Nutrient pools in Sitka spruce and lodgepole pine forest biomass

A thesis presented by

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Under the supervision of

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ABSTRACT

Biomass harvesting may affect the nutrient pools of forests and impact negatively on forest ecosystems in the long-term. Appropriate knowledge regarding nutrient pools and potential nutrient removal is required for a good forest management to attain sustainable productivity. The main aims of this work were to give information of nutrient status (nitrogen N, phosphorus P, potassium K, calcium Ca, and magnesium Mg) of forests by studying a chronosequence Sitka spruce (*Picea sitchensis* (Bong.) Carr) and several mature Sitka spruce and lodgepole pine (*Pinus contorta Dougl.* var. *latifolia*) stands, and to determinate the potential nutrient removal in a site applying different harvest scenarios: stem-only harvest, stem-and-branch harvest and whole-tree harvest.

The database of this study comes from selected and sampled forest harvest residue in brash bundles and from standing trees, which were divided in six components (needles, branches, deadwood, roots, stembark and stemwood). Nutrient concentrations of these samples were analysed. Both tree species showed that needles was the component with higher nutrient concentration, and stemwood that with the lowest. In general, nutrient concentration in a tree for both species was identified from large to lesser concentration: N > Ca > K > Mg > P. Nitrogen pool generally increased over time. Sitka spruce stands had larger nutrient pools than lodgepole pine stands. WTH system potentially removed approximately double the amount of nutrients than SOH system. Several investigators had suggested different percentages of harvest residues to be retained on site in order to manage the forest sustainably. More research will be needed to verify what amount of harvest residue and what type of it must be left on site.

DECLARATION

"I hereby declare that this thesis is my own work, gathered and utilized especially to fulfill the purposes and objectives of this study, and has not been previously submitted for any other qualification. Where material from other sources has been used, it has been acknowledged."

SIGNED ______________________   DATE ________________

EVA ROS MANGRIÑÁN

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CHAPTER 1. INTRODUCTION

Over the last decades, there have been significant environmental problems caused or accelerated by human activities such as the use of fossil fuel energy sources. Pressure to decrease this activity had led to interest in the generation of energy from renewable sources. As energy produced from forest biomass is renewable, considered carbon neutral and sustainable (Irish Forestry and Forest Products Association, 2013), it has acquired greater importance to the point that forest biomass is expected to be a large source of energy (Jacobson *et al.*, 2000; Röser, 2008; Chum *et al.*, 2011; Thiffault *et al.*, 2011). The development of the forest biomass market increases competitiveness of the forest sector and supports rural economies at the same time that it may solve environmental problems (Thiffault *et al.*, 2011). In Ireland, this market is still in the early stages of its development but since 2006, it has risen considerably (Irish Forestry and Forest Products Association, 2013).

Despite forest biomass markets offering many benefits, biomass harvesting may also bring negative impacts on forest ecosystems in the long-term. The land-use change associated with bioenergy growth, afforestation or deforestation can affect greenhouse has (GHG) balances and other climates variables in many ways (EIA, 2012; IPCC, 2014). For instance, it is known that the more forest biomass is removed from the sites, the more nutrients are exported from the forests (Ericsson, 1994) which disturbs soil properties, biodiversity, biomass production and water quality (Helmisaari *et al.*, 2014). Achieving sustainable land management is vital in order to limit the extraction of the residues, conserve the healthy ecosystems and avoidance of soil degradation (Chum *et al.*, 2011; EIA, 2012; IPCC, 2014).

Forest harvesting is one of the actions that affect this nutrient removal. The main harvesting system in Ireland is stem-only harvesting (SOH). In this type of harvesting, needles and branches are left on site, which usually provide enough nutrients for future forest growth. However, the market of forest biomass for energy can take advantage of all tree components (Whole tree harvesting (WTH)) and there are concerns over how large on impact this system will have in a forest. Research is underway to address these concerns, and to identify the "Critical Biomass Removal", the amount of long-term biomass removal below which impacts to site nutrient supply will not occur, according to current knowledge (http://www.ucd.ie/forsite/). In order to achieve this goal, the ForSite project aims to assess the nutrient impact of increased biomass harvesting in Irish forests, by developing databases of forest nutrient exchanges, and a tool for policymakers to assess biomass-harvesting scenarios. To calculate the Critical Biomass Removal it is necessary take into account all the forest nutrient exchanges.

This thesis is part of ForSite project and it is contributing to quantification of the nutrient output in harvested biomass. The overall goal is to assess the nutrient removal in a site applying different harvest scenarios: stem-only harvest, stem-and-branch harvest and whole-tree harvest. Besides this, the other aims of this study are to give information about the nutrient status in mature Irish forests.

As such, the objectives are as followed:

- To determine nutrient concentration in Sitka spruce and lodgepole pine stands.
- To determine the biomass accumulation and nutrient pools of mature Sitka spruce and lodgepole pine stands.
- To determine the biomass accumulation and nitrogen pool in a Sitka spruce chronosequence.
- To compare the nutrient concentration, biomass accumulation and nutrient pool among Sitka spruce and lodgepole pine trees and stands.
- To determine the nutrient removal in stands according the type of harvesting, age and species.

CHAPTER 2. LITERATURE REVIEW

2.1 Climate change and renewable energy

Nowadays there is growing recognition of the need to reduce greenhouse gas (GHG) emissions. For instance, all European Union countries, in the Copenhagen Climate Change Conference on December 2009, committed to reduce their GHG emissions by at least 20% in 2020 compared to the reference year 1990. In order to achieve the desired objective there is a need to develop an alternative option to fossil fuel based energy. An alternative option is renewable energy (RE) which is any form of energy that is replenished by natural processes at a rate that equals or exceed its rate of use (Verbruggen *et al.*, 2011). Countries perceive this alternative a valid option to achieve the energy required while lowering GHG emissions (Lunnan *et al.*, 2008; Thiffault *et al.*, 2011).

Renewable energy not only has large potential for climate change mitigation, but also may contribute to social and economic progress, energy access, a secure energy supply and the reduction of negative impacts on the environment and health (Chum *et al.*, 2011). At the moment, RE constitutes a small fraction of global energy supply, however, it has been increased significantly (IPCC, 2014). Ireland's target for 2020, under the EU RE Directive, is to provide 16% of the final energy consumption through RE (Irish Forestry and Forest Products Association, 2013). There are several types of RE such as direct solar energy, geothermal energy, hydropower ocean energy, wind energy and bioenergy.

Bioenergy is the energy in the form of solid biomass fuel, or material processed into liquid and gases that is derived from the conversion of biomass (EIA, 2012). Biomass is any organic matter that originates from plants or animals including wood (forest) and agricultural crops, herbaceous and woody energy crops and organic waste, which could be harnessed by combustion for energy (Penman *et al.*, 2003; Sessa and Dolman, 2008; Global Terrestrial Observing System, 2009; EIA, 2012).

To date, bioenergy has been mainly used in developing countries such as Asia and Africa in the residential sector, especially in basic cookstoves or three-stone fires. It has played a minor role in developed countries (EIA, 2012). However, bioenergy has seen rapid developments in recent years such as the use of modern biomass for liquid and gaseous energy (Jacobson *et al.*, 2000; EIA, 2012). According to the Annual Energy Review carried out by EIA (2012) , this new use of biomass has increased by 37% between 2006 and 2009. Nowadays, it is the second largest source of RE used in Ireland to generate energy (Department of Agriculture Food and the Marine, 2014). For the future, Chum *et al.* (2011) reviewed available scientific literature and calculated potential deployment levels of biomass for energy for the World of 100 to 300 EJ/year by 2050. Residues originating from forestry, agriculture and organic wastes are expected to amount to 40 to 170 EJ/year, with a mean estimation of about 100 EJ/yr. Biomass is therefore expected to be a large source of energy, especially agricultural and forestry residues (Jacobson *et al.*, 2000; Röser, 2008; Chum *et al.*, 2011; Thiffault *et al.*, 2011) as at the moment more than 80% of biomass feedstock used for energy is derived from wood (trees, branches, residues and shrubs) (Chum *et al.*, 2011). In Ireland, it is estimated that energy wood volumes will increase to 0.63 M m^3 $year^{-1}$ in 2028 or a total of 10.75 M m^3 over the period 2011-2028 (Irish Forestry and Forest Products Association, 2013).

2.2 Irish forests

Forest is an area of land of at least 0.05 ha with tree-crown cover (or equivalent stocking level) of more than 10-30% with trees with the potential to reach a minimum height of 2-5 m at maturity in situ (Penman *et al.*, 2003; Verbruggen *et al.*, 2011). Forest land has many social, economic and environmental benefits and provides many ecosystem services (Clarke, 2012; Irish Forestry and Forest Products Association, 2013; Mullan, 2014). Forest ecosystem services are divided in four categories: provisioning services (food, fuel, timber, medicine), regulating services (soil protection, water purification, climate regulation, pollination), supporting services (nutrient cycling, soil formation, seed dispersal, primary production) and cultural services (recreation, traditional knowledge, spiritual wellbeing, education) (Mullan, 2014).

2.2.1 Afforestation in Ireland

In the early 20th century, the area of forest in Ireland was between 1% and 1.5% of the total land area (Forest Service, 2008). After the Second World War, a new Forestry Act (1946) was introduced. Through this, the Government adopted the first long-term afforestation plan and the rate of afforestation increased during 10 years, achieving an afforestation rate of 10,162 hectares in 1960 (Fig 2.1) (Forest Service, 2008). During the next two decades the afforestation rate decreased gradually becoming 5,700 hectares because of the difficulties to get suitable land by the public sector (Forest Service, 2008). So far, afforestation by the public sector has continued to decline. However, on the other hand, private afforestation greatly increased over a decade from the late 1980s. It was due to the introduction of a special grant scheme, achieving the maximum afforestation rate of almost 25,000 ha in 1995 (Forest Service, 2008). By the end of the 20th century, Ireland had approximately 650,000 ha of forestry (Forest Service, 2008) and in 2012 the forest cover was 731,650 ha (Forest Service, 2012).

Afforestation is an important carbon sink, therefore it is important to maintain a high afforestation rate. Byrne and Milne (2006) and Hendrick and Black (2009) recommend that the annual afforestation rate must be at least 10,000 ha yr^{-1} for the next two decades to provide both a renewable energy resource and a system to remove carbon dioxide from the atmosphere. Nowadays, the general rate of afforestation has declined and Irish Forestry and Forest Products Association (2013) thinks that is inadequate as it does not reach the level of planting required to achieve the national C sequestration levels. Nevertheless, the government plans to increase the level of annual afforestation to 15,000 ha and achieve a forest cover of 1,230,000 ha by 2045 (Department of Agriculture Food and Forestry, 1996).

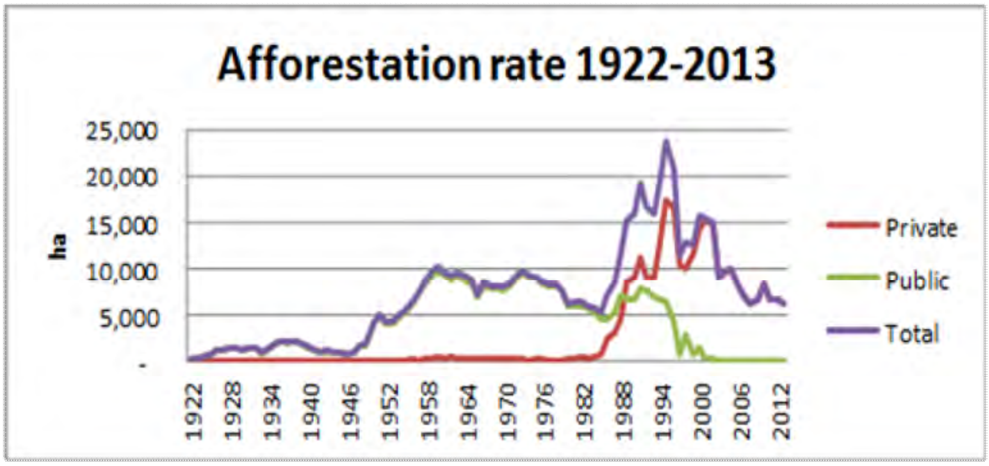

Fig 2. 1: Afforestation rate in Irish forests from 1922 to 2013 (Forest Service, 2012)

2.2.2 Irish forests nowadays

Ireland is one of the countries with the lowest forest cover in Europe (Vítkováa *et al.*, 2013). However, between 2006 and 2012, forest land increased by 0.5% of the total land area, occupying 731,650 ha or 10.5% of the country in 2012 (Forest Service, 2012).

Forests in Ireland are mostly established by humans. Approximately 54% of Irish forests are public and 46% are private (Forest Service, 2012). Afforestation is the man-made establishment most common in Ireland, especially in private (grant aided) forests. It comprises 64.2% of forests, followed by reforestation for 24.7% of forests. Semi-natural forests represent 11.1% of forests (Forest Service, 2012). Less than 30% of stands are identified as monocultures. In general, public forests have few tree species while private forests are more diverse (Forest Service, 2012). Approximately three quarters (74.2%) of Irish forests are comprised of conifers and the remaining fraction (25.8%) is broadleaved forests (Forest Service, 2012). Native species and non-native species occupy 23.8% and 73.2% respectively, Sitka spruce *Picea sitchensis* (Bong.) Carr. being the most abundant tree species in Irish forests (52.5%), followed by lodgepole pine *Pinus contorta* Dougl. (9.7%) (Forest Service, 2012). The most common broadleaf species are willow *Salix* sp. and hazel *Corylus avellana* (in other short-lived species broadleaves group) which represent 7.3% of forests. Forests are mostly found at elevations below 300 m and they are distributed across mineral soils (56%) and on peats (44%) (Forest Service, 2012). The average age of trees in stock is approximately 20 years, although private forests average age is usually lower. The oldest forest stands consists principally of oak *Quercus* sp., beech *Fagus sylvatica*, birch *Betula* sp, and scots pine *Pinus sylvestris* L. (Forest Service, 2012).

