencing any major tree planting initiative, it is important to first understand our existing resource, allowing for informed decisions to be made – not only for the intended end-use of the forest resource, but also the management operations required to achieve these. As a result, the focus of this research – detailed in Chapter 2 – was to determine the potential of the UK's existing forest resource for use in energy generation, specifically to help supplement the current reliance on imported biomass fuels, such as wood pellets.

## 7.2. Knowledge of Forest Resource

The fundamental understanding of a subject is a vital component of any decision making process; details of the benefits, the negatives and how these relate to one another are undeniably valuable. This is particularly pertinent for forestry, which is characterised – as a research area – by different scientific disciplines, each requiring thought and attention. Considering the stated aims outlined in Chapter 2, the desire to disseminate knowledge of global forest feedstocks, and any associated issues, would be beneficial.

The foundations of this thesis are built upon an understanding of the existing academic research, utilising extensive sources of published data and materials to inform this investigation. As evidenced throughout both the collated literature results and the completed experimental analysis of UK-grown wood samples – the heterogeneous nature of wood biomass is evident. Indeed, this variability is apparent amongst different wood categories, ranging from the simplest forms of genetic classification, through to individual species and differing tree sections. Accepting the presence of heterogeneity between different wood sources, this research has helped quantify wood variation – utilising both statistical and visual methods to aid the comparison of feedstocks. The magnitude of variability also differs; softwood species are more homogenous than hardwoods, a factor that can be intensified by their management. This ability to influence the growth of softwoods – coupled with their increased homogeneity – has prompted species, such as Sitka spruce, to become dominant within UK forestry.

The analysis completed within Chapter 4 – specifically relating to different tree sections – has helped identify opportunities for improving the suitability of different woodfuel sources. By blending the branches and roots of birch or Sitka spruce with their felled stem wood, the energy content and the volume of the resulting fuel could be potentially increased; two factors that are of particular value in the context of bioenergy. This research has also highlighted a number of relationships that exist between the elemental, chemical and structural contents of the different species. One of the most interesting of these – again concerning birch and Sitka spruce – are the derived species-specific correlations, evident between their ash, fixed carbon and lignin contents. Detailed in Chapter 5, increases in their ash contents coincide with increased amounts of fixed carbon and lignin; although apparent for both species, there is a clear – and now defined – association between the two.

In addition to increasing our academic knowledge of the UK's forest resource, the research contained within Chapters 4 and 5 would also be useful for other stakeholders within the wood fuel industry. Understanding the chemical composition, fuel properties and energy content of the UK's existing wood resource could help support wood fuel producers with the development of home-grown wood fuel – and other refined products such as pellets – while also informing stove and boiler designers, helping them to improve the combustion design and efficiency of different technologies. It should also be noted that there are important relationships between a tree's genetics and its growing environment, especially when considering wood formation; both are key influences on a tree's successful establishment and the final quality of its produced wood. This places extra impetus on making good forest management decisions, such as planting the correct species on the correct site. A number of poor decision-making examples exist within UK forestry; particularly the planting of species – such as Norway spruce – on sites that are unsuitable, resulting in the production of low value wood products. Forests and woodlands have dominated our landscapes for thousands of years, aiding considerably in mankind's successful establishment. Although our forest feedstocks are clearly important, they are often underappreciated – especially within the UK – prompting both a lack of interest in forest research and the poor dissemination of any previously completed projects. This thesis has therefore, hopefully, gone some way to rectifying this. Indeed, from the thorough – albeit by no means conclusive – literature review, through to the extensive analysis of fundamental characteristics, this research should help further the knowledge of our existing forest resource.

## 7.3. Feedstock for Energy Generation

The interdisciplinary nature of this thesis is apt, suitably mirroring the known traits of forestry and wood research. However, throughout the diverse research disciplines considered, a consistent influence has been maintained – the role of forest wood as a potential fuel for bioenergy. Understandably, giving clarity on the energy generation potential of a feedstock is vital for establishing its viability; therefore, the second research aim proposed within this thesis was to consider the possible role of the UK's current forest resource for generating energy.

Combustion technologies represent the most mature, simple and cost effective option for utilising biomass in energy generation, ranging from small-scale stove use to large industrial fluid bed and co-firing systems. As previously established, the roots and branches of both the birch and Sitka spruce – when blended with their stem wood – could potentially increase the energy content of the produced fuel. As a result, Chapter 5 focused on the combustion characteristics of the two species and their different tree sections, determining how the compositional values and combustion behaviours differ.

Visual observations of firewood properties for different species, were made nearly a century ago – as part of *The Firewood Poem* – which proposed that birch burns quicker than other wood species, making it an inferior fuel. The analysis produced in Chapter 5 has indeed shown this to be the case, with the birch stem, root and branch wood determined as more reactive than those of the Sitka spruce; this is evidenced from the initial combustion of the wood samples, through to their burnout. The thermal degredation of wood – and the resulting burning profiles – are linked to the lignocellulosic composition, emphasising the importance of producing quality characterisation data to properly understand the feedstocks. In addition, genetic-based heterogeneity – present between hardwoods and softwoods – extends to the combustion characteristics; unlike softwood species, birch is typified by an increased composition of carbohydrate-based hemicelluloses, resulting in their burning profiles differing from those produced by the Sitka spruce.

The UK's woodfuel market has continued to grow during the last decade, forming an important income source for forest owners. With current estimates indicating a net growth within UK forests, there is scope for this to increase; although this should of course be achieved sensitively, avoiding any detrimental impacts on the environment. Wood feedstocks – and biomass in general – will continue to form an important part of energy generation within the UK, across both the short- to mid-term. Particularly in small-scale combined heat and power systems and other domestic heating technologies, the research completed within this thesis could help support the UK's current climate change mitigation policy, helping to increase the sustainable use of wood in energy generation.

Producing fuels from UK-grown birch or Sitka spruce – blending their branches and root wood with their stems – could increase the volume and energy content of the fuel, however this thesis has indicated that it could also impact reactivity. Potassium is known to influence this; increases in the potassium content results in a more reactive fuel. Although this inference is supported within the research, the extent of its impact varies between the tree sections. Indeed, there are potential fundamental differences in the catalytic availability of the potassium, contained within the branches and the roots, which is evident for both species. It would therefore appear that – further to the known impact of potassium – the choice of species and the actual section of tree will have a considerable influence on the reactivity of wood during combustion.

## 7.4. Assessing the Potential of the UK's Forests

The final stated research aim of this thesis focused on the accessibility and consequent economic viability of the UK's forested resource, relating specifically to their distribution and capacity. Preserving the environmental and societal benefits of our forests and woodlands is undoubtedly of great importance, however – in the context of bioenergy – the sustainability of the UK's woodfuel industry is also reliant upon the cost-effective felling and extraction of timber.

Assessing this economic viability first requires an understanding of the different processes utilised in forest harvesting; specifically their limitations, costs and productivities. Although mechanised felling and extraction processes have larger capital and operational costs, their increased productivity – when compared to other methods – make them the most cost-effective forest wood supply route, albeit the most environmentally insensitive. Indeed, there is a fine line that exists between the profitable production of woodfuel and the protection of the forest environment. When considering the UK, the geographical location of its forests differ greatly; ranging from lowland areas – typified by hardwood species – through to the more mountainous regions of Scotland and Wales, which contain more softwoods. These differences in terrain and spatial location can severely impact harvesting productivity, prompting potential wood feedstocks to become prohibitively expensive, a factor which is exacerbated by low timber market prices. The research conducted in Chapter 6 indicates that currently – when utilising mechanised methods of felling and extraction – the vast majority of the UK's forest feedstocks are economically viable for use in bioenergy. As a result, there is the potential for UK forest owners to increase the use of their wood feedstocks for bioenergy production. Commercial forestry prioritises the stem wood produced from tree growth, however this represents only part of the total available biomass. Producing woodchip from harvesting wastes – including the residues and a small proportion of stump wood – and additional thinnings can result in an estimated 2,645 TJ $yr^{-1}$ of additional energy, discussed in Section 6.3.2.4.

There is however, undoubtedly, a fine balance that must be maintained when increasing the utilisation of wood fuel in the UK; specifically between achieving an economically viable product, while still protecting the environment from where the resource has been sourced. As a result, increasing the utilisation of the UK's forest feedstocks should be completed alongside a defined planting policy – this would help replace sequestered carbon, while also maintaining the longevity and sustainability of utilising local woodfuels. Additionally, there are certain environmental issues that relate to the use of residues and stumps which should be considered; the branch and stump wood often contains high concentrations of nutrients, such as nitrogen and potassium, which are important components of wood growth. Although representing an additional income source, removing an excessive volume of stumps and residues from a site – for use in the woodfuel market – could affect its future productivity, impacting the sustainability of the fuel source. Quantifying the magnitude of this impact – which is most certainly site-dependent – is therefore vital when increasing woodfuel use in the UK.

The production of a geospatial framework has enabled the combination of different data sources, produced throughout this thesis; this includes the experimentally-determined energy contents, the distribution of the UK's forests, the nation's existing terrain and road infrastructure and the produced felling and extraction costs. Utilising these, optimal locations for increasing the uptake of locally-sourced woodchip – across the UK – have been determined, tending to be situated away from the UK's urban hotspots, in areas typified by small towns and rural communities. Often the most forgotten parts of the country, these communities are underfunded and lack access to amenities that are taken for granted, such as gas or high-speed broadband. The work completed in Chapter 6 – and throughout the rest of this thesis – could therefore help to empower people within these communities, replacing their dependence on fossil fuels with wood biomass sourced from local forest feedstocks.

## 7.5. Future Work

When initiating change it is important to do the simple things first, exploring the avenues that offer the most benefit for the least amount of effort. In effect, to utilise the low hanging fruit. In doing so, the more complex problems can then receive our full attention, helping to improve the chances of success. This is no different when considering research; we start by examining the readily available literature, using this to inform our further explorations. This thesis contains a substantial volume of work, however – due to the diverse nature of forest research – it still represents just a small percentage of the issues that surround wood biomass, and its role in bioenergy. There are however, a number of opportunities for additional research, arising as a direct consequence of the work completed; indeed, there is still plenty of accessible fruit at the top of the tree.

### 7.5.1. Extensive UK Wood Database

The dataset contained within Appendix B – produced utilising repeatable and comprehensive methods of analysis – is an invaluable source of detailed wood characterisation data, specific to the UK. Although a similar resource exists

(*Phyllis2*), the dataset produced from this thesis is unique, containing greater characterisation details while also documenting the samples' location. The first additional research option is to expand upon this work, producing an extensive library of fundamental characteristic data for UK-grown wood. The dataset is already substantial, however with the UK's forest feedstocks rich in species diversity, the final database should be more representative of this. Consequently, other key native hardwood species – such as beech, sycamore and ash – should also be analysed, in addition to non-native softwoods like Norway spruce, Corsican pine and Douglas fir. Expanding the database would therefore allow for further analysis to be conducted, inferring more in-depth relationships between the different UK-grown wood species.