Forest Service (2012) observed that 86% of trees show normal growth and vitality. The average tree basal area is 25 m^{-2} ha^{-1}. Cummins *et al.* (2011) monitored different sites in Ireland and they found that forests are in good health, air quality was good and high values of productivity for managed spruce stands.

2.2.3 Forest management

In Ireland the majority of forests are non-native even-aged conifer monoculture plantations managed primarily under the clearfell system (Ní Dhubháin, 2010). Most Sitka spruce forests have a minimum Yield Class (a productivity index based on top height and stand age) of Sitka spruce of 14 m^3 $year^{-1}$ (Department of Agriculture Food and the Marine, 2014) and they are managed under a clearfell system on a rotation of 40 to 60 years (Mason and Perks, 2011). In terms of the area of thinning, around two thirds (61.7%) of forests have not yet reached the age of thinning and 23.1% of forests are categorised as "no thin". Only 15.2% of forests have been thinned or re-spaced at least once (Forest Service, 2012).

Four harvesting methods can be applied in Irish forests: whole-tree harvesting (WTH), stem-only harvesting (SOH), integrated method and roundwood harvesting, being WTH and STH the most common (Serup *et al.*, 2005).

1. Whole-tree harvesting (WTH): trees are felled and above-ground biomass is removed, leaving the site completely clear. Trees can be left to dry on the forest, and perhaps chipped. The machinery used to fell the trees is usually a chainsaw or a feller-buncher.

2. Stem-only harvesting (SOH) (Conventional harvesting): merchantable stem wood is removed and branches, needles and non-merchantable stems remain on site. The harvester fell the trees and creates brash roads from the limbs.
3. Integrated method: the valuable small sawlog and stake are harvested and anything else is cut. It is usually applicable where thinning is delayed and in areas where pulpwood has low price.

2.3 Forest biomass

Forest biomass for energy purposes includes primary residues derived from first thinning or final felling of wood crops, but also secondary residues from wood industry, construction, packing processes and untreated recycled wood (Röser, 2008). This source has several advantages over agricultural biomass (McCarthy, 1979). Firstly, they grow on poor or infertile soils and the fertilizers applied to the land are less than on an agricultural crop. Secondly, woody crops can be harvested throughout the year and the deterioration in storage is slow. Furthermore, they can also have other purposes besides energy.

Forest biomass is an important variable regarding climate change (Global Terrestrial Observing System, 2009). It is a large global store of carbon (Lunnan *et al.*, 2008; Global Terrestrial Observing System, 2009; Hendrick and Black, 2009) (Fig 2.2) and also reduces global GHGs emissions as it substitutes fossil fuels (Global Terrestrial Observing System, 2009; Hendrick and Black, 2009; EIA, 2012). GHGs are emitted when the biomass is extracted and combusted to create energy (EIA, 2012; IPCC, 2014) but it is sustainable because the source is part of the active carbon cycle (Irish Forestry and Forest Products Association, 2013). The extraction of biomass can impact the environment (Lunnan *et al.*, 2008; Global Terrestrial Observing System, 2009) as it can cause degradation of the soil or damage the biodiversity of the ecosystem.

It is shown in different studies that the amount of biomass in each forest is different depending on several factors such a stand densities (Pearson *et al.*, 1984; Tobin and Nieuwenhuis, 2007), site conditions (Cole and Rapp, 1981; Pearson *et al.*, 1984; Tobin and Nieuwenhuis, 2007), stand age (Pearson *et al.*, 1984), yield class and management

(Tobin and Nieuwenhuis, 2007). As the source of information for this study is limited, the estimation of biomass accumulation of the studied stands is a sampled approximation. For instance, Ní Dhubháin and O'Leary (2002) reported that lodgepole pine stands are less productive when they are in sites with bad drainage, low light exposure and unthinned. Rodgers *et al.* (2010) observed good tree growth in blanket peat despite having high tree density. Under poor conditions, lodgepole pine growth has been shown to be greater than the Sitka spruce (Bothwell *et al.*, 2001).

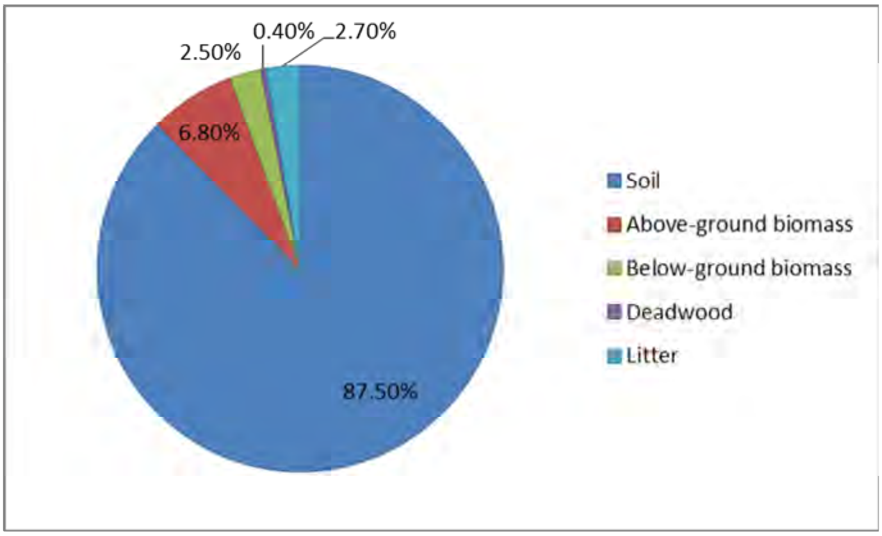

Fig 2. 2: Proportion of carbon stored (%) in different pools in forests (Hendrick and Black, 2009)

Forest biomass estimation is a component of quantifying nutrient content in a forest ecosystem (Ericsson 1994). Several techniques used to predict the amounts of biomass in forests are listed below (Global Terrestrial Observing System, 2009):

- In situ destructive direct biomass measurement. It consists of harvesting one or more trees, drying them and weighing the biomass. This method is the most accurate but the cost is high.
- In situ non-destructive biomass estimations. This method involves the stem diameter at breast height (DBH) and height (H) of the trees. Through these variables and allometry equations or conversation factors and biomass expansion factor (BEF), it is possible to estimate the amount of biomass (Tobin and Nieuwenhuis, 2007). Allometry equations are functions that are used to

extrapolate sampled data to a larger area and to derive biomass from other variables. Conversion factors and biomass expansion factor is a ratio that converts the stem volume to the total biomass. It is also possible to calculate the total biomass through biomass expansion factor (BEF) and density of the wood.

- Inference from remote sensing. This technique measures the total of microwave, optical or infrared radiation that is reflected or scattered by the vegetation. Biomass can be measured via a direct or indirect relationship such as leaf area index (LAI).
- Models: they are general empirical models used to extrapolate biomass estimates over time and space. The dataset is generally limited and comes from the same sample plots.

Ericsson (1994) estimated an average forest biomass production in a natural stand between 150 and 325 t ha^{-1}. He also explained that edaphic and climatic conditions' influence on the productivity of the stands. For instance, cold and warm temperate species did not surpass 10 tons ha^{-1} $year^{-1}$ under natural conditions. Forest biomass is usually separated in four parts for its study: above-ground biomass, below-ground biomass, litter layer and deadwood.

2.3.1 Above-ground biomass

According to Penman *et al.* (2003), above-ground biomass is all living biomass located above the soil, including stem, bark, branches and needles. It can be calculated by biomass expansion factors or biomass functions and the independent variables DBH and H are usually needed (Green *et al.*, 2007).

Needles and leaves are the components with the largest quantity of nutrients in a tree (Ranger *et al.*, 2003; Tobin *et al.*, 2006; Kofman *et al.*, 2007; Zhang *et al.*, 2014). This relationship is predicted from the existing linear relationship between above-ground dry matter production and intercepted light (Ericsson, 1994). Irish forests usually have smaller crowns than American forest because they are denser and thus light cannot penetrate (De Kovel *et al.*, 2000; Black *et al.*, 2004).

2.3.2 Below-ground biomass

Below-ground biomass is all living biomass of live roots and stump (Penman *et al.*, 2003). The root system, in general, constitutes about 20% of the total biomass of a tree (Ericsson, 1994; Olajuyigbe *et al.*, 2012a). This system tends to be smaller when it is subject to low light conditions and greater in water excess (Ericsson, 1994). In particular, fine roots are important in water and mineral nutrient uptake and therefore in the growth process of a tree (Butler *et al.*, 2010; Makita *et al.*, 2011). The study of this part of the biomass is limited (Butler *et al.*, 2010).

The estimation of below-ground biomass has a high variability due to the methodological difficulties related to studying root system components (Helmisaari *et al.*, 2007). An alternative to calculate below-ground biomass is using the above-ground biomass stock and a biomass function (Green *et al.*, 2007).

2.3.3 Litter layer

According to Penman *et al.* (2003), litter includes all dead biomass with a small diameter (usually less than 10 centimetres). This includes litter, fumic and humic layers. Live fine roots which cannot be distinguished as roots for being too small are also included. The seasonal litterfall patterns in forest ecosystem worldwide varies in the range of 3-11 Mg ha^{-1} $year^{-1}$ (Zhang *et al.*, 2014). Litter is greater in spring or winter for tropical forests, in autumn for temperate deciduous broadleaved and boreal evergreen needle-leaved forests and various seasons for broadleaved and needle-leaved evergreen forests (Zhang *et al.*, 2014). Environmental variables can change the quantity of litterfall (Zhang *et al.*, 2014). Tobin *et al.* (2006) explain that the exact estimation of litter input is obtained through knowing the needle retention time and the annual turnover rate, generally before and after canopy closure.

2.3.4 Deadwood

Deadwood consists of all non-living woody biomass above 10 cm. It includes any wood lying on the surface, standing dead trees, dead windthrows, dead roots and dead stumps (Penman *et al.*, 2003; Olajuyigbe *et al.*, 2011). Deadwood provides many advantages for the biodiversity of a forest (Harmon *et al.*, 1986; Tobin *et al.*, 2007). It forms major structural features with many crucial ecological functions as habitats for organisms, in energy flow and nutrient cycling, and by influencing soil and sediment transport and storage (Harmon *et al.*, 1986; Tobin *et al.*, 2007).

On the other hand, the decomposition of roots is an important process in the loss of carbon (C) and the mineralization of nitrogen (N) in forest ecosystems, hence it is important quantify the C stored in dead roots, their nutrients and the decomposition rates (Olajuyigbe *et al.*, 2012a). Nevertheless, Laiho and Prescott (2004) investigated northern coniferous forest and they found little evidence that Coarse Wood Debris (CWD), which is a component of deadwood, plays an important role in nutrient cycling due to its low nutrient concentration and slow rate of decomposition. Even so, after a review, they considered that the influence of CWD in the amount of nutrients can vary among forest types.

2.3.5 Forestry logging residues and bundling system

Forestry logging residues (LR) referred to as brash in the UK and Ireland, are thinned or clearfell forestry residues composed of branches, crowns, tree tops with a DBH smaller than 7 cm, undersized or dead trees and defective stem sections (Hakkila, 1989). Mockler (2013) found that the percentage of residual material in a stand of lodgepole pine in Ireland represents 53% and a stand of Sitka spruce 44% of the above-ground biomass.

Forestry logging residues are a potential source of biomass for fuel but their low density ratio and high volume makes their exploitation inefficient (Forbes *et al.*, 2010). To solve this problem, a bundling system has been applied across many countries and more recently in Ireland (Coates *et al.*, 2014). This system consists of gathering forest residues and compacting them into cylindrical bales which are stored prior to chipping (Forbes *et* *al.*, 2010; Coates *et al.*, 2014). This tactic ensures that moisture content decreases below 30% under suitable weather conditions (Forbes *et al.*, 2010). Forbes *et al.* (2014) demonstrated that a residue bundling supply chain in Northern Ireland is feasible when transporting distances are short.

Other research has been done in order to make the most out of this new market. For instance, moisture content in fresh wood is usually around 50%. This percentage must be reduced at least reduced to 25% in order to be able to use it as a fuel. Forbes *et al.* (2014) discovered that the moisture content in brash reduced from 61% to 28.96% after having remained in the forest as bundles for two years. (Kent and Coates, 2011) demonstrated that green bundles dried better during storage than brown bundles. They also found that cover on top of the bundle stacks improved drying significantly in green bundles, but not in brown bundles. Coates *et al.* (2014) found that residues were most available for harvest and with highest energy content when they were not used as a brash mat prior to bundling, and consequently were least available, with lowest energy content, when used as a brash mat and driven on. As a downside, the use of the bundling system can affect the emergence of pests. There may be an increased risk of pests but also can reduce them as pest have less accessibility in large amount of stacked wood (Clarke, 2012).

2.4 Tree species of the study

2.4.1 Sitka spruce (*Picea sitchensis* (Bong. Carr)

2.4.1.1 Distribution

Sitka spruce (*Picea sitchensis* (Bong.) Carr) belongs to the Pinaceae family and it is a native of North America, specifically from a narrow belt of the Pacific North West coast (Joyce and O'Carroll, 2002). This species was introduced to Europe in the XIX century. Ireland was one of the first countries which established this species, in 1835. It has been proven to be superior to the common European (Norway) spruce (Joyce and O'Carroll, 2002). This species requires both a moist climate and a moist soil, therefore Ireland is appropriate. In 1909, the first Sitka spruce monocultures were established (Farrelly *et al.*, 2009) and since that time, Sitka spruce has become a dominant species in Irish forests (Knaggs, 1977; Tobin and Nieuwenhuis, 2007; Mason and Perks, 2011; Forest Service, 2012). It can be found in the forest planted as a single species or mixed with other conifers such as Norway spruce and Douglas fir *Pseudotsuga menziesii* (Green *et al.*, 2007).

2.4.1.2 Characteristics

Sitka spruce plantations are usually uniform with defined growth rates and rotations (Joyce and O'Carroll, 2002). The production of this species varies from 4 to 34 $m^3 ha^{-1} a^{-1}$ (Farrelly *et al.*, 2009). The wide ranging sites suited to growing this species vary from very fertile mineral soils to impoverished peaty and podzolic conditions. Farrelly *et al.* (2009) observed in their study that Sitka spruce stands located on grey-brown podzolic soils had the highest Yield Class (27.6 m^3 ha^{-1} $year^{-1}$) while stands on blanket peats are less productive with a Yield Class of 14.1 m^3 ha^{-1} $year^{-1}$ (Farrelly *et al.*, 2009) or less (Farell and Boyle, 1990). In relation to altitude, Sitka spruce are viable at elevations of up to 450 meters, although the highest productivity is below 300 m (Farrelly *et al.*, 2009).

Sitka spruce will not grow well in the shade or as an under-storey as it requires light to develop. It is also not suited to sites where late spring frosts are prevalent (Joyce and O'Carroll, 2002; Farrelly *et al.*, 2009), or on sites underlain by calcareous marl. In Ireland, these plantations are located predominately below the 450 m contour and most commonly planted on mountain and hill sites and on peats (Farrelly *et al.*, 2009).

Despite being a species that is well adapted to Irish climate conditions, there are many hazards to its health and survival: climatic factors, fauna, disease and fire. The most hazardous factor is the wind. Ireland is a windy country and Sitka spruce is considered, at least in Ireland and Britain, a shallow-rooting species (Joyce and O'Carroll, 2002). Wind damage in Sitka spruce generally causes uprooting stem breakage.

2.4.1.3 Management

The management of Sitka spruce is different around Ireland. It depends on the specific site conditions where the stands are located. Firstly, it is necessary to prepare the soil before planting Sitka spruce. Sitka spruce is usually established on impermeable soils and therefore it is essential to create good drainage. Furthermore, an elevated planting position is also beneficial. Mounding and ripping are the most common types of cultivation and trees are planted at 2 m × 2 m spacing (Joyce and O'Carroll, 2002). This species accepts different plantation techniques as long as it is planted in the appropriate season, which is from October to March, and for cold-stored plants until May (Joyce and O'Carroll, 2002).

Forest thinning is an important silvicultural procedure with effects in the soil by disturbing microclimatic conditions, nutrient budgets, root density, microbial communities and organic matter turnover (Olajuyigbe *et al.*, 2012b). Furthermore, Skovsgaard (2009) also demonstrated an effect on the volume growth in response to thinning in even-aged Sitka spruce stands. Thinning is used depending on local conditions and particularly with the risk of windthrow. The first thinning occurs when Sitka spruce achieve a height from 9 to 12 metres (after canopy closure). Sitka spruce is usually between 15 and 22 years of age when this occurs (Joyce and O'Carroll, 2002). From then on, thinning should be occurring every three years for high yield classes and every six years for low yield classes. Final felling occurs when Sitka spruce is between 35 and 45 years of age (Joyce and O'Carroll, 2002). Pruning is also recommended at an early age.

2.4.1.4 Benefits and harms

Benefits of Sitka spruce plantations are several. On the one hand, Sitka spruce is the most widely planted tree species in Ireland (Tobin and Nieuwenhuis, 2007). Sitka spruce timber is light in weight, maintains good strength and has a pale colour. Sawn timber is used for the construction market (structural timber, in roofing, flooring and studding). Pallets are made using Sitka spruce wood of smaller dimensions or lower quality.

Transmission poles, fencing stakes, particleboard and oriented strandboard (OSB) are also made from Sitka spruce trees (Joyce and O'Carroll, 2002). Sitka spruce stands also play an important role in reducing atmospheric carbon dioxide over the short to long term, as over 50% of Irish forest is occupied by stands of this species (Black *et al.*, 2009). The presence of Sitka spruce plantations also has certain disadvantages. For instance, large scale afforestation of this species affects landscape quality (Joyce and O'Carroll, 2002). Another problem is the possible emergence of diseases because of the exotic monocultures of Sitka spruce (Joyce and O'Carroll, 2002).

2.4.2 Lodgepole pine (*Pinus contota* var. *latifolia*)

2.4.2.1 Distribution

Lodgepole pine (*Pinus contota Dougl.* Var. *latifolia*) is a two-needled pine of the Pinaceae family (Burns and Honkala, 1990). The distribution of this species is very large as it covers very wide ecological amplitude, both climatic and edaphic (Satterlund, 1973; O'Driscoll, 1980; Burns and Honkala, 1990; Forest Service, 2000). It is native to north west America where it is located in three large areas: along the coast from Alaska to California (*Pinus contorta* var. *contorta*); Intermountain region and Rocky Mountain systems (*Pinus contorta* var. *latifolia*); and on the Cascade and Sierra Nevada Mountains in Oregon and California (*Pinus contorta* var. *Murrayana*) (Pearson *et al.*, 1984; Burns and Honkala, 1990).

2.4.2.2 Characteristics

Lodgepole pine has several provenances but in Ireland there are two common provenances: south coastal and north coastal. South coastal provenance usually has 10-20% lower yield class but trees have better form than north coastal (Forest Service, 2000). While pure crops of north coastal provenance are routinely planted at a density of

2,500 stems ha^{-1} (as other conifers), south coastal provenance can contain 3,300 stems ha^{-1} (Forest Service, 2000).

This species occurs in mixed and especially in pure or nearly pure stands (Forest Service, 2000) and grows under a wide variety of ecological conditions (Evertsen, 1988). It can develop on poor and infertile soils which are unfavourable for the growth of other species. Sites suitable for this species in Ireland are blanket peats, midlands peats, Old Red Sandstone Podsols and Cutaway bog (Forest Service, 2000). Blanket peat areas were the most afforested by this species. Stands on this type of soil are routinely planted at a density of 2800 stems ha^{-1} (Rodgers *et al.*, 2010) compared with other countries that barely reach 1000 stems ha^{-1} (Asam *et al.*, 2014). The volume of the tree stand at harvesting stage is also greater than other countries. Furthermore, it has been demonstrated that fertilization, particularly nitrogen, can lead to improved growth of the stand (Burns and Honkala, 1990). According to the orography, lodgepole pine grows in many types of land, but the best places are on gentle slopes and in basins (Burns and Honkala, 1990). Stands of this species are also resistant to frost injury where other species are not (O'Driscoll, 1980; Burns and Honkala, 1990).

Despite being a species which has adapted well in Ireland, lodgepole pine is affected by disease and insects pests (O'Carroll and Joyce, 2004). Furthermore, the quality and quantity of timber is not as good as expected (Cochran and Dahms, 2000). There are many and varied causes of basal sweep in lodgepole pine trees (Evertsen, 1988). The intensity and extent of branching and knots in lodgepole pine stem is also a problem (Evertsen, 1988).

2.4.2.3 Management

Stands of lodgepole pine are straightforward to establish and respond well to treatment with rapid early growth (Lotan *et al.*, 1985). When the stand is mature enough, the most common silvicultural method used is clearcutting (Lotan *et al.*, 1985).

Ní Dhubháin and O'Leary (2002) found four factors that affect the natural regeneration of lodgepole pine: drainage, thinning, exposure and the percentage of the clearfelled crop comprising lodgepole pine. Sites with good drainage, high exposure, thinned and with a large percentage of the clearfelled crop comprising lodgepole pine were the best sites for natural regeneration. Thinning, apart from reducing forest residue, achieves a lower mortality of lodgepole pine stands and promotes growth of good merchantable-sized trees (Cochran and Dahms, 2000).

2.4.1.4 Benefits

Lodgepole pine trees have a multiple uses i.e. values for watershed management, wildlife habitat, forage and recreational purposes (lodgepole pine is common used as a Christmas tree), all of which are important (Lotan *et al.*, 1985). Furthermore, lodgepole pine final crop timber can be of a quality and size to meet criterion for carpentry and construction timber (Evertsen, 1988). Panelling is another use of this species timber, which needs to be processed quickly in order to avoid degradation (O'Driscoll, 1980). In Ireland, it is used mainly for the manufacture of Oriented Strand Board (OSB) and Medium Density Fibreboard (MDF) (Evertsen, 1988).

2.5 Nutrients

2.5.1 Nutrients fluxes to and from forest ecosystems

The nutrients in the biosphere move from one compartment to another, with continuous transformations between organic and inorganic forms. In ecosystems, there is a phenomenon known nutrient cycling which means elements are exchanged between the living and non-living components of the ecosystem (Foster and Bhatti, 2006). The processes in forest nutrient cycling are (Fig 2.3): nutrient inputs to the ecosystem (chemical weathering of rocks, biological fixation of atmospheric nitrogen, deposition of nutrients from the atmosphere in rain, wind-blown particles or gases and fertilization in managed forest ecosystems), a nutrient flux between soil and plants (foliar and root absorption, retranslocation, through fall, decomposition and litterfall and losses to herbivory), and ecosystem nutrient outputs (leaching, runoff, emission of gases and aerosols, biotic transfers and resource exploitation) (Chapin *et al.*, 2002; Valladares, 2004; Foster and Bhatti, 2006).

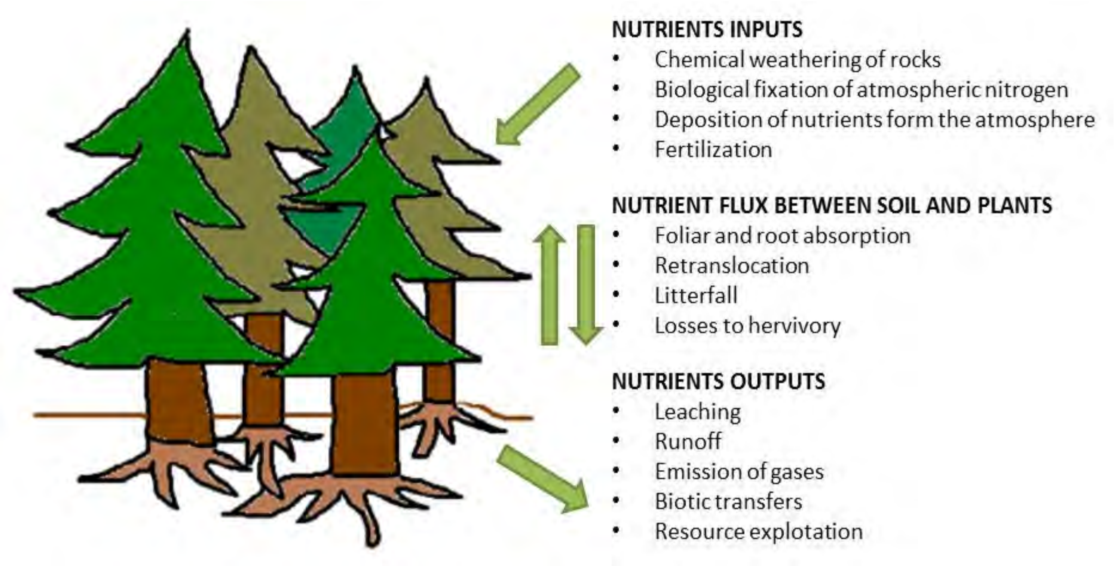

Fig 2. 3: Processes in nutrient cycling

Nutrient cycle is a partly closed system, as many nutrients are sequestered in different compartments and recycled internally (Chapin *et al.*, 2002; Valladares, 2004; Röser, 2008). Nutrients in biomass are an important pool of the nutrients in the ecosystem. Although they are not accessible for nutrient uptake, they can be recycled for instance through decomposition of leaves, fine roots, branches and deadwood. (Röser, 2008).

The forest nutrient cycle strongly influences the productivity and continuity of the forest (Johnson *et al.*, 1982). In order to understand the dynamics of forest ecosystems and promote sustainable management, it is necessary to study the forest nutrient cycle (Cole and Rapp, 1981; Johnson *et al.*, 1982). Knowledge of the inherent fertility of different soil types will inform species selection along with site specific (topography, etc.) and climatic factors. For instance, if it is known that a site is low in nitrogen availability, the best choice of species to plant may be nitrogen-fixing species as they can provide their own nitrogen (Johnson *et al.*, 1982). Some nutrient exchanges that should be considered are nutrient uptake rates, rates of nutrient turnover, loss of nutrients by leaching and addition by weathering fixation, and atmospheric deposition (Cole and Rapp, 1981).

2.5.2 Essential mineral elements in a tree

Trees require the same basic nutrients for living regardless of whether they are coniferous or deciduous trees (Cole and Rapp, 1981; Savill and Evans, 1986; Ericsson, 1994; Foster and Bhatti, 2006). These nutrients are also called “essential mineral elements” and their function is unique and irreplaceable in the plant’s life cycle, as they are involved directly in the plant metabolism (Arnon and Stout, 1939).

There are about 20 essential elements required for plant health. Three of them, carbon, hydrogen, and oxygen (C, H, and O) constitute 80-90% of the dry weight of a plant and they are supplied to the plant by water and carbon dioxide. The remaining nutrients comprise between 10% and 20% of the dry weight and they are called mineral elements. Most of these nutrients come from the soil or recycling the nutrients previously used by trees, especially when the stand approaches canopy closure (Ericsson, 1994). They can be separated in two groups (Mengel *et al.*, 2001; Na, 2007)

- Macronutrients: nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg). The first three elements are required in abundance, whilst the other three are required much less but still needed in large quantities.
- Micronutrients: zinc (Zn), iron (Fe), manganese (Mn), boron (B), chlorine (Cl), copper (Cu), molybdenum (Mo), cobalt (Co), vanadium (V), sodium (Na), and silicon (Si). Their concentrations in plants are usually below the 100 parts per million (ppm) levels.