### 7.5.2. Potassium – Variation in Reactivity

Another key outcome from this thesis are the identified relationships between potassium content and the different tree sections, specific to their impact on reactivity. As established in Chapter 5, the increased reactivity witnessed for the root and branch wood – when compared to the stem – isn't dictated entirely by larger potassium contents, apparent for both the birch and Sitka spruce. Firstly, it would be worthwhile investigating the different tree sections of other species, determining if the proposed relationships can be extended to them. In addition, it would be interesting to discover why the roots appear to be less reactive than the branches, even when containing a greater concentration of potassium. This could prove to be a fundamentally important area of research, directly linking the formation of wood to its behaviour during combustion.

### 7.5.3. Assessing the Carbon Impact

The potential influence of this thesis covers a wide range of different disciplines, however one of the most important relates to carbon, especially in the context of mitigating climate change. Increasing forest management and wood harvesting – specifically for woodfuel production – have impacts that range from increased $CO_{2e}$ emissions, associated with felling and extraction processes, to the physical removal and loss of previously sequestered carbon in forest stands. Effectively establishing the cumulative carbon impacts of increased woodfuel use, within the UK, would help inform policymakers on its potential contribution to climate change mitigation. This, in turn, could then be used to develop the required tree planting policies which would ensure the long-term viability and sustainable use of locally-grown wood in the UK. Building upon the knowledge and data contained within this thesis, it would therefore be beneficial to complete a greenhouse gas assessment of the felling and extraction processes of wood from the UKs forest feedstocks; this would consider emissions from mechanised wood harvesting operations, such as those discussed in the previous chapter, combined with the estimated removal of carbon contained within the wood.

### 7.5.4. Decision Support System Improvements

Finally, the decision support system produced in Chapter 6 has the potential to be further developed, incorporating different data sources to refine the outputs. The determined optimal locations – although based on large amounts of data – is still simple in its premise, overlaying just three weighted datasets. These can certainly be enhanced, particularly the demand-based assumptions; for example, if the intended end-use technology is heating, it would be useful to incorporate the known local air temperatures – colder locations will logically have a greater demand for heating. This could be achieved by calculating the total number of heating degree days (HDDs) – a measurement for quantifying heat demand – for different areas, during a 12 month period. As intimated previously within this chapter, there are still a substantial number of rural communities within the UK that do not have access to the gas network; instead, depending on alternative forms of energy generation, such as oil central heating. Incorporating their known locations – achieved using available data from the 2011 *Census* and Energy Performance Certificates (EPC's) – would allow for the identification of potential $CO_2$ emission reduction opportunities, replacing fossil fuels with wood biomass.

The framework could also incorporate geospatial deprivation datasets, namely related to income- and unemployment-based figures; including impoverished areas that would benefit from investments in local energy generation schemes, could help improve the life quality of its inhabitants. Finally, there are a variety of additional societal, ecological and environmental considerations – relating to forests as a natural resource – that are not applicable to fossil fuels sources. Unlike coal mines or offshore oil and gas platforms, forests and woodlands are areas that have a social value; they are utilised by the local population for a range of recreational activities that contribute to social cohesion. They are also home to a diverse number of species, which are reliant on the continued existence of the forest environment. Therefore, the recognition of forested areas that have additional value – such as sites of special scientific interest (SSSI) or ancient woodlands – would help maintain the sustainability of the UK's forest resource, ensuring their continued existence for future generations to enjoy.

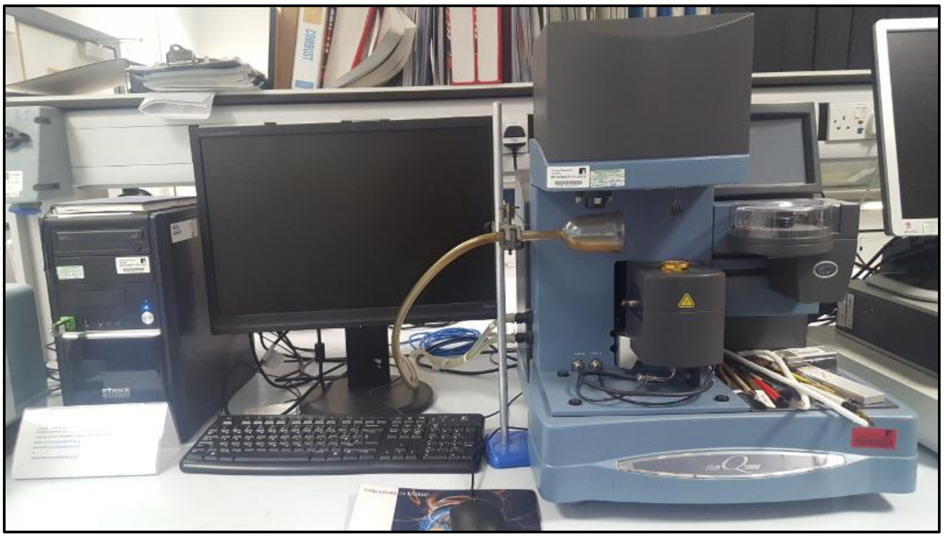
# Appendices

# Appendix A:

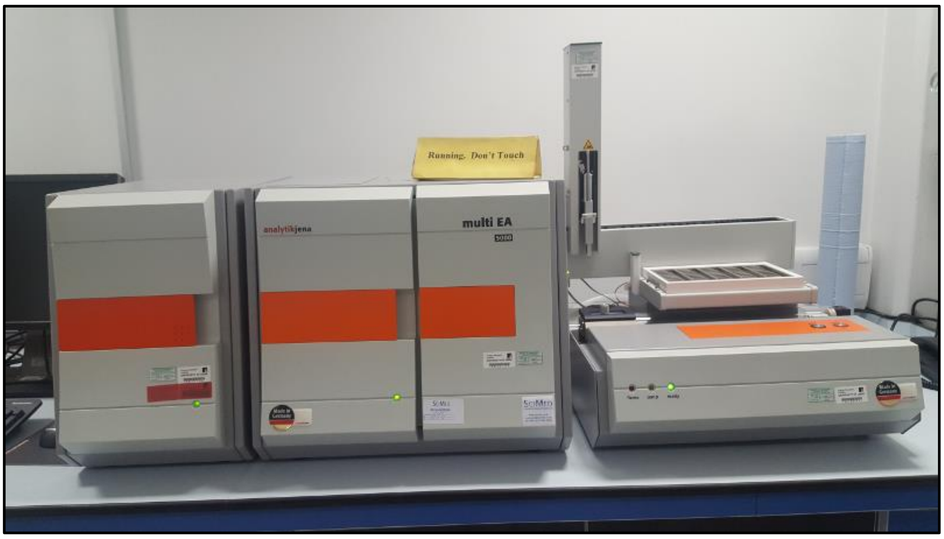
# Experimental Laboratory Equipment

A.1 – ***Retsch Cryomill*** **connected to a liquid nitrogen dewar**

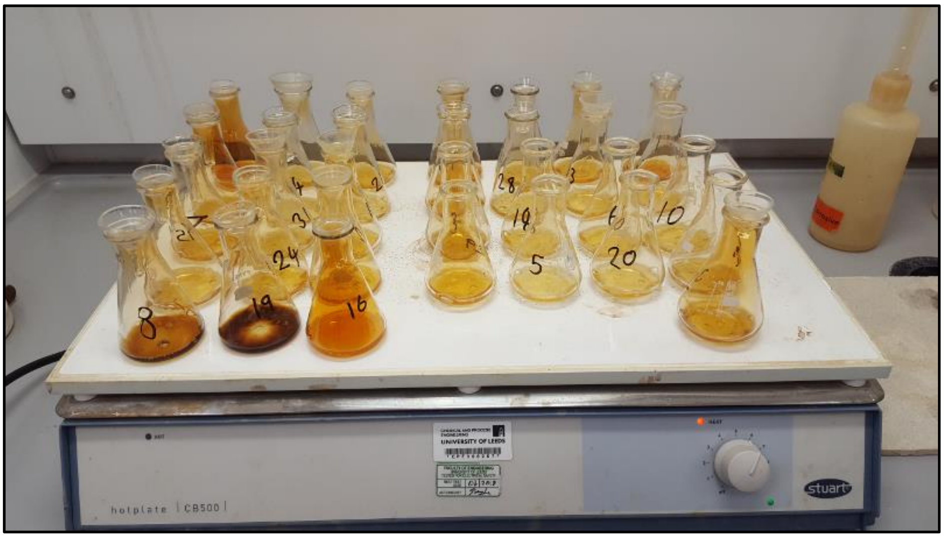
A.2 – ***CE Instruments Flash*** **EA1112 elemental analyser**



A.3 – ***TA Instruments* TGA Q5000 thermogravimetric analyser**



A.4 – ***Analytik Jena* Multi 5000 elemental analyser**



A.5 – **Nitric acid ($HNO_3$) digestions of wood samples using a hotplate**

A.6 – ***Varian* 240FS AA atomic absorption system**

# Appendix B:
# Experimental Characterisation Data

## Table B.1 – Sample Key

**Species**: *OK=oak, BI=birch, SP=Scots pine, SS=Sitka spruce*

**Tree Section**: *S=stem, R=root, B=Branch*

**Site***: *1=Frith End, 2=Haldon, 3=Whitestone, 4=Whitestone, 5=Wordwell, 6=Wheldrake, 7=Didlington, 8=Hazelborough, 9=Thetford Forest, 10=Wykeham, 11=Dalby Forest, 12=Dartmoor, 13=Ae Village, 14=Lairg*

** see Table 4.3 for further details*

Table B.1 – **Experimental characterisation data for 145 analysed UK-grown wood samples; Ultimate, Proximate and Lignocellulose**

| | **Ultimate**[a] | | | **Proximate**[a] | | | | **Lignocellulose**[a] | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **C** | **H** | **N** | **VM** | **FC** | **Ash** | **GCV**[ab] | **He.** | **Ce.** | **Li.** |
| **OK.S.1** | *47.8 (±0.35)* | *6.1 (±0.11)* | *0.12 (±0.01)* | *86.2 (±0.19)* | *13.4 (±0.23)* | *0.4 (±0.04)* | *18.94* | *19.0* | *49.1* | *25.1* |
| **OK.S.1** | *47.8 (±0.19)* | *6.1 (±0.06)* | *0.14 (±0.00)* | *86.0 (±0.04)* | *13.8 (±0.04)* | *0.2 (±0.08)* | *18.97* | *20.5* | *49.5* | *25.7* |
| **OK.S.1** | *46.9 (±0.29)* | *6.1 (±0.04)* | *0.13 (±0.00)* | *86.2 (±0.05)* | *13.4 (±0.15)* | *0.4 (±0.10)* | *18.60* | *21.2* | *49.3* | *28.1* |
| **OK.S.1** | *47.0 (±0.38)* | *6.2 (±0.19)* | *0.14 (±0.02)* | *86.2 (±0.31)* | *13.5 (±0.24)* | *0.2 (±0.06)* | *18.65* | *19.9* | *50.0* | *24.8* |
| **OK.S.1** | *47.7 (±0.13)* | *6.2 (±0.04)* | *0.13 (±0.01)* | *88.0 (±0.13)* | *11.9 (±0.09)* | *0.1 (±0.05)* | *18.94* | *21.3* | *51.8* | *25.5* |
| **OK.S.1** | *47.5 (±0.48)* | *6.0 (±0.28)* | *0.12 (±0.00)* | *86.3 (±0.08)* | *13.4 (±0.19)* | *0.2 (±0.12)* | *18.80* | *20.4* | *52.1* | *23.0* |
| **OK.S.1** | *46.5 (±0.43)* | *6.2 (±0.13)* | *0.12 (±0.01)* | *85.9 (±0.08)* | *13.9 (±0.07)* | *0.2 (±0.01)* | *18.44* | *19.6* | *50.4* | *23.2* |
| **OK.S.1** | *46.7 (±0.17)* | *6.1 (±0.12)* | *0.15 (±0.00)* | *88.5 (±0.25)* | *11.0 (±0.23)* | *0.5 (±0.02)* | *18.50* | *21.1* | *54.9* | *22.1* |
| **OK.S.4** | *47.4 (±0.82)* | *5.9 (±0.22)* | *0.10 (±0.01)* | *85.5 (±0.06)* | *13.8 (±0.12)* | *0.7 (±0.06)* | *18.75* | *19.5* | *49.8* | *25.4* |
| **OK.S.4** | *47.2 (±0.09)* | *6.0 (±0.07)* | *0.13 (±0.01)* | *85.5 (±0.23)* | *14.1 (±0.22)* | *0.4 (±0.00)* | *18.68* | *19.2* | *50.4* | *25.1* |
| **OK.S.4** | *46.7 (±0.54)* | *6.0 (±0.22)* | *0.13 (±0.00)* | *87.8 (±0.04)* | *11.9 (±0.07)* | *0.4 (±0.11)* | *18.49* | *20.2* | *50.4* | *25.1* |
| **OK.S.4** | *47.4 (±0.54)* | *6.2 (±0.05)* | *0.16 (±0.02)* | *87.7 (±0.08)* | *12.2 (±0.01)* | *0.1 (±0.08)* | *18.83* | *21.9* | *52.7* | *24.9* |
| **OK.S.4** | *47.0 (±0.39)* | *6.2 (±0.07)* | *0.14 (±0.01)* | *88.3 (±0.10)* | *11.5 (±0.08)* | *0.2 (±0.18)* | *18.62* | *21.1* | *50.6* | *23.8* |
| **OK.S.7** | *47.2 (±0.38)* | *6.1 (±0.06)* | *0.13 (±0.00)* | *85.6 (±0.01)* | *14.4 (±0.00)* | *0.1 (±0.01)* | *18.69* | *19.0* | *49.1* | *25.6* |
| **OK.S.7** | *46.7 (±0.31)* | *6.0 (±0.09)* | *0.16 (±0.00)* | *86.7 (±0.27)* | *12.6 (±0.15)* | *0.6 (±0.12)* | *18.50* | *20.1* | *50.1* | *25.2* |
| **OK.S.7** | *47.1 (±0.21)* | *6.0 (±0.08)* | *0.13 (±0.01)* | *84.4 (±0.29)* | *15.3 (±0.17)* | *0.3 (±0.12)* | *18.66* | *19.6* | *48.6* | *26.0* |
| **OK.S.7** | *46.9 (±0.72)* | *6.1 (±0.10)* | *0.16 (±0.02)* | *87.5 (±0.51)* | *12.1 (±0.21)* | *0.4 (±0.30)* | *18.62* | *20.3* | *51.6* | *24.9* |
| **OK.S.7** | *46.6 (±0.25)* | *6.1 (±0.09)* | *0.15 (±0.00)* | *87.5 (±0.04)* | *12.2 (±0.10)* | *0.3 (±0.06)* | *18.47* | *21.1* | *52.1* | *24.3* |
| **OK.S.8** | *47.1 (±0.28)* | *6.2 (±0.06)* | *0.13 (±0.00)* | *89.1 (±0.07)* | *10.5 (±0.11)* | *0.4 (±0.03)* | *18.69* | *20.2* | *51.9* | *22.2* |
| **OK.R.4** | *45.8 (±0.50)* | *6.0 (±0.07)* | *0.35 (±0.02)* | *85.2 (±0.25)* | *13.3 (±0.20)* | *1.6 (±0.45)* | *18.14* | *18.3* | *44.3* | *26.1* |
| **OK.R.7** | *46.2 (±0.37)* | *5.9 (±0.19)* | *0.39 (±0.02)* | *83.9 (±0.60)* | *13.3 (±0.16)* | *2.8 (±0.45)* | *18.31* | *17.0* | *45.9* | *31.3* |
| **OK.R.7** | *44.9 (±0.31)* | *5.7 (±0.16)* | *0.41 (±0.01)* | *81.0 (±0.07)* | *13.9 (±0.06)* | *5.1 (±0.01)* | *17.80* | *18.6* | *48.9* | *26.7* |
| **OK.R.7** | *43.4 (±0.26)* | *5.6 (±0.15)* | *0.32 (±0.01)* | *80.7 (±0.24)* | *12.2 (±0.19)* | *7.1 (±0.43)* | *17.21* | *19.3* | *48.0* | *24.9* |
| **OK.R.7** | *45.9 (±0.58)* | *6.0 (±0.14)* | *0.23 (±0.01)* | *86.6 (±0.18)* | *11.5 (±0.19)* | *1.9 (±0.01)* | *18.19* | *18.1* | *50.6* | *24.9* |
| **OK.B.1** | *46.9 (±0.28)* | *6.0 (±0.10)* | *0.28 (±0.00)* | *85.9 (±0.27)* | *12.0 (±0.23)* | *2.1 (±0.04)* | *18.60* | *17.1* | *46.7* | *30.4* |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **OK.B.1** | *47.1 (±0.09)* | *6.0 (±0.12)* | *0.27 (±0.00)* | *84.2 (±0.36)* | *12.7 (±0.36)* | *3.1 (±0.00)* | *18.67* | *17.3* | *44.7* | *31.5* |
| **OK.B.1** | *47.5 (±0.24)* | *6.2 (±0.09)* | *0.26 (±0.00)* | *86.8 (±0.07)* | *11.8 (±0.01)* | *1.4 (±0.08)* | *18.89* | *17.3* | *47.6* | *30.7* |
| **OK.B.1** | *47.6 (±0.58)* | *6.2 (±0.18)* | *0.25 (±0.01)* | *86.8 (±0.27)* | *11.6 (±0.17)* | *1.5 (±0.10)* | *18.92* | *19.4* | *49.6* | *28.0* |
| **OK.B.4** | *48.2 (±0.23)* | *6.2 (±0.07)* | *0.23 (±0.00)* | *85.1 (±0.15)* | *13.3 (±0.07)* | *1.5 (±0.08)* | *19.16* | *17.1* | *44.0* | *30.9* |
| **OK.B.4** | *47.9 (±0.16)* | *6.0 (±0.13)* | *0.28 (±0.00)* | *84.8 (±0.08)* | *13.3 (±0.03)* | *1.9 (±0.05)* | *18.99* | *14.6* | *41.0* | *33.1* |
| **OK.B.4** | *47.6 (±0.10)* | *6.1 (±0.07)* | *0.23 (±0.00)* | *84.3 (±0.02)* | *13.9 (±0.05)* | *1.8 (±0.08)* | *18.88* | *15.3* | *43.4* | *32.0* |
| **OK.B.4** | *46.9 (±0.85)* | *6.1 (±0.01)* | *0.25 (±0.00)* | *86.5 (±0.01)* | *12.3 (±0.10)* | *1.2 (±0.08)* | *18.59* | *18.0* | *47.2* | *28.8* |
| **OK.B.7** | *47.7 (±0.57)* | *6.1 (±0.07)* | *0.21 (±0.00)* | *84.4 (±0.01)* | *14.5 (±0.06)* | *1.2 (±0.08)* | *18.94* | *19.1* | *44.9* | *30.5* |
| **OK.B.7** | *47.5 (±0.72)* | *6.3 (±0.14)* | *0.25 (±0.00)* | *86.4 (±0.16)* | *12.5 (±0.01)* | *1.0 (±0.15)* | *18.89* | *19.0* | *42.1* | *29.4* |
| **OK.B.7** | *47.0 (±0.46)* | *6.3 (±0.06)* | *0.28 (±0.00)* | *88.1 (±0.27)* | *11.1 (±0.08)* | *0.8 (±0.19)* | *18.66* | *20.2* | *51.2* | *26.6* |
| **OK.B.7** | *46.9 (±0.44)* | *6.2 (±0.02)* | *0.23 (±0.00)* | *87.3 (±0.44)* | *11.8 (±0.28)* | *0.9 (±0.16)* | *18.63* | *18.4* | *49.8* | *28.6* |
| **OK.B.8** | *47.0 (±0.25)* | *6.1 (±0.05)* | *0.30 (±0.00)* | *85.5 (±0.13)* | *13.1 (±0.11)* | *1.4 (±0.02)* | *18.66* | *18.6* | *45.5* | *28.1* |
| **OK.B.8** | *47.0 (±0.43)* | *6.2 (±0.01)* | *0.41 (±0.00)* | *85.8 (±0.10)* | *12.9 (±0.02)* | *1.2 (±0.12)* | *18.67* | *16.8* | *47.2* | *30.6* |
| **OK.B.8** | *47.2 (±0.32)* | *6.1 (±0.10)* | *0.26 (±0.00)* | *87.0 (±0.22)* | *12.0 (±0.10)* | *1.0 (±0.12)* | *18.73* | *18.1* | *47.9* | *29.1* |
| **OK.B.8** | *46.6 (±0.31)* | *6.2 (±0.04)* | *0.25 (±0.02)* | *88.0 (±0.19)* | *11.3 (±0.13)* | *0.7 (±0.06)* | *18.50* | *20.0* | *51.8* | *25.4* |
| **BI.S.2** | *47.1 (±0.19)* | *6.4 (±0.11)* | *0.10 (±0.02)* | *91.9 (±0.05)* | *8.0 (±0.05)* | *0.1 (±0.00)* | *18.72* | *22.9* | *56.2* | *20.1* |
| **BI.S.2** | *46.4 (±0.24)* | *6.2 (±0.05)* | *0.11 (±0.00)* | *91.0 (±0.06)* | *8.7 (±0.06)* | *0.3 (±0.01)* | *18.40* | *23.9* | *53.1* | *22.2* |
| **BI.S.2** | *46.2 (±0.55)* | *6.4 (±0.15)* | *0.09 (±0.00)* | *91.4 (±0.03)* | *8.4 (±0.02)* | *0.1 (±0.01)* | *18.33* | *22.8* | *54.8* | *20.9* |
| **BI.S.2** | *46.4 (±0.61)* | *6.4 (±0.05)* | *0.11 (±0.00)* | *90.8 (±0.05)* | *8.9 (±0.07)* | *0.2 (±0.02)* | *18.41* | *23.9* | *51.9* | *19.8* |
| **BI.S.2** | *46.6 (±0.31)* | *6.5 (±0.03)* | *0.09 (±0.00)* | *91.3 (±0.18)* | *8.6 (±0.18)* | *0.1 (±0.01)* | *18.52* | *24.0* | *52.4* | *20.7* |
| **BI.S.2** | *46.1 (±0.18)* | *6.0 (±0.30)* | *0.12 (±0.00)* | *90.7 (±0.06)* | *9.0 (±0.22)* | *0.3 (±0.16)* | *18.26* | *23.3* | *55.2* | *19.9* |
| **BI.S.3** | *46.2 (±0.30)* | *6.1 (±0.28)* | *0.12 (±0.00)* | *90.4 (±0.34)* | *9.3 (±0.18)* | *0.3 (±0.16)* | *18.28* | *23.2* | *55.4* | *19.7* |
| **BI.S.3** | *45.7 (±0.19)* | *5.8 (±0.30)* | *0.13 (±0.00)* | *91.2 (±0.01)* | *8.5 (±0.11)* | *0.2 (±0.13)* | *18.06* | *23.8* | *53.4* | *19.5* |
| **BI.S.3** | *45.9 (±0.35)* | *6.3 (±0.18)* | *0.11 (±0.00)* | *91.3 (±0.00)* | *8.3 (±0.04)* | *0.4 (±0.04)* | *18.21* | *25.1* | *52.2* | *20.2* |
| **BI.S.3** | *46.5 (±0.73)* | *6.5 (±0.14)* | *0.09 (±0.01)* | *91.4 (±0.03)* | *8.5 (±0.06)* | *0.1 (±0.03)* | *18.48* | *23.7* | *55.2* | *18.2* |
| **BI.S.6** | *46.3 (±0.10)* | *6.3 (±0.09)* | *0.13 (±0.00)* | *91.5 (±0.10)* | *8.4 (±0.14)* | *0.1 (±0.04)* | *18.37* | *24.4* | *52.8* | *20.1* |
| **BI.S.6** | *46.3 (±0.20)* | *6.4 (±0.06)* | *0.12 (±0.01)* | *91.8 (±0.12)* | *8.0 (±0.08)* | *0.2 (±0.04)* | *18.41* | *23.5* | *54.7* | *19.3* |
| **BI.S.6** | *46.6 (±0.55)* | *6.4 (±0.15)* | *0.10 (±0.01)* | *91.5 (±0.31)* | *8.4 (±0.22)* | *0.1 (±0.09)* | *18.50* | *24.3* | *54.4* | *20.3* |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **BI.R.2** | *48.2 (±0.38)* | *6.1 (±0.13)* | *0.21 (±0.00)* | *87.6 (±0.25)* | *12.0 (±0.30)* | *0.5 (±0.05)* | *19.13* | *21.3* | *48.4* | *28.2* |
| **BI.R.2** | *50.2 (±0.07)* | *6.4 (±0.09)* | *0.27 (±0.01)* | *85.8 (±0.23)* | *13.7 (±0.03)* | *0.5 (±0.20)* | *20.09* | *20.1* | *48.3* | *27.9* |
| **BI.R.2** | *49.1 (±0.08)* | *6.2 (±0.02)* | *0.34 (±0.00)* | *84.6 (±0.10)* | *14.8 (±0.01)* | *0.5 (±0.11)* | *19.60* | *16.4* | *43.2* | *35.0* |
| **BI.R.2** | *48.6 (±0.65)* | *6.2 (±0.09)* | *0.27 (±0.01)* | *86.3 (±0.12)* | *13.1 (±0.07)* | *0.6 (±0.05)* | *19.36* | *17.6* | *41.9* | *35.6* |
| **BI.R.3** | *48.8 (±0.79)* | *6.4 (±0.18)* | *0.22 (±0.01)* | *88.5 (±0.30)* | *11.1 (±0.27)* | *0.4 (±0.03)* | *19.46* | *15.6* | *44.1* | *34.2* |
| **BI.R.6** | *49.0 (±0.36)* | *6.3 (±0.10)* | *0.31 (±0.00)* | *86.6 (±0.12)* | *12.7 (±0.18)* | *0.7 (±0.06)* | *19.55* | *19.8* | *49.2* | *28.1* |
| **BI.R.6** | *48.6 (±0.24)* | *6.2 (±0.19)* | *0.29 (±0.00)* | *86.7 (±0.04)* | *12.5 (±0.36)* | *0.8 (±0.32)* | *19.35* | *17.8* | *48.8* | *31.1* |
| **BI.R.6** | *47.4 (±0.40)* | *6.2 (±0.21)* | *0.22 (±0.00)* | *89.0 (±0.33)* | *10.7 (±0.08)* | *0.4 (±0.25)* | *18.83* | *22.9* | *51.4* | *24.7* |
| **BI.B.2** | *47.1 (±0.46)* | *6.2 (±0.11)* | *0.20 (±0.00)* | *89.2 (±0.02)* | *10.4 (±0.07)* | *0.4 (±0.05)* | *18.71* | *22.4* | *52.6* | *23.7* |
| **BI.B.2** | *49.4 (±0.32)* | *6.6 (±0.11)* | *0.24 (±0.01)* | *88.8 (±0.29)* | *10.8 (±0.23)* | *0.5 (±0.22)* | *19.83* | *18.6* | *44.1* | *32.0* |
| **BI.B.2** | *47.7 (±0.58)* | *6.3 (±0.12)* | *0.21 (±0.00)* | *88.9 (±0.05)* | *10.6 (±0.00)* | *0.5 (±0.05)* | *18.96* | *21.5* | *49.7* | *25.9* |
| **BI.B.2** | *49.5 (±0.76)* | *6.5 (±0.17)* | *0.23 (±0.01)* | *88.6 (±0.12)* | *10.8 (±0.09)* | *0.6 (±0.03)* | *19.84* | *22.2* | *47.6* | *28.8* |
| **BI.B.3** | *46.3 (±0.48)* | *6.2 (±0.06)* | *0.17 (±0.00)* | *89.0 (±0.04)* | *10.3 (±0.16)* | *0.7 (±0.12)* | *18.37* | *22.4* | *52.2* | *22.6* |
| **BI.B.3** | *46.4 (±0.63)* | *6.1 (±0.07)* | *0.25 (±0.01)* | *88.7 (±0.00)* | *10.3 (±0.06)* | *1.0 (±0.07)* | *18.39* | *21.8* | *49.1* | *24.5* |
| **BI.B.3** | *48.0 (±0.56)* | *6.4 (±0.28)* | *0.19 (±0.01)* | *89.4 (±0.17)* | *10.3 (±0.19)* | *0.3 (±0.02)* | *19.10* | *20.7* | *48.2* | *26.8* |
| **BI.B.3** | *46.9 (±0.20)* | *6.1 (±0.16)* | *0.24 (±0.01)* | *88.2 (±0.03)* | *10.7 (±0.02)* | *1.1 (±0.01)* | *18.61* | *19.4* | *49.8* | *25.4* |
| **BI.B.5** | *46.9 (±0.49)* | *6.2 (±0.01)* | *0.21 (±0.00)* | *87.7 (±0.19)* | *10.6 (±0.07)* | *1.7 (±0.12)* | *18.60* | *21.3* | *49.8* | *26.2* |
| **BI.B.5** | *47.5 (±0.51)* | *6.2 (±0.06)* | *0.25 (±0.00)* | *88.9 (±0.01)* | *10.3 (±0.05)* | *0.8 (±0.06)* | *18.87* | *21.2* | *51.2* | *24.3* |
| **BI.B.5** | *46.8 (±0.36)* | *6.1 (±0.11)* | *0.17 (±0.00)* | *89.0 (±0.01)* | *10.0 (±0.25)* | *1.0 (±0.26)* | *18.54* | *22.3* | *50.7* | *25.4* |
| **BI.B.5** | *46.3 (±0.34)* | *6.2 (±0.13)* | *0.15 (±0.00)* | *89.4 (±0.09)* | *9.5 (±0.09)* | *1.1 (±0.17)* | *18.35* | *20.5* | *52.2* | *23.1* |
| **BI.B.6** | *48.2 (±0.28)* | *6.4 (±0.18)* | *0.29 (±0.01)* | *88.6 (±0.13)* | *10.7 (±0.18)* | *0.6 (±0.05)* | *19.22* | *23.0* | *51.4* | *23.5* |
| **BI.B.6** | *48.4 (±0.21)* | *6.3 (±0.06)* | *0.20 (±0.00)* | *87.3 (±0.23)* | *11.6 (±0.19)* | *1.1 (±0.04)* | *19.28* | *20.9* | *47.5* | *30.2* |
| **BI.B.6** | *47.8 (±0.80)* | *6.4 (±0.11)* | *0.27 (±0.00)* | *89.5 (±0.57)* | *10.2 (±0.61)* | *0.3 (±0.04)* | *19.07* | *23.0* | *50.3* | *25.7* |
| **BI.B.6** | *47.4 (±0.52)* | *6.4 (±0.10)* | *0.21 (±0.00)* | *88.9 (±0.21)* | *10.5 (±0.13)* | *0.6 (±0.08)* | *18.85* | *21.8* | *48.3* | *28.4* |
| **SP.S.9** | *49.4 (±0.66)* | *6.5 (±0.07)* | *0.11 (±0.02)* | *88.7 (±0.00)* | *11.2 (±0.05)* | *0.1 (±0.05)* | *19.78* | *16.1* | *47.6* | *31.4* |
| **SP.S.9** | *47.9 (±0.14)* | *6.4 (±0.06)* | *0.08 (±0.00)* | *88.9 (±0.06)* | *10.8 (±0.09)* | *0.3 (±0.03)* | *19.06* | *15.7* | *50.2* | *25.9* |
| **SP.S.9** | *48.0 (±0.57)* | *6.4 (±0.11)* | *0.10 (±0.01)* | *87.8 (±0.11)* | *12.0 (±0.04)* | *0.2 (±0.07)* | *19.11* | *14.0* | *51.2* | *28.3* |
| **SP.S.9** | *48.3 (±0.42)* | *6.5 (±0.06)* | *0.07 (±0.00)* | *88.9 (±0.23)* | *10.7 (±0.23)* | *0.4 (±0.00)* | *19.27* | *15.4* | *50.0* | *28.5* |