2.5.2.1 Macronutrients

Nitrogen (N)

Nitrogen (N) is an essential component for organisms and it also constitutes the 78% of the terrestrial atmosphere (Vitousek *et al.*, 1997; Maathuis, 2009). However, for two main reasons, it is also the most limiting nutrient in terrestrial ecosystems (Mann *et al.*, 1988; Fenn *et al.*, 1998; Luiro *et al.*, 2009; Johnson and Turner, 2014; Merilä *et al.*, 2014). Firstly, while other major nutrients (P, S, K, Ca, Mg, Mn) are derived from soil minerals and can accumulate to a significant degree on soil exchange complexes, nitrogen comes from the atmosphere as an inert gas that must be fixed in usable form, and rarely accumulates to a significant degree on soil exchange complexes. Secondly, it is necessary that microorganisms decompose the organic nitrogen and create mineral nitrogen through two phases, ammonification and nitrification (Fenn *et al.*, 1998; Johnson and Turner, 2014). Both free living and symbiotic microorganisms are able to fix atmospheric N_2 in the form of NH_4^+ that can be directly taken up by plants or transformed into NO_3^- (Maathuis, 2009). Soils are the largest storage pool for N, although vegetation is also important (Fenn *et al.*, 1998).

Nitrogen used to be the main limiting nutrient and therefore has been well researched over time (Jonard *et al.*, 2015) as it is the most strongly correlated nutrient to the annual growth of conifer forests (Cole and Rapp, 1981). De Kovel *et al.* (2000) suggest that the N content in a temperate forest is usually less than 10,000 kg ha^{-1}. The requirement of nitrogen for an optimal growth varies between 2 and 5% of the plant dry weight (Marschner, 1995) depending on species, climate, region, etc. For instance, this element is 50% less required on coniferous forest than on deciduous forest having the same level of production, due to leaf retention (Cole and Rapp, 1981). Forests in southern latitudes seem to need more nitrogen than the forests in northern latitudes (Cole and Rapp, 1981). Johnson *et al.* (1982) also hypothesizes that mature Douglas-fir forests are more efficient in nitrogen utilization than young forests. A study carried out by Bothwell *et al.* (2001) showed that N concentration in needles of lodgepole pine is higher than in Sitka spruce on 11 year old trees.

Deficiency of N can cause growth reduction in trees (Jacobson *et al.*, 2000; Na, 2007). In some cases the deficiency of nitrogen has been addressed by fertilizer application to increase biomass production. However, if fertilizers are not applied properly, an excess available N will contribute to modify chemical composition of the atmosphere, hydrologic system, soil and biota (Vitousek *et al.*, 1997; Fenn *et al.*, 1998; Fenn *et al.*, 2003). Atmospheric N deposition and the CO_2 have increased during the last decades (Aber *et al.*, 2003). This has led to N limitation being reduced and a consequent increase in forestry production (Aber *et al.*, 1989; Magnani *et al.*, 2007; Jonard *et al.*, 2015). This increment in forest productivity means that trees have higher demands of other nutrients (Jonard *et al.*, 2015).

Phosphorus (P)

Phosphorus (P) is essential to life and is non-substitutable in biological systems (Pierrou, 1976; Filippelli, 2008). The cycling of phosphorus is also an important Earth system process (Pierrou, 1976; Filippelli, 2008). Phosphorus is a constituent of deoxyribonucleic (DNA), ribonucleicacid (RNA), the energy carrying molecule adenosine triphosphate (ATP), and its di- and monophosphate precursors (ADP and AMP) (Pierrou, 1976).

Plants only consume soluble inorganic phosphorus such as orthophosphate ions PO_4^{3-} and they are often present at very low concentrations, especially in managed forests (Pierrou, 1976; Mann *et al.*, 1988). More than 90% of soil P is normally fixed by iron and aluminium and sometimes calcium in the soil, and becomes non-accessible to plants (Pierrou, 1976; Maathuis, 2009). In addition, phosphorus has no stable atmospheric gas phases as do nitrogen and carbon. Therefore, ecosystems have to depend on aqueous transfer of this nutrient (Filippelli, 2008; Maathuis, 2009)

Phosphorus should be present in a plant in the range of 0.3-0.5% of the plant dry matter during the vegetative state of growth for any optimal growth (Marschner, 1995). In order to get this percentage, over 90% of plant species form mycorrhizal symbioses that improve acquisition of this scarce mineral (Maathuis, 2009). Humans have also tried to reach the required percentage of phosphorus using fertilizers. However, this short term solution together with deforestation and human and industrial waste cause the destruction of P cycle (Filippelli, 2008). P foliar has decreased in the last century, especially for sites were the P was already low, so P could be easily become deficient in the future (Jonard *et al.*, 2015). High N deposition could reduce twice the amount of P in needles (Jonard *et al.*, 2015).

Sulphur (S)

Sulphur (S) is a macronutrient element that abounds in the earth. It forms part of various important biological compounds including aminoacids (Cysteine and Methionine), the redox-buffering tripeptide glutathione, the co-enzyme S-adenosyl methionine (SAM), sulpholipids and many secondary metabolites (Maathuis, 2009).

This element is also one of the essential nutrients for the growth of plants. It should be between 0.1 and 0.5% of the dry weight of plants, almost the same quantity as phosphorus (Baird and Service, 1991; Marschner, 1995). Although soils contain inorganic and organic forms of sulphur, it is only accessible to plants as soluble sulphate (SO_4^{2-}) which is taken up by roots (Eriksen *et al.*, 1998; Hell and Rennenberg, 1998; Tandon *et al.*, 2007; Maathuis, 2009). Sandy soils can be more predisposed to S deficiency than high clay-content soils. Although plants get S from the soil, they can also obtain this element through the atmosphere where SO_2 and H_2S occurs (Maathuis, 2009).

Sulphur is usually available enough to satisfy plant growth (Tandon *et al.*, 2007). If S is limited or deficient, this reduces the productivity and the quality of stands. Jonard *et al.* (2015) observed in their investigation that S concentration in needles decreased more intensely over the last decades in stands with high S.

Potassium (K)

Potassium (K) is the seventh most abundant element in the world. It is distributed throughout the Earth (plants, animals, rocks, soils, minerals, rivers, oceans and lakes). The earth’s crust contains around 2.6% K (Maathuis, 2009).

Potassium is an essential macronutrient for plant and animal life. It is the third most required nutrient by plants (between 2-5% of the plant dry weight) and plays a vital role in their nutrition (Marschner, 1995). This element is not part of the chemical structure of a plant, but potassium moves around encouraging growth: it increases root growth, strengthens stems, activates many enzyme systems, maintains turgor, helps in photosynthesis and food formation, transport sugar and starch, aids in protein formation, control diseases, and builds cellulose (International Plant Nutrition Institute, 1998; Wang *et al.*, 2013). Tripler *et al.* (2006) did a review of studies examining tree growth under K manipulations/fertilizations and 69% of studies showed a positive response to increases in K availability in forest soils. However, this response could sometimes be regarded as a condition of deficiency. Tripler *et al.* (2006) also found that concentrations of K usually decreased during growing seasons in streams draining forested areas in the Temperate Zones.

It is unusual for plants to experience K deficiency because there is sufficient supply in soils or fertilizers are applied (Maathuis, 2009). Nevertheless, deficiency of K could cause a reduction of plant growth and the quality of the plant. Potassium is the second element most strongly correlated to biomass production in conifer forests (Cole and Rapp, 1981), but its biotic cycling has however been less studied than other nutrient cycles (Cole and Rapp, 1981; Tripler *et al.* (2006)).

Calcium (Ca)

Calcium (Ca) is a vital nutrient and is very abundant in the lithosphere (White and Broadley, 2003). The mean Ca concentration of the earth's crust is about 36.4 g/kg, which is higher than other plant nutrients such as K (25.8 g/kg) and Mg (20.7 g/kg) (Mengel *et al.*, 2001).

Although Ca is often undervalued, it makes an important role in the physiology of the plants. It especially contributes in the structure of the cell wall and membranes (Cole and Rapp, 1981; Marschner, 1995; Easterwood, 2002; White and Broadley, 2003). Adequate Ca concentrations in plant tissue vary between 1-50 mg Ca/g of dry weight depending on the growing conditions, plant species and plant organ (Marschner, 1995). Mengel *et al.* (2001) state that higher plants generally contain about 5-30 mg Ca/g dry matter. Johnson *et al.* (1982) observed that old stands contain more Ca in the foliage than young stands and argue that it occurs because old stands retain needles for more time, thus Ca has more time to accumulate in the needles. Ca is usually taken up in excess by plants on sites where N is growth limiting (Helmisaari *et al.*, 2014).

Calcium deficiency is rare in nature but may occur on soils with low base saturation and/or high levels of acid deposition. This deficiency may appear in a whole plant or in a particular organ of a plant and one effect that could cause is the destabilization of the permeability of the membranes, leading to a dry zone of necrosis in tissues (Simon, 1978). The study of Cole and Rapp (1981) shows that the correlation between Ca and forest productivity is low. This could be attributed to several reasons such as large variation in soil Ca levels between sites or lack of Ca deficiency in the sites studied.

Magnesium (Mg)

Magnesium (Mg) is an indispensable element for the growth of plants. It is located in the centre of the chlorophyll molecule (especially in needles) and plays an important role in cholophyll synthesis (Mitchell, 2000; Maathuis, 2009). It has also other roles in physiological processes such as taking part in the synthesis of ribonucleic acid (RNA) or being a co-factor in many enzyme reactions, particularly those involving adenosine triphosphate (ATP) (Mitchell, 2000).

Soils usually contain enough Mg for plants. The quantity of this element varies between 0.5 g/kg for sandy soils and 5 g/kg for clay soils (Mengel *et al.*, 2001; Maathuis, 2009). This element has not been widely studied because it has little influence on forest productivity (Cole and Rapp, 1981).

2.5.3 Nutrient concentrations of the trees

Most of the percentage of macronutrients in forest ecosystems is present in the trees (Ericsson, 1994; Paré *et al.*, 2013). The table below shows the range of nutrient concentrations in plants and the suitable concentration.

Table 2. 1: Nutrient Element Adequate Concentrations and Ranges in plants in mg g^{-1} of dry weight (Na, 2007)

	Nutrient concentration (mg g^{-1})	
Element	*Range of Concentrations*	*Adequate concentration*
Nitrogen	0.5-6	1.5
Phosphorus	0.15-0.50	0.2
Potassium	0.80-8	1
Calcium	0.10-6	0.5
Magnesium	0.05-1	0.2
Sulfur	0.10-1.50	0.1

There is a relationship between tree species and nutrient concentration (explained in a following subsection). Different investigators have suggested values to identify the optimal nutrient concentration and a deficiency nutrient concentration for each species through nutrient concentration in needles. Renou-Wilson and Farrell (2007) recompiled information of different investigators (Leaf, 1973; Everard, 1979; Binns *et al.*, 1980; Taylor, 1991; Savill, 1997) modified it and proposed values for Sitka spruce. It should be noted that the sites that Renou-Wilson and Farrell (2007) studied was fertilized twice. Carter (1992) proposed values for Lodgepole pine current year needles (Table 2.2).

Table 2. 2: Deficient and optimum foliar nutrient concentrations (mg g^{-1}) for Sitka spruce and lodgepole pine (Carter R., 1992; Renou-Wilson and Farrell, 2007)

	Sitka spruce			Lodgepole pine		
Nutrient	*Deficient*	*Marginal*	*Satisfactory*	*Deficient*	*Marginal*	*Satisfactory*
Ca	<0.5	0.7-1.0	1.0-2.0	<1.5	1.5-2.5	>2.5
Mg	<0.3	0.3-0.7	>0.7	<0.6	0.6-1.0	>1.0
K	3.0-5.0	5.0-7.0	>7.0	<3.5	3.5-5.5	>5.5
P	<1.2	1.2-1.8	>1.8	<0.9	0.9-1.5	>1.5
N	<12.0	12.0-15.0	>15.0	<10.0	10.0-13.5	>13.5
S	<0.9	0.9-1.5	>1.5	-	-	-

2.5.3.1 Review: nutrient concentrations

Several investigators have estimated the nutrient concentration of trees (Table 2.3; Table 2.4; Table 2.5; and Table 2.6).

Table 2. 3: Nutrient concentrations (mg g^{-1} of dry weight) of conifers

				Nutrients (mg g^{-1})					
Species	**Compartment**	**Source**	**Location**	**N**	**P**	**Ca**	**Mg**	**K**	**S**
Conifers	*Needles*	Pare et al. 2014	Canada	12.25	1.49	4.60	1.12	5.93	-
	Branches	Pare et al. 2014	Canada	3.29	0.58	4.49	0.50	1.97	-
	Stembark	Pare et al. 2014	Canada	3.24	0.46	9.25	0.61	1.87	-
	Stemwood	Pare et al. 2014	Canada	0.75	0.07	1.01	0.16	0.61	-
Pines	*Needles*	Asam et al. 2014	Ireland	14.20	-	-	-	-	-
		Jacobsen 2000	Germany	14.46	1.32	4.08	0.87	5.03	-
	Branches	Jacobsen 2000	Germany	3.61	0.34	2.07	0.43	1.67	-
	Stembark	Jacobsen 2000	Germany	3.85	0.46	5.03	0.61	2.08	-
	Stewood	Jacobsen 2000	Germany	0.76	0.05	0.62	0.18	0.42	-
	Coarse Roots	Jacobsen 2000	Germany	1.77	0.21	0.97	0.30	1.08	-
	Fine Roots	Jacobsen 2000	Germany	0.62	7.44	2.83	0.45	1.47	-
Spruce	*Needles*	Asam et al. 2014	Ireland	10.80	-	-	-	-	-
		Jacobsen 2000	Germany	13.36	1.33	6.03	0.79	5.70	-
	Branches	Jacobsen 2000	Germany	5.24	0.65	3.33	0.53	2.39	-
	Bark	Jacobsen 2000	Germany	5.17	0.65	8.17	0.77	2.83	-
	Stem	Jacobsen 2000	Germany	0.83	0.06	0.70	0.11	0.46	-
	Coarse Roots	Jacobsen 2000	Germany	4.14	0.37	1.59	0.30	1.38	-
	Fine Roots	Jacobsen 2000	Germany	7.44	0.62	2.83	0.45	1.47	-
Radiata pine	*Needles*	Webber 1983	New Zeland	1.21	0.18	0.43	0.13	0.92	0.14
	Branches	Webber 1983	New Zeland	0.18	0.03	0.20	0.05	0.26	0.02
	Deadwood	Webber 1983	New Zeland	0.16	0.02	0.21	0.05	0.07	0.02
	Stembark	Webber 1983	New Zeland	0.21	0.02	0.15	0.04	0.28	0.03
	Stewood	Webber 1983	New Zeland	0.04	0.01	0.05	0.02	0.06	0.01
Scots pine	*Needles*	Bringmark 1977	Sweden	11.57	1.18	1.46	0.79	0.05	0.53
	Branches	Bringmark 1977	Sweden	2.70	0.26	1.98	0.40	0.03	0.30
	Stembark	Bringmark 1977	Sweden	3.13	0.33	3.51	0.41	0.05	0.22
	Stewood	Bringmark 1977	Sweden	0.54	0.04	0.54	0.14	0.01	0.10
	Roots	Bringmark 1977	Sweden	1.50	0.29	0.85	0.26	0.05	0.31
Douglas-fir	*Needles*	Jacobsen 2000	Germany	12.44	2.16	7.41	1.28	5.98	-
	Branches	Jacobsen 2000	Germany	2.98	0.43	4.22	0.41	1.65	-
	Stembark	Jacobsen 2000	Germany	3.58	0.66	2.94	0.46	3.83	-
	Stewood	Jacobsen 2000	Germany	0.60	0.06	0.36	0.06	0.43	-

Table 2. 4: Nutrient concentrations (mg g^{-1} of dry weight) of lodgepole pine

Species	Compartment	Source	Location	Nutrients (mg g-1)					
				N	**P**	**Ca**	**Mg**	**K**	**S**
Lodgepole pine	*Needles*	Pearson et al. 1987	Wyoming	8.82	0.85	4.59	1.14	4.34	-
		Carey & O'Carroll 1981	Ireland	-	-	-	-	7.65	-
		Asam et al. 2014	Ireland	14.20	1.17	1.22	1.01	5.89	-
		Will & Youngberg 1979	Oregon	-	1.60	2.18	1.00	8.06	0.70
		Debyle 1980	Montana	1.30	5.50	0.90	-	2.20	11.75
		Alriksson & Eriksson 1998	Sweeden	13.00	1.20	2.30	0.71	4.80	0.00
		Pare et al 2014	Canada	10.70	1.27	0.23	1.08	5.51	-
	Branches	Pearson et al. 1987	Wyoming	4.31	0.40	5.43	1.17	2.24	-
		Kimmins 1974	B.C. Canada	1.47	0.19	1.79	0.13	0.50	-
		Kimmins 1974	B.C. Canada	4.73	0.75	1.72	0.11	0.48	-
		Alriksson & Eriksson 1998	Sweeden	3.80	0.41	2.20	0.53	1.70	-
		Asam et al. 2014	Ireland	3.70	0.27	1.77	0.72	1.24	-
	Needles+ branches	Little & Shainski 1992	Central Oregon	4.20	0.64	-	-	-	0.16
	Stembark	Pearson et al. 1987	Wyoming	2.96	0.53	9.00	0.80	1.34	-
		Little & Shainski 1992	Central Oregon	4.20	0.64	-	-	-	0.16
		Carey & O'Carroll 1981	Ireland	-	-	-	-	1.80	-
		Pare et al. 2014	Canada	2.73	0.49	14.36	1.30	1.71	-
		Kimmins 1974	B.C. Canada	1.94	0.29	5.51	0.75	0.95	-
	Stemwood	Little & Shainski 1992	Central Oregon	0.60	0.08	-	-	-	0.03
		Carey & O'Carroll 1981	Ireland	-	-	-	-	0.60	-
		Alriksson & Eriksson 1998	Sweeden	1.80	0.15	1.00	0.30	0.85	-
		Pare et al 2014	Canada	0.45	0.08	0.84	0.23	0.41	-
		Kimmins 1974	B.C. Canada	0.36	0.04	0.47	0.13	0.51	-
	Roots	Pearson et al. 1987	Wyoming	2.09	0.52	3.34	1.05	1.25	-
		Little & Shainski 1992	Central Oregon	0.70	0.18	-	-	-	0.07
		Alriksson & Eriksson 1998	Sweeden	3.50	0.23	1.20	0.26	1.40	-
		Debyle 1980	Montana	1.00	3.80	1.50	-	1.50	4.20
		Carey & O'Carroll 1981	Ireland	-	-	-	-	1.00	-

Table 2. 5: Nutrient concentrations (mg g^{-1} of dry weight) of Sitka spruce

Species	Compartment	Source	Location	Nutrients (mg g^{-1}) N	P	Ca	Mg	K	S
Sitka spruce	*Needles*	Pare et al. 2014	Canada	9.15	1.69	3.98	0.99	7.60	-
		Vanguelova et al. 2010	UK	13.89	1.29	6.02	1.03	6.32	-
		Beaton 1965	B.C. Canada	-	-	-	0.90	-	-
		Asam 2014	Ireland	10.80	1.10	3.95	1.27	5.90	-
	Branches	Carey & O'Brien 1979	Ireland	10.55	1.22	-	-	4.09	-
		Carey 1980	Ireland	7.40	0.74	-	-	3.56	-
	Dead wood	Carey & O'Brien 1979	Ireland	8.80	0.52	-	-	0.59	-
		Carey 1980	Ireland	4.18	0.18	-	-	0.22	-
	Stembark	Carey & O'Brien 1979	Ireland	8.00	0.74	-	-	3.29	-
		Carey 1980	Ireland	5.42	0.65	-	-	3.46	-
		Miller 1993	UK	5.69	0.75	4.34	0.88	3.08	-
		Freer-Smith & Kennedy 2003	UK	4.75	-	4.24	0.61	2.41	-
	Stemwood	Carey & O'Brien 1979	Ireland	1.60	0.04	-	-	0.59	-
		Carey 1980	Ireland	0.66	0.06	-	-	0.32	-
		Miller 1993	UK	0.27	0.03	0.44	0.07	0.20	-
		Freer-Smith & Kennedy	UK	0.58	-	0.57	0.09	0.48	-
	Roots	Carey & O'Brien 1979	Ireland	6.05	0.38	-	-	2.19	-
		Carey 1980	Ireland	2.69	0.21	-	-	1.58	-

Table 2. 6: Nutrient concentrations (mg g^{-1} of dry weight) of Sitka spruce windthrow

Species	Compartment	Source	Location	Nutrients (mg g^{-1}) N	P	Ca	Mg	K	S
Sitka spruce	*Needles*	Asam 2014	Ireland	14.20	1.17	1.22	1.01	5.89	-
	Barnches DBH < 10 cm	Asam 2014	Ireland	4.70	0.37	2.31	1.06	1.68	-
windthrow	*Barnches DBH > 10 cm*	Asam 2014	Ireland	2.70	0.18	1.22	0.38	0.80	-

The amount of nutrients available and the type of plantation influence the amount of nutrients in a tree. For instance, Ericsson (1994) shows that plantations managed for short rotations demand more nutrients because they cause the highest losses of nutrients from the site at harvest.

Nutrient concentrations of a tree or stands also varies depending on several factors such as age, location, soil composition, tree species and components of the tree (Cole and Rapp, 1981; Savill and Evans, 1986; Ericsson, 1994; Finer *et al.*, 2003; Palviainen and Finér, 2012; Paré *et al.*, 2013). Fertilization and thinning also influence in the nutrient concentrations. Examples will be shown in the following sub-sections.

N and P are strongly correlated and the N:P ratio can detect the nature of nutrient limitation on one of these two elements (Koerselman and Meuleman, 1996). Jonard *et al.* (2015) found that when N was augmented in needles, P, S and K decreased and Mg increased. This could be due to trees growth is greater when there is an extra N deposition and therefore they need more amount of other nutrients (Peñuelas *et al.*, 2013). However, a related investigation carried out by Paré *et al.* (2013) did not find any correlation among nutrients.

2.5.3.2 Influence of tree components on nutrient concentration

A knowledge of the distribution of nutrient concentrations among tree components is important as a basis for understanding the dynamics of systems in the forest (Gargaglionea *et al.*, 2013). Bringmark (1977) studied the proportion of nutrients in different areas of a tree and found that most of the macronutrients were greater aboveground (up to 87%), especially N and Ca. Ericsson (1994) affirmed that leaves are the component of above-ground with more nutrient concentration although the part of the tree with a greater nutrient pool is the fine roots. Palviainen and Finér (2012) observed that nutrient concentration in stems was lower than in the crowns of pine, spruce and birch species. Hellsten *et al.* (2013) proved that nutrient concentration is significantly higher in the bark of the stumps and roots than in the wood from Norway spruce, Scots pine and silver birch *Betula pendula*.

Ericsson (1994) estimated nutrient pool in needles and roots of conifers in conifer stands (Table 2.7). The size of leaves and their longevity and position in the canopy influence the amount of nutrients in a tree. Ingerslev (1999) investigated Norway spruce stands and found that the concentrations of N, P, K and S were higher in current year needles than in older needles, whilst the opposite pattern was observed for the concentration of Mg and Ca. Recently, Jonard *et al.* (2015) have shown that the nutrient concentrations in needles have decreased in the last century, especially P concentration.

Table 2. 7: Nutrient pool (kg ha^{-1}) in conifer stands (Ericsson, 1994)

	Nutrient pool (kg ha^{-1})				
	N	P	K	Mg	Ca
Leaves	15.0-60.0	2.0-30.0	5.0-160.0	1.0-30.0	5.0-160.0
Roots	10.0-120.0	1.0-20.0	1.0-10.0	0.8-10.0	3.0-30.0

In general, the harvest residue components such as leaves, thin branches and roots and bark contain greater nutrient concentration than larger components such as stem (Mann *et al.*, 1988; Ingerslev, 1999; Raulund-Rasmussen *et al.*, 2008; Röser, 2008). Wang *et al.* (1996) demonstrated that sapwood has more nutrient concentration than hardwood.

2.5.3.3 Nutrient concentration according to age of a tree

The study of a chronosequence is a useful tool to rapidly obtain information on age-related changes in ecosystem as the nutrient content seems to be related to age (Black *et al.*, 2009).

De Kovel *et al.* (2000) showed in his study that carbon and nitrogen amounts increase with site age. There was bigger carbon and nitrogen accumulation during forest formation than during herbaceous stage because new woody tissue, which contained low nutrient content, was formed. They also found that older sites had double the amount of nutrients that younger sites had. Turner (1975) followed the patterns of cycling in Douglas fir stands ranging from 9 to 95 years. His analysis showed that the rate of elemental uptake for this species increased through time until the age of 80. Furthermore, his work also demonstrated that the nutrients of understory vegetation of Douglas fir stands decrease when the canopy of the forest begins to close. Johnson *et al.* (1982) also affirm that the maximum annual uptakes of N, Ca and K coincide with maximum development of the crown. Pearson *et al.* (1987) found that nutrient pools increased over the age. Cole and Rapp (1981) and Ranger and Turpault (1999) and Fernandez Moya *et al.* (2013) determined that nutrient pools increased over the age up to maturity and then decreased. Hellsten *et al.* (2013) could not find any correlation between these two variables.

2.5.3.4 Nutrient concentration according to location of a tree: climate and soil

Hellsten *et al.* (2013) demonstrated that nutrient concentrations of Norway spruce and silver birch were higher in the northern part of Sweden and Finland than in the southern region of these countries. However, they could not demonstrate the same in Scots pine. This variation could be due to the location of the plantations as the type of soils and climatic conditions are different between the northern and southern region.

Boreal forests have larger amount of nutrients in the above-ground biomass than tropical forest. Nevertheless, tropical forest floor has larger amount of nutrients than boreal forest floor, as the decomposition rate of the above-ground biomass is minor in cold conditions (Foster and Bhatti, 2006). Piaggesi (2004) affirms that low extreme temperatures significantly decrease the nutrient uptake. Jonard *et al.* (2015) demonstrated that nutrient concentration in needles is decreasing and argues that the drought periods and heat waves observed in Europe might have played an important role on this.

Sites on coarse-textural soils show more variability of nutrients than those on finer textured soils (Piaggesi, 2004; Kurth *et al.*, 2014). Nutrients of the plants also change their capacity to be absorbed by the roots depending on the pH of the soil (Piaggesi, 2004; Valladares, 2004). For instance, trees have difficulties to get nutrients when soils are alkaline as nutrients are transformed in oxides, hydroxides, phosphates and carbonates (insoluble complexes). The redox potential also affects availability of nutrients. Under reducing conditions, the solubility of nutrients for the plants rises (Piaggesi, 2004). Johnson *et al.* (2015) showed that atmospheric deposition is the most important input in Ca, Mg and a large proportion of K in mature Sitka spruce stands. Little and Shainsky (1992) support the suggestion that nutrient concentration is not associated with any site factor or soil variables.