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|---|---|---|---|---|---|---|---|---|---|---|
| **SP.S.9** | *48.7 (±0.56)* | *6.5 (±0.10)* | *0.11 (±0.00)* | *87.7 (±0.09)* | *12.1 (±0.16)* | *0.2 (±0.07)* | *19.46* | *14.4* | *50.7* | *27.7* |
| **SP.S.9** | *48.2 (±0.36)* | *6.3 (±0.02)* | *0.08 (±0.01)* | *88.5 (±0.17)* | *11.2 (±0.12)* | *0.3 (±0.06)* | *19.17* | *15.4* | *51.9* | *26.3* |
| **SP.S.9** | *48.3 (±0.38)* | *6.5 (±0.04)* | *0.07 (±0.00)* | *88.6 (±0.34)* | *11.0 (±0.30)* | *0.3 (±0.04)* | *19.24* | *15.8* | *52.9* | *25.8* |
| **SP.S.9** | *47.0 (±0.55)* | *6.4 (±0.07)* | *0.08 (±0.00)* | *89.0 (±0.08)* | *10.7 (±0.09)* | *0.2 (±0.01)* | *18.68* | *13.4* | *54.6* | *24.1* |
| **SP.S.10** | *48.0 (±0.35)* | *6.4 (±0.07)* | *0.08 (±0.00)* | *87.7 (±0.03)* | *12.1 (±0.05)* | *0.1 (±0.02)* | *19.10* | *14.4* | *52.4* | *27.2* |
| **SP.S.10** | *48.2 (±0.49)* | *6.4 (±0.06)* | *0.09 (±0.01)* | *88.5 (±0.05)* | *11.2 (±0.01)* | *0.3 (±0.06)* | *19.19* | *15.4* | *51.0* | *27.4* |
| **SP.S.10** | *49.0 (±0.71)* | *6.4 (±0.09)* | *0.10 (±0.00)* | *86.0 (±0.36)* | *13.8 (±0.23)* | *0.2 (±0.12)* | *19.53* | *13.5* | *47.4* | *33.9* |
| **SP.S.10** | *47.4 (±0.34)* | *6.3 (±0.02)* | *0.09 (±0.01)* | *88.0 (±0.01)* | *11.9 (±0.02)* | *0.1 (±0.01)* | *18.84* | *14.1* | *49.4* | *29.1* |
| **SP.S.10** | *48.1 (±0.25)* | *6.4 (±0.06)* | *0.10 (±0.00)* | *87.8 (±0.06)* | *12.1 (±0.07)* | *0.1 (±0.02)* | *19.15* | *15.5* | *50.1* | *27.4* |
| **SP.S.10** | *48.0 (±0.75)* | *6.4 (±0.11)* | *0.13 (±0.01)* | *87.2 (±0.01)* | *12.4 (±0.01)* | *0.3 (±0.00)* | *19.09* | *14.1* | *50.7* | *28.4* |
| **SP.S.14** | *47.4 (±0.66)* | *6.4 (±0.06)* | *0.09 (±0.01)* | *88.1 (±0.08)* | *11.6 (±0.02)* | *0.3 (±0.06)* | *18.84* | *14.1* | *50.0* | *29.1* |
| **SP.S.14** | *47.1 (±0.88)* | *6.4 (±0.16)* | *0.08 (±0.00)* | *88.4 (±0.25)* | *11.4 (±0.15)* | *0.3 (±0.10)* | *18.69* | *14.0* | *51.5* | *28.4* |
| **SP.S.14** | *45.9 (±0.29)* | *6.3 (±0.04)* | *0.10 (±0.00)* | *87.7 (±0.27)* | *11.8 (±0.13)* | *0.5 (±0.14)* | *18.20* | *14.6* | *49.2* | *29.7* |
| **SP.S.14** | *46.8 (±0.67)* | *6.3 (±0.07)* | *0.09 (±0.00)* | *88.4 (±0.28)* | *11.2 (±0.15)* | *0.4 (±0.13)* | *18.57* | *13.9* | *50.1* | *27.1* |
| **SP.S.14** | *47.1 (±0.59)* | *6.3 (±0.07)* | *0.07 (±0.00)* | *88.6 (±0.20)* | *10.9 (±0.20)* | *0.5 (±0.00)* | *18.71* | *14.3* | *51.3* | *27.6* |
| **SP.R.9** | *47.1 (±0.77)* | *6.1 (±0.15)* | *0.17 (±0.00)* | *85.1 (±0.18)* | *13.4 (±0.07)* | *1.5 (±0.11)* | *18.70* | *13.0* | *50.9* | *27.8* |
| **SP.R.9** | *46.0 (±0.59)* | *6.1 (±0.09)* | *0.18 (±0.01)* | *85.1 (±0.09)* | *12.9 (±0.02)* | *2.0 (±0.06)* | *18.25* | *10.6* | *50.3* | *30.1* |
| **SP.R.9** | *47.5 (±0.69)* | *6.3 (±0.20)* | *0.14 (±0.00)* | *86.8 (±0.21)* | *12.7 (±0.05)* | *0.5 (±0.17)* | *18.86* | *11.2* | *50.4* | *29.2* |
| **SP.R.9** | *47.1 (±0.12)* | *6.2 (±0.07)* | *0.20 (±0.01)* | *84.5 (±0.07)* | *13.6 (±0.02)* | *1.8 (±0.09)* | *18.71* | *12.1* | *48.5* | *30.2* |
| **SP.R.10** | *46.7 (±0.82)* | *6.2 (±0.05)* | *0.16 (±0.00)* | *85.7 (±0.00)* | *13.5 (±0.03)* | *0.8 (±0.03)* | *18.53* | *10.6* | *48.8* | *29.6* |
| **SP.B.9** | *48.2 (±0.48)* | *6.4 (±0.09)* | *0.11 (±0.00)* | *85.7 (±0.11)* | *13.9 (±0.03)* | *0.4 (±0.13)* | *19.20* | *12.7* | *45.8* | *32.6* |
| **SP.B.9** | *47.6 (±0.36)* | *6.3 (±0.10)* | *0.15 (±0.00)* | *84.9 (±0.18)* | *14.6 (±0.26)* | *0.6 (±0.08)* | *18.94* | *15.0* | *44.1* | *32.9* |
| **SP.B.9** | *47.8 (±0.20)* | *6.4 (±0.03)* | *0.12 (±0.00)* | *85.3 (±0.04)* | *14.1 (±0.21)* | *0.5 (±0.25)* | *19.04* | *13.2* | *45.7* | *33.2* |
| **SS.S.11** | *48.2 (±0.19)* | *6.4 (±0.09)* | *0.07 (±0.00)* | *88.2 (±0.30)* | *11.4 (±0.20)* | *0.4 (±0.10)* | *19.18* | *14.8* | *54.8* | *25.1* |
| **SS.S.11** | *47.4 (±0.09)* | *6.4 (±0.11)* | *0.07 (±0.01)* | *88.0 (±0.03)* | *11.6 (±0.08)* | *0.4 (±0.11)* | *18.86* | *6.9* | *47.0* | *30.8* |
| **SS.S.11** | *46.8 (±0.74)* | *6.4 (±0.06)* | *0.10 (±0.01)* | *87.8 (±0.12)* | *11.9 (±0.16)* | *0.3 (±0.03)* | *18.61* | *14.3* | *56.4* | *25.0* |
| **SS.S.11** | *47.3 (±0.49)* | *6.3 (±0.03)* | *0.24 (±0.00)* | *83.6 (±0.05)* | *15.5 (±0.02)* | *0.9 (±0.06)* | *18.80* | *14.9* | *54.1* | *26.4* |
| **SS.S.11** | *48.1 (±0.31)* | *6.4 (±0.14)* | *0.06 (±0.00)* | *88.5 (±0.35)* | *11.3 (±0.23)* | *0.3 (±0.12)* | *19.16* | *15.3* | *55.4* | *24.4* |

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| **SS.S.11** | *47.1 (±0.74)* | *6.4 (±0.05)* | *0.09 (±0.01)* | *89.3 (±0.07)* | *10.6 (±0.09)* | *0.1 (±0.02)* | *18.71* | *15.0* | *54.1* | *25.6* |
| **SS.S.11** | *47.0 (±0.72)* | *6.4 (±0.05)* | *0.09 (±0.00)* | *88.1 (±0.18)* | *11.5 (±0.05)* | *0.4 (±0.12)* | *18.68* | *15.0* | *50.7* | *27.3* |
| **SS.S.12** | *48.4 (±0.55)* | *6.4 (±0.06)* | *0.09 (±0.00)* | *87.9 (±0.23)* | *11.8 (±0.01)* | *0.3 (±0.22)* | *19.30* | *15.2* | *48.8* | *29.3* |
| **SS.S.12** | *48.3 (±0.46)* | *6.5 (±0.18)* | *0.07 (±0.00)* | *88.5 (±0.16)* | *11.4 (±0.12)* | *0.1 (±0.04)* | *19.26* | *15.8* | *51.1* | *27.1* |
| **SS.S.12** | *46.6 (±0.91)* | *6.3 (±0.10)* | *0.08 (±0.00)* | *88.7 (±0.00)* | *11.1 (±0.04)* | *0.1 (±0.04)* | *18.49* | *14.9* | *54.7* | *24.9* |
| **SS.S.12** | *46.5 (±0.58)* | *6.3 (±0.07)* | *0.08 (±0.01)* | *87.7 (±0.19)* | *11.8 (±0.04)* | *0.5 (±0.15)* | *18.42* | *14.1* | *53.6* | *26.6* |
| **SS.S.12** | *46.8 (±0.78)* | *6.4 (±0.05)* | *0.08 (±0.01)* | *88.6 (±0.35)* | *11.0 (±0.18)* | *0.4 (±0.18)* | *18.58* | *14.5* | *50.8* | *28.5* |
| **SS.S.12** | *48.3 (±1.06)* | *6.5 (±0.14)* | *0.08 (±0.00)* | *87.5 (±0.07)* | *12.3 (±0.10)* | *0.2 (±0.03)* | *19.27* | *14.9* | *48.9* | *30.5* |
| **SS.S.12** | *48.5 (±0.45)* | *6.4 (±0.09)* | *0.07 (±0.00)* | *87.2 (±0.05)* | *12.5 (±0.10)* | *0.3 (±0.05)* | *19.33* | *14.5* | *53.8* | *26.5* |
| **SS.S.12** | *46.7 (±0.87)* | *6.4 (±0.07)* | *0.07 (±0.01)* | *88.5 (±0.04)* | *11.3 (±0.05)* | *0.2 (±0.09)* | *18.54* | *14.6* | *47.0* | *33.0* |
| **SS.S.12** | *47.1 (±0.68)* | *6.4 (±0.13)* | *0.09 (±0.01)* | *88.3 (±0.04)* | *11.6 (±0.13)* | *0.1 (±0.09)* | *18.71* | *15.4* | *55.1* | *25.9* |
| **SS.S.12** | *47.7 (±0.27)* | *6.4 (±0.18)* | *0.06 (±0.01)* | *88.8 (±0.28)* | *11.0 (±0.16)* | *0.2 (±0.12)* | *18.98* | *14.5* | *51.9* | *27.7* |
| **SS.S.12** | *46.3 (±0.64)* | *6.3 (±0.03)* | *0.08 (±0.00)* | *88.5 (±0.01)* | *11.3 (±0.02)* | *0.2 (±0.03)* | *18.35* | *14.7* | *55.4* | *25.8* |
| **SS.S.13** | *47.3 (±0.40)* | *6.5 (±0.15)* | *0.07 (±0.01)* | *88.8 (±0.18)* | *11.1 (±0.14)* | *0.1 (±0.04)* | *18.80* | *14.1* | *54.7* | *25.3* |
| **SS.S.13** | *45.9 (±0.89)* | *6.3 (±0.06)* | *0.05 (±0.00)* | *88.6 (±0.06)* | *11.3 (±0.14)* | *0.1 (±0.09)* | *18.18* | *15.4* | *54.7* | *25.2* |
| **SS.S.13** | *47.2 (±0.39)* | *6.4 (±0.25)* | *0.07 (±0.01)* | *89.2 (±0.08)* | *10.6 (±0.09)* | *0.2 (±0.01)* | *18.77* | *13.1* | *54.4* | *24.0* |
| **SS.S.13** | *46.7 (±0.34)* | *6.4 (±0.07)* | *0.09 (±0.01)* | *89.0 (±0.22)* | *10.7 (±0.29)* | *0.3 (±0.07)* | *18.55* | *12.4* | *53.7* | *26.7* |
| **SS.S.13** | *47.9 (±1.16)* | *6.4 (±0.19)* | *0.07 (±0.01)* | *86.9 (±0.20)* | *12.9 (±0.24)* | *0.2 (±0.04)* | *19.07* | *14.7* | *50.7* | *28.1* |
| **SS.S.13** | *46.4 (±0.87)* | *6.3 (±0.08)* | *0.09 (±0.01)* | *88.5 (±0.11)* | *11.3 (±0.09)* | *0.1 (±0.02)* | *18.40* | *15.4* | *56.1* | *25.2* |
| **SS.S.13** | *47.2 (±0.54)* | *6.4 (±0.16)* | *0.05 (±0.00)* | *88.3 (±0.19)* | *11.4 (±0.24)* | *0.3 (±0.05)* | *18.77* | *14.7* | *54.5* | *28.4* |
| **SS.S.13** | *46.9 (±0.38)* | *6.4 (±0.16)* | *0.07 (±0.01)* | *88.8 (±0.30)* | *10.6 (±0.07)* | *0.6 (±0.24)* | *18.63* | *13.4* | *55.3* | *25.0* |
| **SS.S.13** | *46.7 (±1.18)* | *6.3 (±0.10)* | *0.08 (±0.01)* | *88.8 (±0.17)* | *11.0 (±0.15)* | *0.2 (±0.02)* | *18.54* | *15.4* | *57.5* | *24.2* |
| **SS.S.13** | *45.8 (±0.43)* | *6.4 (±0.10)* | *0.08 (±0.00)* | *88.3 (±0.01)* | *11.3 (±0.09)* | *0.4 (±0.10)* | *18.19* | *11.6* | *54.0* | *27.9* |
| **SS.S.13** | *46.8 (±0.42)* | *6.5 (±0.14)* | *0.08 (±0.01)* | *88.4 (±0.04)* | *11.3 (±0.04)* | *0.3 (±0.08)* | *18.59* | *15.9* | *54.5* | *26.9* |
| **SS.R.12** | *47.7 (±0.49)* | *6.2 (±0.19)* | *0.15 (±0.01)* | *87.6 (±0.16)* | *12.2 (±0.09)* | *0.2 (±0.07)* | *18.94* | *13.2* | *52.4* | *27.3* |
| **SS.R.12** | *48.5 (±0.73)* | *6.2 (±0.15)* | *0.14 (±0.01)* | *85.9 (±0.18)* | *13.5 (±0.03)* | *0.6 (±0.22)* | *19.28* | *11.1* | *44.8* | *34.8* |
| **SS.R.12** | *47.7 (±0.64)* | *6.3 (±0.13)* | *0.12 (±0.00)* | *87.5 (±0.16)* | *12.2 (±0.15)* | *0.4 (±0.01)* | *18.95* | *12.8* | *48.8* | *30.9* |
| **SS.R.12** | *47.7 (±0.35)* | *6.4 (±0.12)* | *0.14 (±0.00)* | *86.7 (±0.05)* | *13.1 (±0.02)* | *0.3 (±0.07)* | *18.99* | *14.6* | *53.3* | *26.9* |