2.5.3.5 Nutrient concentration according tree species

Palviainen and Finér (2012) collected literature data from 34 pine, 26 spruce and 5 birch stands. They also observed that N, K, P and Ca content of total above-ground biomass was higher in spruce than in pine. Paré *et al.* (2013) also reported different nutrient concentration between species in stemwood, foliage, branch and bark.

Augusto *et al.* (2000) found higher nutrient concentration in European beech than in Douglas fir *Pseudotsuga menziesii*, Norway spruce *Picea abies* and Scots pine *Pinus sylvestris* L.. Ericsson (1994) also reviewed information of several authors which studied nutrient concentration in trees. He found many differences between species, especially in mature trees. In conclusion, he affirms that conifers contain in general half the nutrients than the fast-growing deciduous trees. However, a study carried out by Hellsten *et al.* (2013) in Sweden and Finland revealed that nutrient concentrations is higher in birches than in spruces and pines.

Forbes *et al.* (2014) studied the concentration of N, P and K between brash of Sitka spruce and lodgepole pine. They found no significant difference in nutrient content though gross energy content of pine was a little higher than spruce.

2.5.3.5 Nutrient concentration according fertilizers and thinning

Pinno et al. (2012) studied the foliar nutrient concentration in lodgepole pine under different fertilization treatments and thinning. While foliar K, Ca and Mg concentrations did not response to either fertilization or thinning, foliar P and S concentration increased with complete fertilization. Foliar N concentration increased with fertilization, thinning and fertilization + thinning. Smith and McKay (2002) found positive effect in height and basal area growth of Sitka spruce from repeated application of N or NPK.

2.5.4 Nutrient removals in forest biomass harvesting

The harvesting system in a forest's management, together with the factors tree species and tree age, affects in the quantity of nutrient removal of that forest (Augusto *et al.*, 2000; Finer *et al.*, 2003; Clarke, 2012; Palviainen and Finér, 2012). Besides these, Johnson et al. (1982) and De Kovel et al. (2000) also considered important the frequency of harvesting. Carey (1980) affirmed that the removal of Sitka spruce brash might increase removal of nitrogen by 240%, potassium by 180% and phosphate by 330%. Coates *et al.* (2014) found that the nutrient removal is greater when the brash is removed from the site after harvesting than when it is left on site during seven months. For instance, the percentage of N in the brash at the time of harvesting was 0.98 % while it was 0.86 % after seven months remained in the site.

Whole-tree harvesting (WTH), although it has advantages such as getting more biomass to make energy (Proe et al., 2001b; Kofman et al., 2007), presents drawbacks such as negative visual impact (Vítkováa et al., 2013) and causes greater ground-level wind speed, higher temperatures in soils and extreme moisture fluctuations, which affect the microclimate and the quantity of weeds in a site (Proe et al., 2001a). Vanguelova *et al.* (2010) suggest that the WTH system increases acidity, reduces soil base saturation and increases C and N concentration in soils. Kurth *et al.* (2014) did not find any difference in soil C and N between soil under WTH and SOH systems although they also argued that differences may be greater after multiple rotations. Furthermore, WTH system exports a large amount of nutrients from sites which may affect long-term productivity if this removal is greater than the nutrient inputs through deposition and weathering (Palviainen and Finér, 2012). Luiro *et al.* (2009) and Palviainen and Finér (2012) declared that the impact of WTH after thinning can be even more hazardous than if it is done after clear-felling as in this state, crown contains two-thirds of the total amount of nutrients as the recovering stand demands more nutrients to develop the canopy following thinning. - Fahey et al. (1991) studied the evolution of a new plantation after being clearfelled under WTH and SOH system. While there were not significant differences between these two systems the year after the new plantation, they found significantly higher concentrations of N in the SOH than the WTH system. Fahey *et al.* (1991) also determined higher N, P and K concentrations in younger vegetation. Assuming a lineal change in tissue nutrient concentration, Fahey *et al.* (1991) also conclude that the net nutrient accumulation in vegetation is greater through time.

One of the consequences more found by investigators is the reduction in the growth of trees planted in sites previously whole-tree harvesting, especially on fertile soils (Jacobson *et al.*, 2000; Thiffault *et al.*, 2011): Mason et al. (2011) examined the impact of complete residues (brash) and above-ground biomass removal at clearfelling on the subsequent growth and yield of replanted Sitka spruce in England. After 10 years, medium risk sites that had retained brash contained trees that were 4% higher and 2% wider than sites where brash had been removed. A different range, from 9% to 19% was found in poorest sites. The results show that the impacts of brash removal due to WTH are significantly affected by site type and soil fertility and also that it may take nearly a decade before the impacts on such stands are evident. Proe et al. (1996) demonstrated that the diameter at breast height (DBH), the height (H) and the volume growth on second rotation Sitka plantations were 12%, 13% and 32% respectively less than the previous stands. Jacobson et al. (2000) also found a volume reduction of 5% on Scots pine stands and of 6% on Norway spruce *Picea abies* stands. Carey (1980) affirmed that the removal of Sitka spruce brash might raise the harvested biomass production by 20%.

In contrast, sites managed with SOH contain greater height, biomass accumulated and nutrients pools (Proe and Dutch, 1994; Proe *et al.*, 1996). These sites have less weed competition and increased shelter for transplants and nutritional effects because of the harvesting residues (Mann *et al.*, 1988; Proe and Dutch, 1994).

The investigation carried out by Mann *et al.* (1988) found that WTH harvesting removes much greater nutrient content than SOH in both hardwood and conifer stands because twigs and branches contain higher nutrient concentrations than stems. Investigations in Finland, Norway and Sweden also revealed that WTH increases the removal of nutrients by two or three times compared to SOH (Luiro *et al.*, 2009; Helmisaari *et al.*, 2014). Thiffault *et al.* (2011) found that WTH reduces C concentration between 44% and 92% compared with SOH with potential repercussions on global C cycling. Fertilisation associated with thinning is essential to maintain the productivity of forest ecosystems especially during an intensive timber harvest (Kellomaki and Seppala, 1987). Klockow *et al.* (2013) also showed that biomass, C, Ca, K and P was lower in WTH than in SOH system.Little and Shainsky (1992) found differences of 3% in N removal and 1% in S and P removal depending on the harvesting system.

Other authors reported different trends. Luiro *et al.* (2009) studied the amount of nutrients in the needles and they had many different results, therefore cannot prove that

WTH will affect the amount of nutrients, at least in needles component. Kurth *et al.* (2014) concluded of their research that there are not significant differences in the amount of N and C on soils between SOH and WTH treatments, suggesting that logging debris from a single harvest does not contribute to these pools within the 15 years' time frame. Fahey *et al.* (1991) estimated that the aboveground biomass average in a stand following WTH was about 50% higher than that following SOH through 2 – 5 year period following cutting.

The amount of nutrients removed from a site can be calculated through the estimation of weight and nutrient concentrations of tree components but the impact of such removals on the site in future stands is more difficult to determine (Little and Shainsky, 1992). For instance, Johnson et al. (2015) assumed that the unharvest residue of 30% of needles and branches on site ensure a suitable development of stands in the future. At contrast, Merilä *et al.* (2014) thought that this percentage is not enough. Pyörälä *et al.* (2012) proposed 60% for a good development of future tree stands.

CHAPTER 3. MATERIALS AND METHODS

3.1 Dooary Sitka spruce chronosequence

3.1.1 Site description

The work described here uses a combination of data from Tobin and Nieuwenhuis (2007) as well as unpublished data (Brian Tobin pers.comm.). Five even-aged Sitka spruce stands were selected in Portaloise area, Co. Laois (~52°57' N, 7°15') (Appendix 1). They represent the typical commercial rotation of Sitka spruce in Ireland (9 to 45 year old trees). Details of the five plots used in this thesis are described in Table 3.1. The general Yield Class of the stands was 18-22 m^3 ha^{-1} $year^{-1}$. The principal soil type in the area is wet mineral Gley (Stagnosol).

Table 3. 1: Site and stand characteristics of the Sitka spruce chronosequence

Site	Age (year)	Thinning	Plot size (ha)	Stocking density (tree ha^{-1})	DBH (cm)	Tree Top Height (m)	Stem volume (m^3 ha^{-1})
Baunoge	9.00	0	0.01	2333	6.00	3.50	60.40
Clontycoe	14.00	0	0.01	2533	13.00	7.30	173.60
Glenbarrow	21.00	1	0.02	1250	22.00	14.30	363.40
Dooary	30.00	4	0.02	1033	24.00	16.80	500.30
Cullenagh	45.00	5	0.03	767	32.00	26.70	835.30

3.1.2 Sampling and laboratory analysis

Six trees in each stand, representative of the DBH distribution, were harvested and destructively sampled. They were divided into six components (stem, bark, branches, standing deadwood, needles and roots) and sub-samples were taken and dried to constant weight at 70°C (see Tobin and Nieuwenhuis (2007) for more details of the procedure). Carbon (C) and Nitrogen (N) content of the dried biomass sub-samples were measured using a C-N analyser (Analitik Jena micro N/C Analyser).

3.1.3 Data analysis

Descriptive statistics and the analysis of variance were calculated by the SPSS Statistics 20 software (International Business Machines Corp. (IBM)). Graphs were created using SigmaPlot 12.0 (Systat Software Inc. (SSI)) and SPSS Statistics 20 software.

The amount of biomass per component was calculated by weighing the harvested and destructively sampled trees. The dry weight is the amount of biomass. Nitrogen concentration was analysed in the laboratory (subsection 3.1.2). The nitrogen pool in each component was calculated by multiplying the nutrient concentration by the amount of biomass in each component.

Mean and standard deviation of the sampled trees were calculated for nitrogen concentration, nitrogen pool and biomass in each component of a tree and within and between the chronosequence of Sitka spruce stands. Factorial Analysis of variance (Factorial ANOVA) was used to test for differences of nitrogen concentration, nitrogen pool and the amount of biomass depending on the age of a stand. This test was carried out for each component of a tree. All statistical tests throughout the text are considered significant with $\alpha=0.05$.

The three nitrogen removal scenarios calculated were as follows:

- Whole-tree harvest (WTH) → total nitrogen pool: nitrogen pool in needles, branches, stemwood, stembark and deadwood.
- Stem plus branch harvest (SBH) → total nitrogen pool: nitrogen pool in branches, stemwood, stembark and deadwood.
- Stem-only harvest (SOH) → total nitrogen pool: nitrogen pool in stemwood, stembark.

3.2. Nutrient pools in lodgepole pine and Sitka spruce

3.2.1 Site description

This study was carried out on five lodgepole pine and three Sitka spruce stands. Lodgepole pine stands were located in the north-west of Ireland and Sitka spruce stands in three different regions of Ireland (Appendix 1). Four of the lodgepole pine stands are included in the Irish National Forest Inventory (NFI) and the remaining forest is part of the International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forest Level I plot). One Sitka spruce stand is also a current ICP Forests Level II plot. The study sites were classified as temperate coniferous forests and the climate was temperate oceanic according to the Kopper climate classification system (Peel *et al.*, 2007). Further information on the stands is shown in Table 3.2.

Specific criteria were followed to choose the best stands for the study:

- Lodgepole pine stands were mature (age > 32 year old) and pure. They were first rotation stands and unthinned.
- Sitka spruce stands were mature (age > 26 year old) and pure. They were located on the most common afforested soil types of the country. Castledown is an unthinned stand while Cloonagh and Dooary were thinned.

Table 3. 2: Sites characteristics of mature Sitka spruce and lodgepole pine stands. LP: lodgepole pine. SS: Sitka spruce

Name of Site	Species	Year of Planting	Stocking density	County	Coordinates		Soil group	Thinning
NFI 2555	LP	1978	1700	Galway	54.1894	-9.7312	Blanket Peat	0
NFI 1412	LP	1978	1200	Galway	53.471	-9.6578	Lithosol	0
NFI 1539	LP	1957	2000	Mayo	53.9738	-9.6472	Lithosol	0
NFI 1551	LP	1976	2800	Mayo	53.4017	-9.3838	Blanket Peat	0
Glenamoy	LP	1968	1800	Mayo	53.6501	-9.6343	Blanket Peat	0
Castledown	SS	1982	2200	Westmeath	53.5193	-7.2116	Basin peat	0
Cloonagh	SS	1983	1300	Sligo	54.1646	-8.3687	Gley	1
Dooary	SS	1988	1345	Laois	52.9489	-7.2552	Gley	2

3.2.2 Stand inventory and tree sampling

A 10 × 10 m^2 square plot was located within each site. All trees in these plots were numbered and their diameter at breast height (DBH) measured.

Five lodgepole pine trees and three Sitka spruce were selected in each plot according to their DBH distribution and were taken for sampling. Therefore a total of 25 lodgepole pine and 15 Sitka spruce were sampled in this study. Each selected tree was divided into stemwood, stembark, roots, standing deadwood (dead branches) and live branches (with needles) and samples of each tree were taken in June 2014. Samples of stemwood, stembark, roots, deadwood and live branches were collected. Two samples of stemwood per tree were taken at the base of the tree with an increment borer so the stemwood would not be damaged. Two samples of stembark were taken for each tree between 1 m and 1.3 m. Roots samples were taken from near-surface horizons because of the difficulty of obtaining it from subsoil. Deadwood was removed from the lower part of the stem (below 2.0 m) of each tree. A live branch with needles per tree was taken from the lowest part of the crown of each tree in a manner to be representative of the whole tree. All samples were put into labelled paper bags except for live branches which were stored in labelled plastic bags.