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|---|---|---|---|---|---|---|---|---|---|
| **SS.R.13** | 47.0 (±0.33) | 6.3 (±0.17) | 0.13 (±0.00) | 87.1 (±0.07) | 12.5 (±0.18) | 0.3 (±0.11) | 18.67 | 12.8 | 45.5 | 28.6 |
| **SS.R.13** | 47.2 (±0.45) | 6.3 (±0.09) | 0.15 (±0.00) | 87.1 (±0.14) | 12.8 (±0.10) | 0.1 (±0.03) | 18.76 | 12.7 | 48.5 | 29.6 |
| **SS.R.13** | 46.9 (±0.38) | 6.2 (±0.06) | 0.17 (±0.00) | 85.3 (±0.09) | 13.9 (±0.09) | 0.8 (±0.01) | 18.62 | 14.9 | 32.7 | 33.2 |
| **SS.B.12** | 48.9 (±0.72) | 6.6 (±0.12) | 0.21 (±0.01) | 85.5 (±0.62) | 14.0 (±0.46) | 0.5 (±0.16) | 19.57 | 12.5 | 42.5 | 32.3 |
| **SS.B.12** | 47.7 (±0.82) | 6.4 (±0.07) | 0.16 (±0.00) | 85.3 (±0.10) | 14.6 (±0.16) | 0.1 (±0.05) | 18.99 | 14.4 | 43.3 | 31.7 |
| **SS.B.12** | 48.1 (±0.29) | 6.4 (±0.07) | 0.18 (±0.01) | 85.3 (±0.03) | 14.3 (±0.15) | 0.4 (±0.13) | 19.18 | 13.9 | 42.1 | 32.6 |
| **SS.B.13** | 48.3 (±0.32) | 6.5 (±0.03) | 0.16 (±0.01) | 84.7 (±0.05) | 14.8 (±0.00) | 0.5 (±0.05) | 19.26 | 12.6 | 40.4 | 32.1 |
| **SS.B.13** | 47.5 (±0.07) | 6.4 (±0.01) | 0.13 (±0.00) | 85.7 (±0.20) | 14.2 (±0.17) | 0.1 (±0.03) | 18.92 | 14.3 | 41.4 | 30.5 |

[a] *calculated on a dry basis,* [b] *MJ/kg*

# Appendix C:
# Statistical Analysis Data

Table C.1 – **Independent** t**-test results, calculated between experimental and literature data showing statistically significant differences (*p*≤0.05)**

| | ***t*-test** | | | | | |
|---|---|---|---|---|---|---|
| | **Hardwood** | | | **Softwood** | | |
| | *t* | *df* | Sig. (2-tailed) | *t* | *df* | Sig. (2-tailed) |
| **VM** | *-4.240* | *41* | *0.000* | *-5.279* | *30* | *0.000* |
| **FC** | *3.698* | *41* | *0.001* | *4.557* | *30* | *0.000* |
| **Ash** | *4.763* | *32* | *0.000* | *4.265* | *30* | *0.000* |
| **FC:VM** | *3.830* | *39* | *0.000* | *4.384* | *30* | *0.000* |
| **GCV** | *3.793* | *51* | *0.000* | *6.540* | *45* | *0.000* |
| **H:C** | *-3.993* | *47* | *0.000* | *-6.569* | *34* | *0.000* |
| **O:C** | *-4.422* | *43* | *0.000* | *-6.568* | *42* | *0.000* |
| **N** | *4.618* | *38* | *0.000* | *3.226* | *33* | *0.003* |
| **L:H** | *-2.035* | *51* | *0.047* | *-0.765* | *22* | *0.453* |

*Data highlighted in green indicates statistically significant difference*

Table C.2 – **Data matrix of Tukey's HSD post-hoc analysis; statistically significant differences between specific tree sections ($p$≤0.05)**

| | | **Between Tree Sections** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **OK** | | **BI** | | **SP** | | **SS** | |
| | | Root | Branch | Root | Branch | Root | Branch | Root | Branch |
| **VM** | Stem | *0.000* | *0.671* | *0.000* | *0.000* | *0.000* | *0.001* | *0.054* | *0.000* |
| | Root | - | *0.000* | - | *0.003* | - | *1.000* | - | *0.450* |
| **FC** | Stem | *1.000* | *0.980* | *0.000* | *0.000* | *0.015* | *0.000* | *0.019* | *0.000* |
| | Root | - | *1.000* | - | *0.000* | - | *0.929* | - | *0.128* |
| **Ash** | Stem | *0.000* | *0.000* | *0.932* | *0.096* | *0.003* | *1.000* | *1.000* | *1.000* |
| | Root | - | *0.000* | - | *0.995* | - | *0.531* | - | *1.000* |
| **N** | Stem | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* | *0.809* | *0.001* | *0.000* |
| | Root | - | *0.000* | - | *0.029* | - | *0.789* | - | *0.973* |
| **H:C** | Stem | *1.000* | *0.999* | *0.000* | *0.008* | *0.710* | *0.999* | *0.014* | *0.996* |
| | Root | - | *0.999* | - | *0.008* | - | *1.000* | - | *0.808* |
| **O:C** | Stem | *1.000* | *0.022* | *0.000* | *0.000* | *0.984* | *1.000* | *0.961* | *0.091* |
| | Root | - | *0.147* | - | *0.025* | - | *0.984* | - | *0.919* |
| **GCV** | Stem | *0.000* | *0.999* | *0.000* | *0.001* | *0.213* | *1.000* | *0.996* | *0.146* |
| | Root | - | *0.000* | - | *0.011* | - | *0.691* | - | *0.888* |
| **Ce.** | Stem | *0.418* | *0.000* | *0.000* | *0.002* | *1.000* | *0.056* | *0.000* | *0.000* |
| | Root | - | *1.000* | - | *0.430* | - | *0.444* | - | *0.135* |
| **He.** | Stem | *0.131* | *0.000* | *0.000* | *0.000* | *0.000* | *0.987* | *0.650* | *0.989* |
| | Root | - | *1.000* | - | *0.002* | - | *0.651* | - | *1.000* |
| **Li.** | Stem | *0.771* | *0.000* | *0.000* | *0.000* | *0.988* | *0.023* | *0.016* | *0.000* |
| | Root | - | *0.314* | - | *0.000* | - | *0.531* | - | *0.976* |

*Data highlighted in green indicates statistically significant difference*

Table C.3 – **Data matrix of Tukey's HSD post-hoc analysis; statistically significant differences between species ($p \leq 0.05$)**

| | | | **Between Species** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Stem** | | | **Root** | | | **Branch** | | |
| | | | BI | SP | SS | BI | SP | SS | BI | SP | SS |
| **VM** | **Stem** | OK | *0.000* | *0.007* | *0.001* | - | - | - | - | - | - |
| | | BI | - | *0.000* | *0.000* | - | - | - | - | - | - |
| | | SP | - | - | *1.000* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *0.000* | *0.135* | *0.000* | - | - | - |
| | | BI | - | - | - | - | *0.410* | *1.000* | - | - | - |
| | | SP | - | - | - | - | - | *0.631* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.000* | *0.989* | *0.952* |
| | | BI | - | - | - | - | - | - | - | *0.000* | *0.000* |
| | | SP | - | - | - | - | - | - | - | - | *1.000* |
| **FC** | **Stem** | OK | *0.000* | *0.001* | *0.000* | - | - | - | - | - | - |
| | | BI | - | *0.000* | *0.000* | - | - | - | - | - | - |
| | | SP | - | - | *1.000* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *1.000* | *1.000* | *1.000* | - | - | - |
| | | BI | - | - | - | - | *0.974* | *1.000* | - | - | - |
| | | SP | - | - | - | - | - | *1.000* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.000* | *0.090* | *0.002* |
| | | BI | - | - | - | - | - | - | - | *0.000* | *0.000* |
| | | SP | - | - | - | - | - | - | - | - | *1.000* |
| **Ash** | **Stem** | OK | *1.000* | *1.000* | *1.000* | - | - | - | - | - | - |
| | | BI | - | *1.000* | *1.000* | - | - | - | - | - | - |
| | | SP | - | - | *1.000* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *0.000* | *0.000* | *0.000* | - | - | - |
| | | BI | - | - | - | - | *0.215* | *1.000* | - | - | - |
| | | SP | - | - | - | - | - | *0.079* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.014* | *0.138* | *0.002* |
| | | BI | - | - | - | - | - | - | - | *0.999* | *0.831* |
| | | SP | - | - | - | - | - | - | - | - | *1.000* |
| **N** | **Stem** | OK | *0.516* | *0.002* | *0.000* | - | - | - | - | - | - |
| | | BI | - | *0.900* | *0.310* | - | - | - | - | - | - |
| | | SP | - | - | *0.999* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *0.005* | *0.000* | *0.000* | - | - | - |
| | | BI | - | - | - | - | *0.000* | *0.000* | - | - | - |
| | | SP | - | - | - | - | - | *0.953* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.003* | *0.000* | *0.000* |
| | | BI | - | - | - | - | - | - | - | *0.001* | *0.118* |
| | | SP | - | - | - | - | - | - | - | - | *0.835* |
| **H:C** | **Stem** | OK | *0.000* | *0.000* | *0.000* | - | - | - | - | - | - |
| | | BI | - | *0.669* | *1.000* | - | - | - | - | - | - |
| | | SP | - | - | *0.187* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *1.000* | *0.638* | *0.251* | - | - | - |
| | | BI | - | - | - | - | *0.350* | *0.065* | - | - | - |
| | | SP | - | - | - | - | - | *1.000* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.082* | *0.683* | *0.003* |
| | | BI | - | - | - | - | - | - | - | *1.000* | *0.667* |
| | | SP | - | - | - | - | - | - | - | - | *0.987* |

| | | | Between Species | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Stem | | | Root | | | Branch | | |
| | | | BI | SP | SS | BI | SP | SS | BI | SP | SS |
| **O:C** | **Stem** | OK | *0.070* | *0.022* | *1.000* | - | - | - | - | - | - |
| | | BI | - | *0.000* | *0.004* | - | - | - | - | - | - |
| | | SP | - | - | *0.064* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *0.000* | *0.979* | *0.795* | - | - | - |
| | | BI | - | - | - | - | *0.014* | *0.021* | - | - | - |
| | | SP | - | - | - | - | - | *1.000* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *1.000* | *1.000* | *0.998* |
| | | BI | - | - | - | - | - | - | - | *1.000* | *0.992* |
| | | SP | - | - | - | - | - | - | - | - | *1.000* |
| **GCV** | **Stem** | OK | *0.257* | *0.022* | *1.000* | - | - | - | - | - | - |
| | | BI | - | *0.000* | *0.023* | - | - | - | - | - | - |
| | | SP | - | - | *0.080* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *0.000* | *0.031* | *0.000* | - | - | - |
| | | BI | - | - | - | - | *0.001* | *0.046* | - | - | - |
| | | SP | - | - | - | - | - | *0.927* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.982* | *0.944* | *0.290* |
| | | BI | - | - | - | - | - | - | - | *1.000* | *0.853* |
| | | SP | - | - | - | - | - | - | - | - | *1.000* |
| **Ce.** | **Stem** | OK | *0.049* | *1.000* | *0.086* | - | - | - | - | - | - |
| | | BI | - | *0.032* | *1.000* | - | - | - | - | - | - |
| | | SP | - | - | *0.054* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *1.000* | *0.976* | *1.000* | - | - | - |
| | | BI | - | - | - | - | *0.775* | *1.000* | - | - | - |
| | | SP | - | - | - | - | - | *0.656* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.048* | *1.000* | *0.048* |
| | | BI | - | - | - | - | - | - | - | *0.252* | *0.000* |
| | | SP | - | - | - | - | - | - | - | - | *0.883* |
| **He.** | **Stem** | OK | *0.000* | *0.000* | *0.000* | - | - | - | - | - | - |
| | | BI | - | *0.000* | *0.000* | - | - | - | - | - | - |
| | | SP | - | - | *1.000* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *0.999* | *0.000* | *0.000* | - | - | - |
| | | BI | - | - | - | - | *0.000* | *0.000* | - | - | - |
| | | SP | - | - | - | - | - | *0.601* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.000* | *0.000* | *0.000* |
| | | BI | - | - | - | - | - | - | - | *0.000* | *0.000* |
| | | SP | - | - | - | - | - | - | - | - | *1.000* |
| **Li.** | **Stem** | OK | *0.000* | *0.000* | *0.062* | - | - | - | - | - | - |
| | | BI | - | *0.000* | *0.000* | - | - | - | - | - | - |
| | | SP | - | - | *0.692* | - | - | - | - | - | - |
| | **Root** | OK | - | - | - | *0.089* | *0.752* | *0.242* | - | - | - |
| | | BI | - | - | - | - | *0.997* | *1.000* | - | - | - |
| | | SP | - | - | - | - | - | *1.000* | - | - | - |
| | **Branch** | OK | - | - | - | - | - | - | *0.000* | *0.398* | *0.681* |
| | | BI | - | - | - | - | - | - | - | *0.000* | *0.000* |
| | | SP | - | - | - | - | - | - | - | - | *1.000* |

*Data highlighted in green indicates statistically significant difference*

# Appendix D:
# Licensing Data Declarations

The raw data utilised in this thesis – specifically in Chapter 6 – has been attained from Open Data sources. Their licensing declarations can be found below;

# Appendix E:

# Mapping Examples & Data

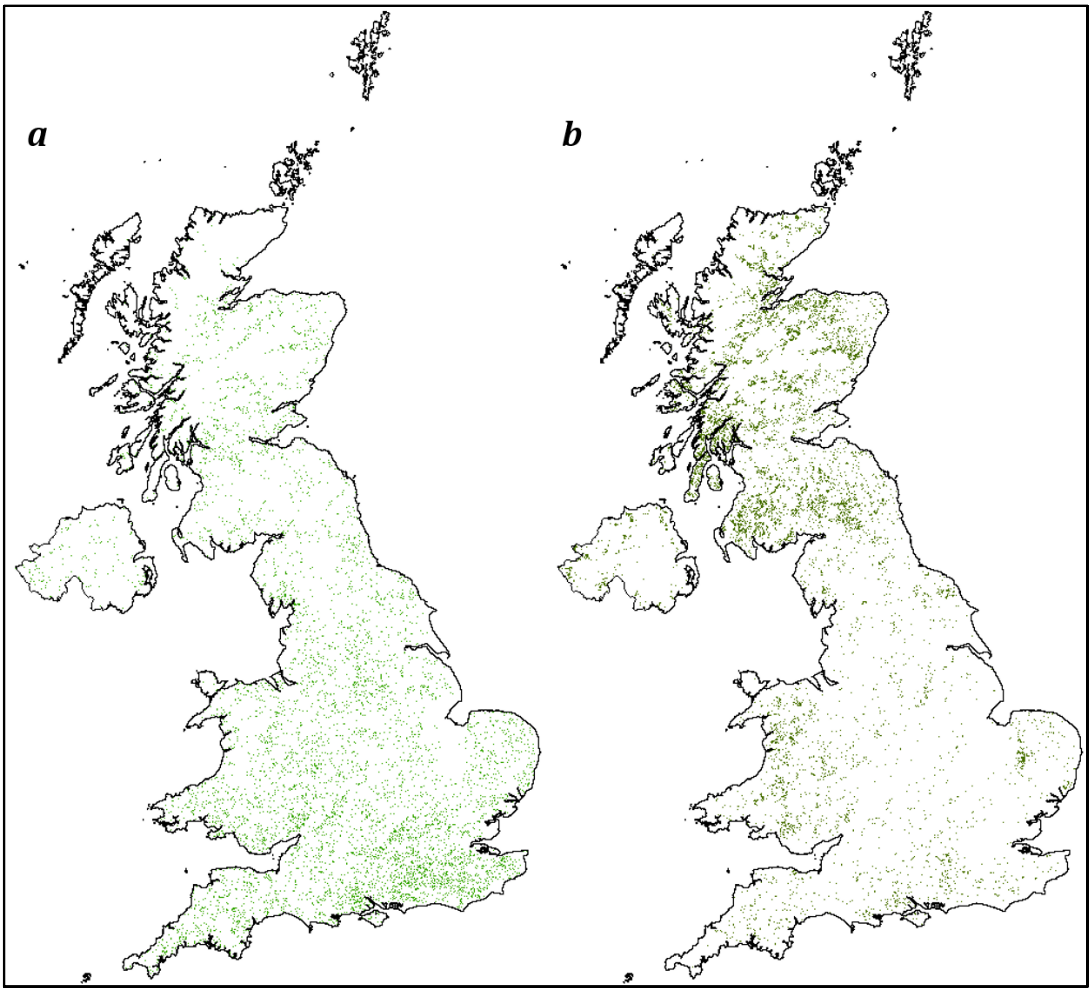

Figure E.1 – **National Forest Inventory (NFI) and Northern Ireland Forest Service (NIFS) combined polygon data; a) hardwood, and b) softwood coverage in the UK**

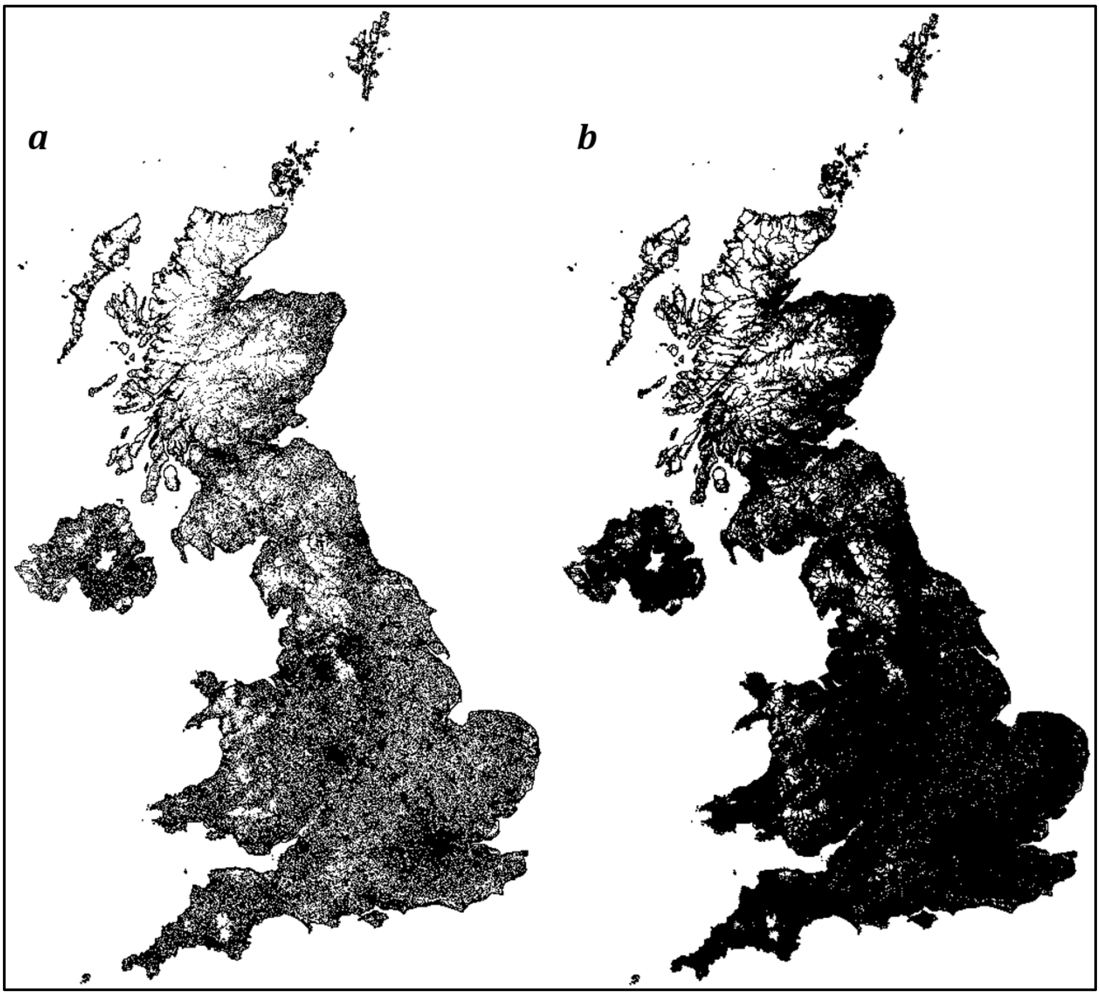

Figure E.2 – **Produced buffer zones for UK roads using GIS; a) 250m, and b) 750m**