3.2.3 Laboratory

Live branches (with needles) and deadwood samples were large and sub-sampling was done to facilitate further analysis. Samples were oven-dried at 70°C to a constant weight and the dry weight of the sample tree components determined. After drying, branches and needles of the component “live branches” were separated.

Sub-samples of each of the dried live branches and dead branches were created by coning and quartering method. Thereby, live and dead branches were ready to be ground along with the other samples. Grinding was necessary to generate a particle size suitable for laboratory analysis and also to ensure uniformity in sample composition (Benton Jones Jr, 2001). Grinding was carried out using a Retsch SM 100 cutting mill. All the samples were passed three times through a 0.5mm sieve. Subsequently, the cone and quartering method (McNaught and Wilkinson, 1997) was carried out to produce a reduced representative sub-sample from the large initial sample. Two grams of each sample were put in bags and sent to the lab for nutrient analysis.

3.2.4 Chemical analysis

The carbon, hydrogen and nitrogen content of the samples were obtained using a LECO SC-144DR elemental analyser. The CHN analysis was carried out at the Micro Analysis Laboratory in the School of Chemistry and Chemical Biology at University College Dublin, Ireland.

Sub-samples of 1.5 g were prepared and used for acquiring base cations and P. They were ashed for 10 hours at 470°C and digested in a nitric – hydrochloric acid solution as Benton Jones Jr (2001) proposes. Afterwards, the sub-samples were analysed using a Flame Atomic Absorption Spectroscopy to get the content of calcium, magnesium and potassium, while phosphorus was determined by ascorbic acid method. The chemical analysis was carried by the Aquatic Service Unit of the Environmental Research Institute (UCC), Ireland. The results of this analysis are shown in Appendix 2.

3.2.5 Data analysis

Descriptive statistics and the analysis of variance were calculated by the SPSS Statistics 20 software. Graphs were design using SigmaPlot 12.0 and SPSS Statistics 20 software.

Published regression equations (allometric equations) were used to estimate the biomass of each component of a tree in the two studied species (Table 3.3). A regression model of the component deadwood for lodgepole pine was unobtainable. Nutrient concentration was analysed in the laboratory (subsection 3.2.4). The nutrient pool in each component was calculated by multiplying the relevant nutrient concentration by the amount of biomass in each component. The three nutrient removal scenarios were calculated as previously mentioned in section 3.1.3.

Table 3. 3: Allometric equations used to estimate the amount of biomass in Sitka spruce and lodgepole pine. Different allometric equations depending on the species and the tree component (stemwood, stembark, needles, branches, deadwood and roots). Variables: Y *is biomass (kg tree^{-1}); **a** and **b** are parameters;* dbh *is diameter at breast height (cm);* Aboveground *is aboveground biomass.*

	Component	Source	Equation	a	b
Sitka spruce	(1) Stemwood	Green *et al.* , 2007	Y= a × (dbh)^b	0.2261	1.903
	(2) Stembark	Green *et al.* , 2007	Y= a × (dbh)^b	0.0449	1.8097
	(3) Needles	Green *et al.* , 2007	Y= a × (dbh)^b	0.0241	2.2002
	(4) Live branches	Green *et al.* , 2007	Y= a × (dbh)^b	0.0798	1.9182
	(5) Dead branches	Green *et al.* , 2007	Y= a × (dbh)^b	0.0046	2.5015
	(6) Roots	Pearson *et al.* , 1984	Y= a + b × dbh	-1.14	0.069
Lodgepole pine	(7) Stem (wood+bark)	Means *et al.* , 1994	ln(Y) = a+b × ln(dbh)	-9.10508	2.3363
	(8) Stemwood	Means *et al.* , 1994	ln(Y) = a+b × ln(dbh)	-9.24342	2.3438
	(9) Stembark	Means *et al.* , 1994	(7)-(8)	-	-
	(10) Needles	Gholz *et al.* , 1979	ln(Y) = a+b × ln(dbh)	-3.6187	1.8362
	(11) Live branches	Gholz *et al.* , 1979	ln(Y) = a+b × ln(dbh)	-4.6004	2.3533
	(12) Roots	Kurz *et al.* , 1996	Y=0.222*Aboveground	-	-

Mean and standard deviation of the sampled trees were calculated for nutrient concentration, nutrient pool and biomass in each component of Sitka spruce and lodgepole pine stands. Factorial ANOVA and non-parametric K independent samples (Kruskall-Wallis test) tests were conducted on the amount of biomass in each tree component (stemwood, stembark, deadwood, roots, branches and needles) and on the nutrient (Ca, Mg, N, P, K) concentrations in each tree component in order to determine the differences or similitudes between the two studied species. These tests were also used to study the relationship between the type of harvesting used on the site and the nutrient pools. The selection of the test depended on the homogeneity, the distribution and the amount of data that was available. Correlation between the different nutrient concentrations was also calculated by the correlation bivariate function. All statistical tests throughout the text are considered significant with $\alpha = 0.05$.

3.3 Nutrient removals in 45 years-old Sitka spruce harvest residue

3.3.1 Site description

This section uses data collected by Coates *et al.* (2014). The investigator collected information of bundles made in a 45 year old stand of Sitka spruce mixed with 5% grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.) located near Inistioge, Co. Kilkenny ((52°28’10’’N, 7°4’23’’W) (Appendix 1). The objectives of the Coates *et al.* (2014) study were to determine how the impact on supply-chain costs, quantity and quality of the fuel through forest biomass if bundling is implemented during harvesting timber.

The top height was 26 m and the quadratic mean DBH was 24 cm. The stand was divided into three treatments plots (Table 3.4) and four 4 m^2 subplots per treatment area were studied. The treatments used are described below:

- All Residues Driven upon (ARD): Forest logging residues were used as a brash mat for all timber harvester and forwarder machine passes.
- Driving on Residues Reduced (DRR): Forest logging residues were used as a brash mat. The harvester passes on all extraction racks and the forwarder only on alternate extraction racks.
- No Residues Driven on (NRD): Forest logging residues were not used as a brash mat, but instead were piled to side of the racks.

Table 3. 4: Characteristics of each treatment area of the 45 years old Sitka spruce plantation.

Treatment	Area (ha)	Average stocking (tree ha^{-1})	Tree volume (m^3 $tree^{-1}$)
ARD	0.91	619	0.58
DRR	1.58	569	0.53
NRD	1.21	681	0.45
Total	3.7	623	0.52

3.3.2 Sampling and laboratory

The site was harvested and the roundwood was brought to the roadside. A grab of forest harvest residues (brash) at 15 random intervals over each treatment area was extracted at the time of timber harvesting by a forwarder. The brash was separated into three piles depending on the treatment and chipped. Five samples of each pile were taken (green brash) and dried at 105°C and moisture, calorific value and content of ash, carbon, hydrogen, nitrogen, chlorine and sulphur were measured.

After seven months, a John Deere residue bundler bundled the forest logging residues that had been left. Twenty bundles per treatment plot were sampled for moisture content and then divided. Thereafter, three subsamples per bundle (brown brash) were taken to determine the same variables as in the study with the green brash. Lastly, nutrient analysis (N, P, K, Ca, Mg, S) of green and brown brash for each treatment was done for this project. The analysis was conducted by Eurofins Food Testing UK Ltd.

3.3.3 Data analysis

Descriptive statistics and the analysis of variance were calculated by the SPSS Statistics 20 software. Graphs were designed using SigmaPlot 12.0 and SPSS Statistics 20 software.

The amount of biomass in a Sitka spruce bundle (with brown material) was obtained by weighing it. The nutrient concentration of a bundle was analysed in the laboratory (subsection 3.3.2). The nutrient pool of harvest residue per hectare of the study site was calculated by multiplying the nutrient concentrations of a bundle by the amount of biomass in each bundle by the number of bundles per hectare. Mean and standard deviation were calculated for the nutrient concentrations in a bundle and the nutrient pools of harvest residue in a hectare of Sitka spruce plantation. As the amount of data is small, the Kruskall-Wallis test was used to study the relationship between the treatment and the nutrient concentration in bundles and also among the type of material and the nutrient concentration. All statistical tests throughout the text are considered significant with $\alpha=0.05$.

CHAPTER 4. RESULTS

4.1 Dooary Sitka spruce chronosequence

4.1.1 Nitrogen concentration

The change in N concentration with age for each component of Sitka spruce is shown in Table 4.1. A significant difference was found between N concentration and age in the components stembark, deadwood and stemwood. Nitrogen concentration in deadwood and stemwood tends to increase through time. However, decreases observed in samples of 45 years old. Nitrogen concentration in stembark decreases with time. The component with the most N concentration was needles, and stemwood contained the lowest (Table 4.1).

Table 4. 1: Summary of N concentration (mg g^{-1}) in different tree components in a Sitka spruce chronosequence between 9 and 45 years old. Mean and standard deviation are reported. (*): correlation was found between age and N concentration in the component considered.

	N concentration (mg g^{-1})					
Age	Needles	Branches	Stembark*	Deadwood*	Roots	Stemwood*
9	14.78 ± 1.49	6.19 ± 0.41	7.67 ± 0.61	- ± -	4.03 ± 0.25	2.04 ± 0.38
14	14.28 ± 0.53	5.92 ± 0.23	8.21 ± 0.85	6.37 ± 1.13	3.76 ± 0.27	2.06 ± 0.13
21	15.77 ± -	6.20 ± -	6.92 ± 1.39	7.52 ± 1.22	3.83 ± 0.41	2.28 ± 0.36
30	16.30 ± 1.45	6.25 ± 0.34	6.32 ± 0.42	7.14 ± 0.49	4.11 ± 0.09	2.72 ± 0.17
45	15.41 ± 1.63	6.15 ± 0.68	5.01 ± 0.40	5.99 ± 0.79	3.70 ± 0.21	1.73 ± 0.26

4.1.2 Biomass accumulation

Biomass was significantly different between ages for all tree components. Biomass increases over time in all the components (Table 4.2, Fig 4.1). Large standard error bars (Fig 4.1) are associated with the amount of biomass and the standard deviation (Table 4.3) indicated that there was a variation within each of the means, especially in the 30 years old stand.

Table 4. 2: Summary of biomass per component (kg) in Sitka spruce tree (between 9 and 45 year old). Mean and standard deviation are reported. (*): correlation was found between age and the component considered.

	Biomass (kg)					
Age	Needles*	Branches*	Stembark*	Deadwood*	Roots*	Stemwood*
9	2.8 ± 0.5	3.6 ± 0.6	1.4 ± 0.1	- ± -	4.2 ± 0.7	3.7 ± 0.3
14	4.8 ± 1.4	7.2 ± 2.3	4.9 ± 1.4	2.1 ± 1.7	16.1 ± 6.8	19.3 ± 5.8
21	7.0 ± 2.4	8.4 ± 2.9	21.8 ± 4.3	14.9 ± 4.4	31.9 ± 6.8	124.6 ± 26.6
30	11.2 ± 4.1	17.0 ± 6.8	28.1 ± 4.5	27.8 ± 7.4	53.2 ± 19.7	164.8 ± 31.9
45	20.9 ± 3.8	30.1 ± 6.0	49.7 ± 6.1	19.5 ± 4.1	112.8 ± 17.3	453.6 ± 59.5

Table 4. 3: Summary of biomass per component (kg ha^{-1}) in Sitka spruce stands (between 9 and 45 year old). Mean and standard deviation are reported (calculated based on a data in Table 4.2 and stocking from Table 3.1).

	Biomass (kg ha^{-1})					
Age	Needles*	Branches*	Stembark*	Deadwood*	Roots*	Stemwood*
9	6332 ± 1019	8362 ± 1342	3172 ± 699	- ± -	9601 ± 1900	8643 ± 1795
14	12269 ± 3525	18222 ± 5668	12312 ± 3271	5372 ± 4159	40449 ± 15752	48571 ± 13163
21	8865 ± 3494	10602 ± 4147	27242 ± 5901	18683 ± 5480	40007 ± 9112	156471 ± 37699
30	15818 ± 5779	24029 ± 9579	39528 ± 7720	39257 ± 12115	74088 ± 28095	232403 ± 53028
45	16009 ± 2956	23030 ± 4392	38189 ± 5813	15004 ± 3753	86822 ± 17706	349884 ± 67759