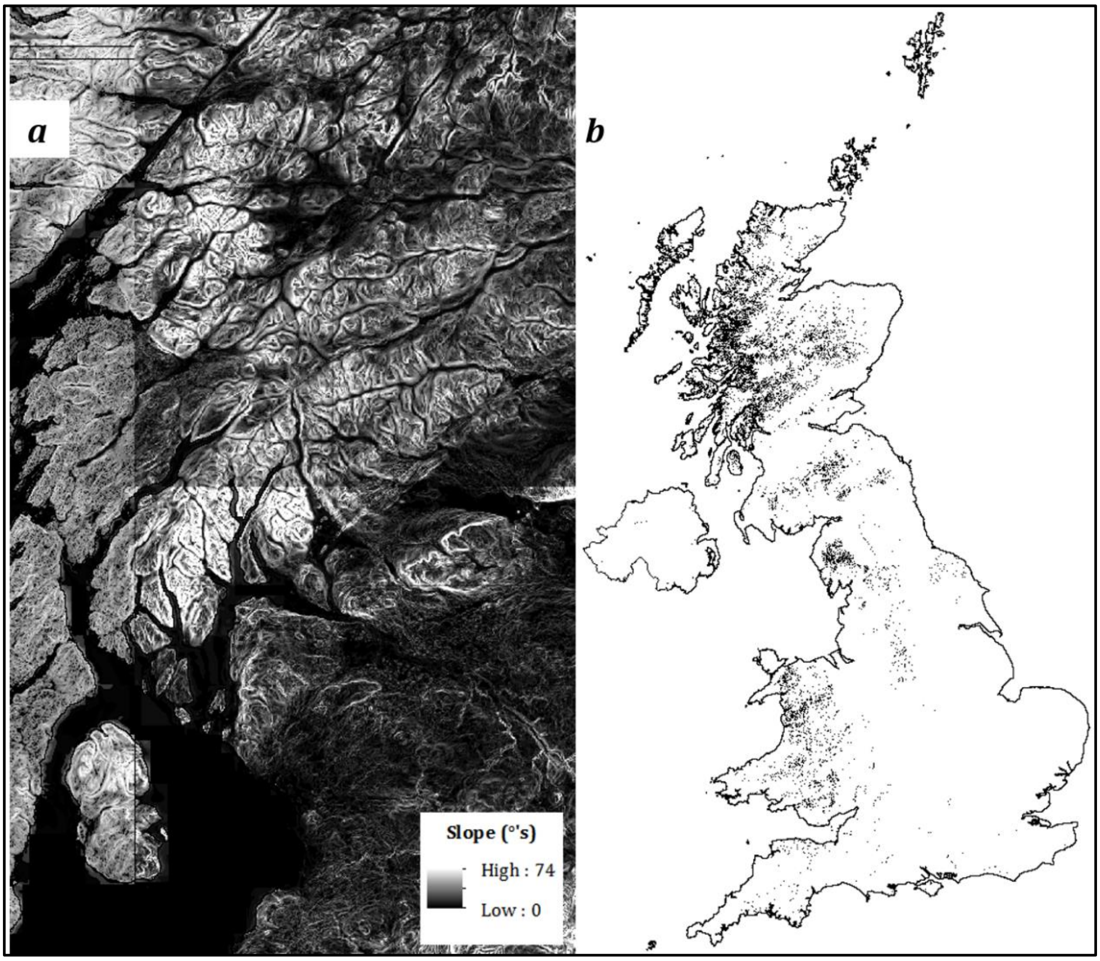

Figure E.3 – **Produced slope data for the UK using GIS; a) example of truncated raster slope data for west Scotland, and b) polygon dataset for slopes ≥17°**

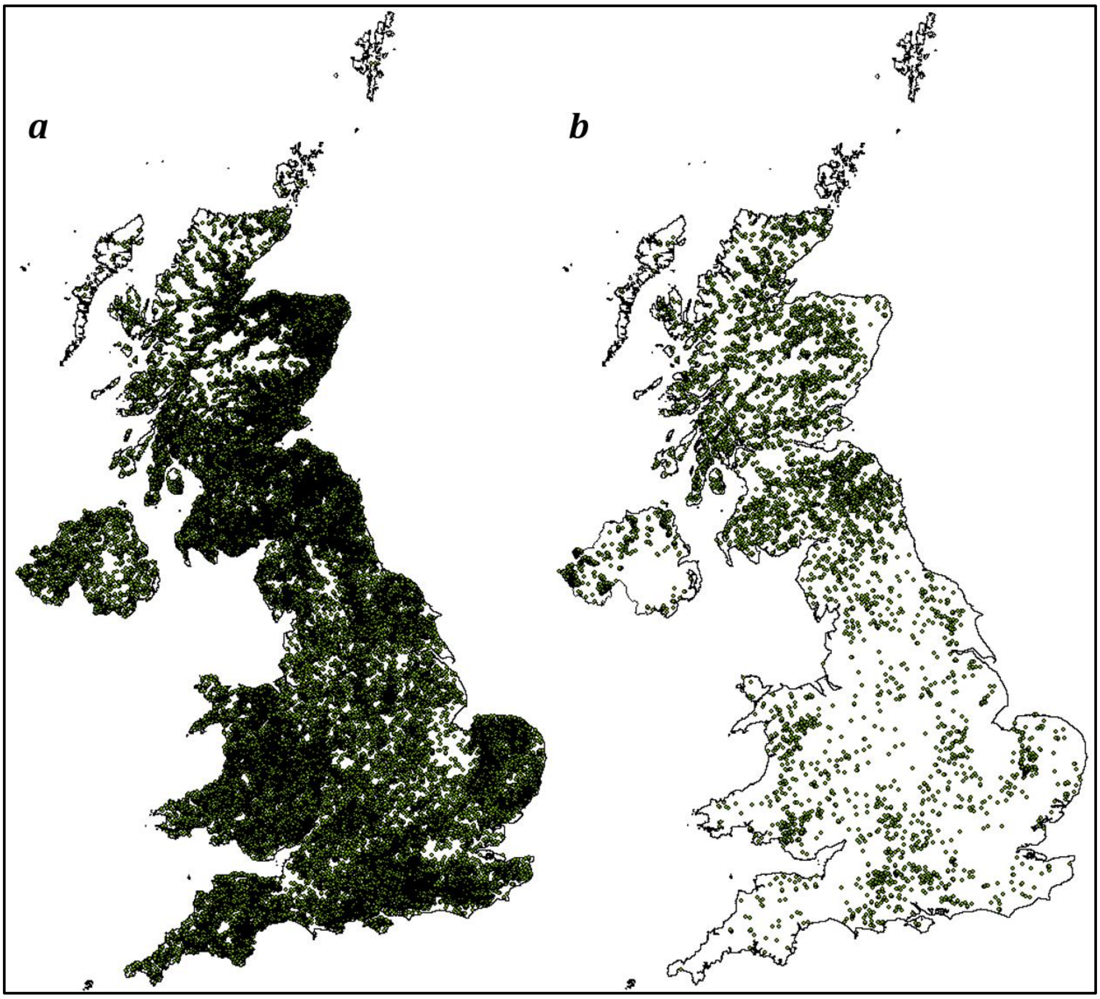

Figure E.4 – **Data produced in GIS using the feature to point method; examples of a) softwood data points <250m on slopes <17°, and b) softwood data points ≥750m on slopes <17° (see Table 6.3)**

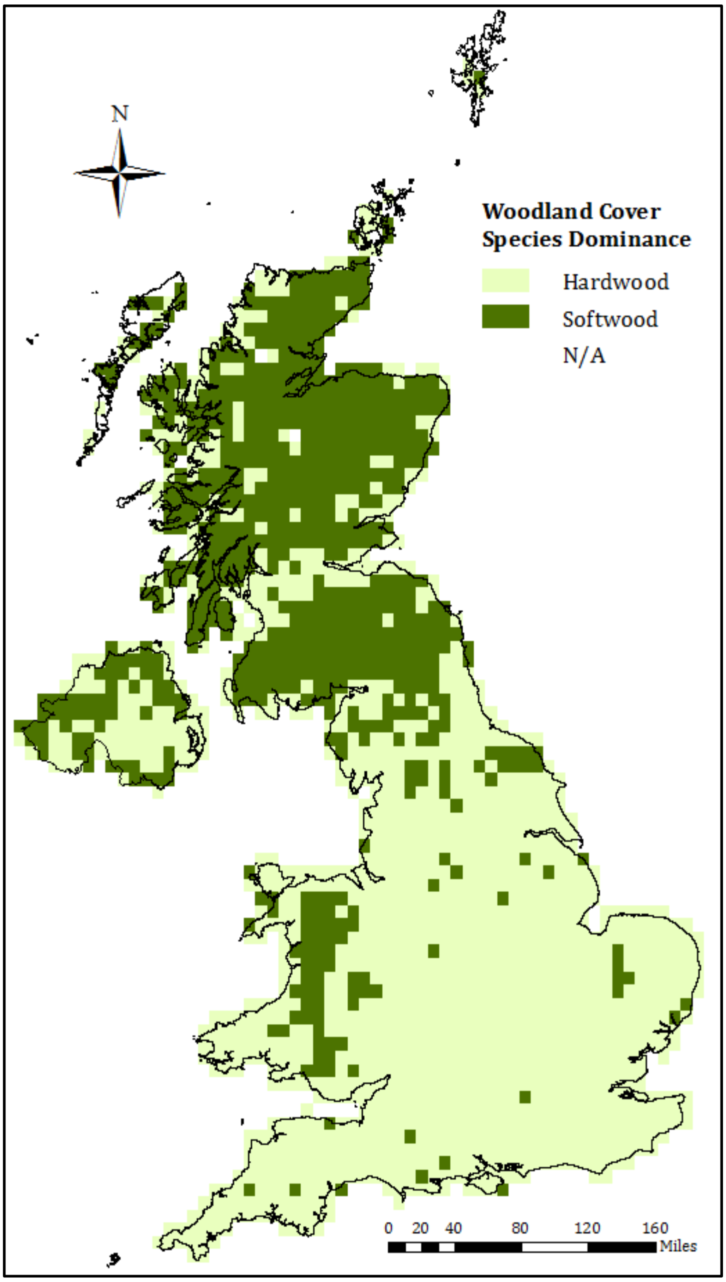

Figure E.5 – **The spatial dominance and distribution of the UK's hardwoods and softwoods, within the produced framework (see Figure 6.3)**