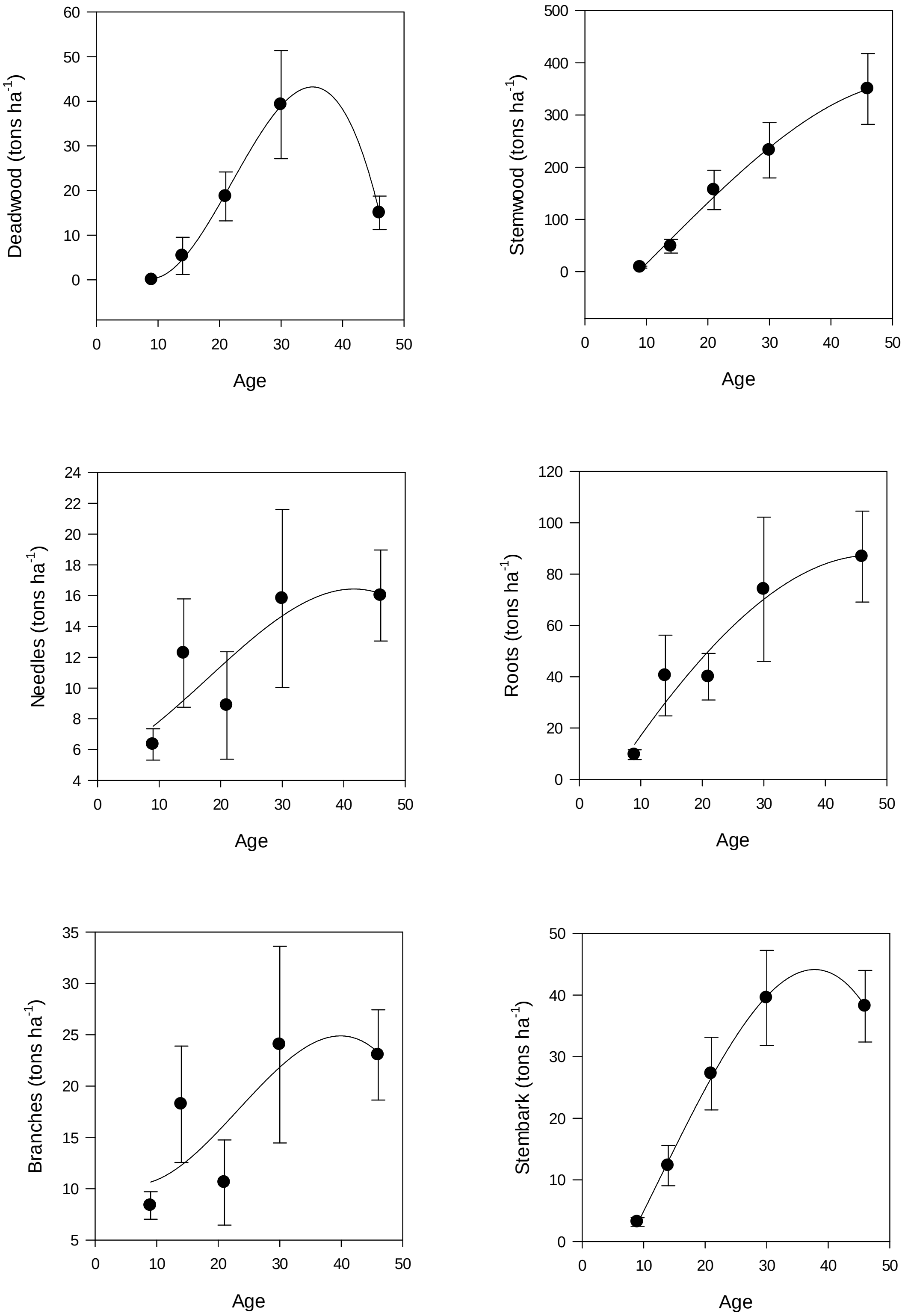

Fig 4. 1: Summary of biomass accumulation (tons ha^{-1}) in different tree compartments in a Sitka spruce chronosequence between 9 and 45 year old. Error bars are the standard deviation.

Components did not grow in the same proportions. In 9 year old Sitka spruce, needles and branches comprised a high proportion (41%) of the tree. Nevertheless, over the years, these components become relatively small. In contrast, in 45 year old Sitka spruce, needles and branches occupied 7.4% of biomass. Stemwood, on the contrary, was 23% in 9 year old Sitka spruce and 66% in the 45 year old stand (Fig 4.2).

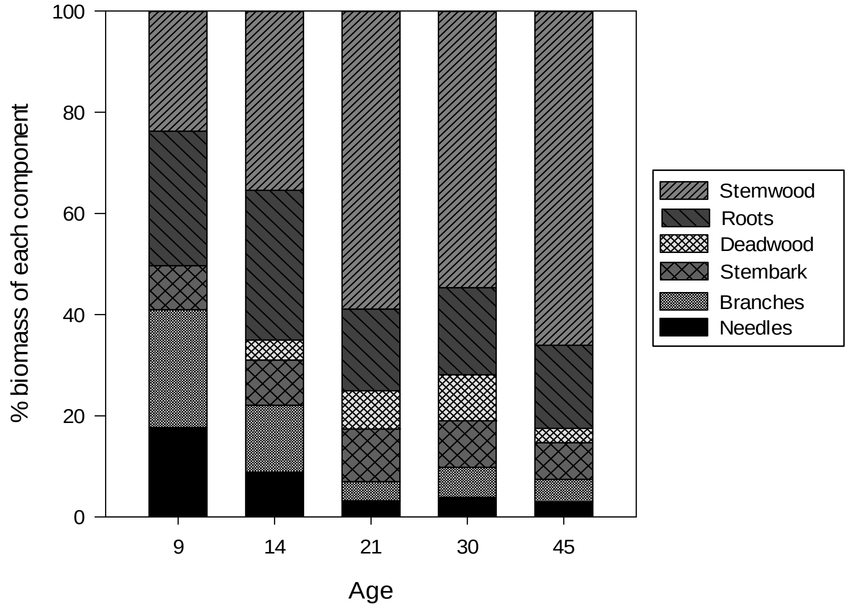

Fig 4. 2: Representative percentage of biomass in each component of a Sitka spruce tree in different ages

4.1.3 Nitrogen accumulation

A significant difference was found between N pool and age in all components of a Sitka spruce tree with N pool increasing over time. However, at 45 year old, there is a decrease in the N pool (Table 4.4, Fig 4.3). Analysing per component, N pool in branches and roots was higher in the 45 year old stand than in the 30 year old and needles had a similar pool between 30 and 45 year old (Fig 4.4). Nitrogen pool of stembark, stemwood and deadwood decreased but it was in the component deadwood where N pool declined most (Table 4.4, Fig 4.4). Large standard error bars (Fig 4.4) are associated with the amount of biomass and the standard deviation (Table 4.4) indicated that there were significant differences in each of the means, especially at in the 30 year old stand.

Table 4. 4: Summary of N pool (kg ha^{-1}) per component in a Sitka spruce chronosequence between 9 and 45 year old. Mean and standard deviation are reported. (*): correlation was found between age and the component considered.

	Nitrogen pool (kg ha^{-1})						
Age	Needles*	Branches*	Stembark*	Deadwood*	Roots*	Stemwood*	Total N
9	93 ± 16	52 ± 9	25 ± 7	- ± -	39 ± 7	17 ± 4	225 ± 38
14	175 ± 50	108 ± 34	102 ± 35	33 ± 25	151 ± 55	100 ± 28	669 ± 207
21	130 ± 56	61 ± 26	184 ± 46	150 ± 60	159 ± 42	349 ± 105	1034 ± 265
30	248 ± 126	116 ± 94	266 ± 24	299 ± 85	134 ± 159	681 ± 82	1745 ± 194
45	245 ± 39	140 ± 23	192 ± 38	90 ± 24	322 ± 73	598 ± 109	1587 ± 240

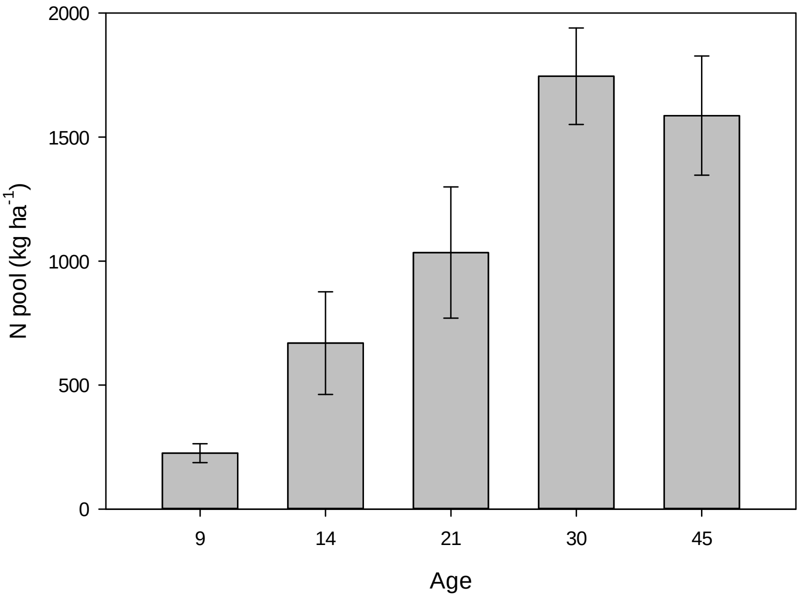

Fig 4. 3: Total N pool (kg ha^{-1}) in in a Sitka spruce chronosequence between 9 and 45 years old. Error bars are the standard deviation.

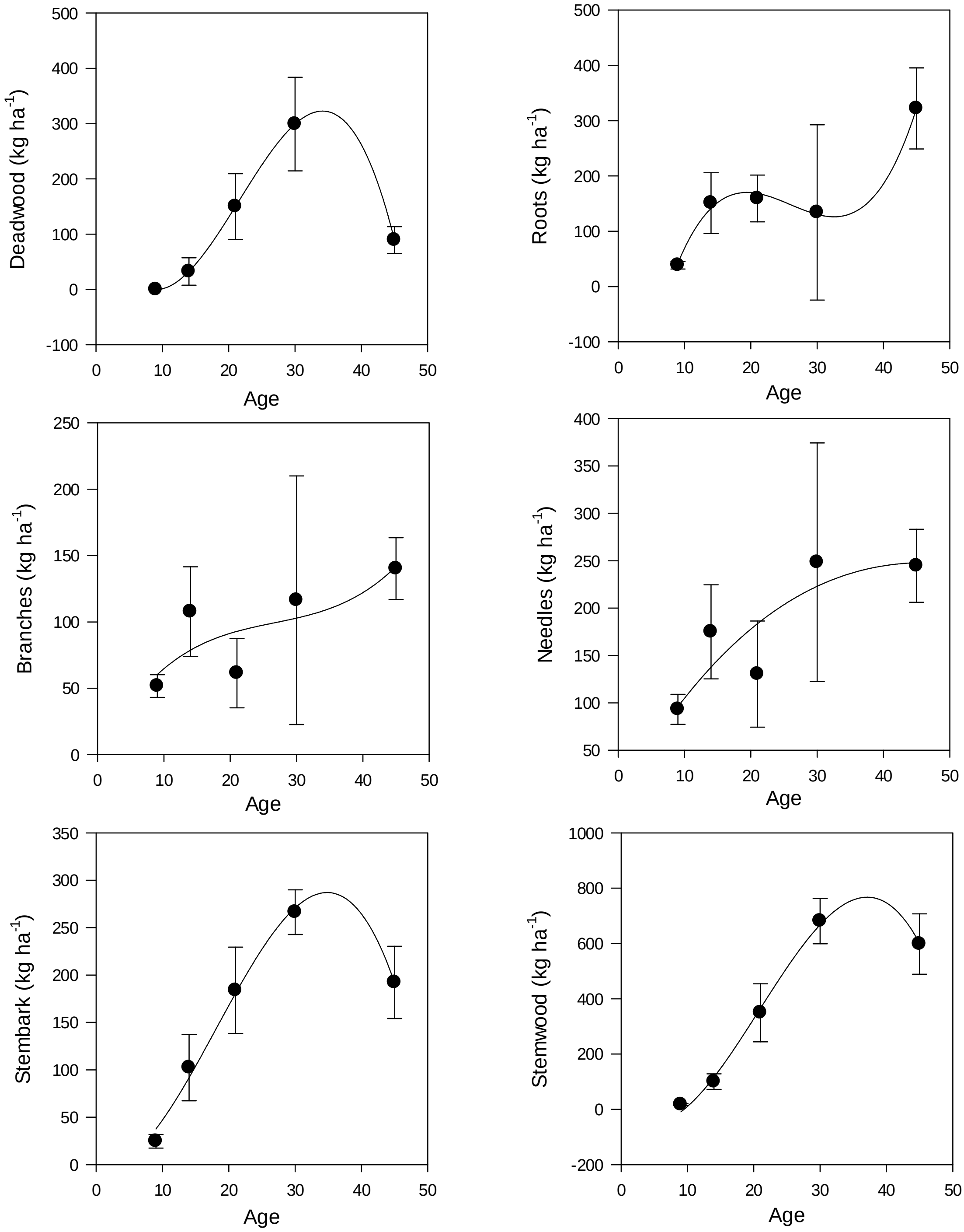

Fig 4. 4: Summary of N pool (kg ha^{-1}) in different tree compartments in a Sitka spruce chronosequence between 9 and 45 year old.

In the youngest Sitka spruce stand, 42% of the N pool was in needles and 23% in branches (Fig 4.5). Meanwhile, in the mature Sitka spruce stand, these percentages reduced to a mean of around 20% for both tree components (Fig 4.5). Stemwood contained only 8% of N pool when it was 9 year old but it was increasing up to 39% when it was 30 and 45 year old (Fig 4.5).

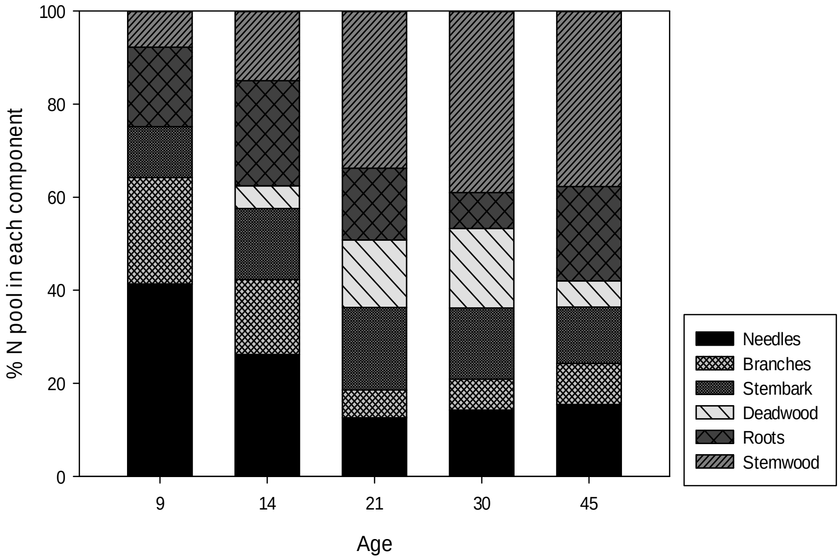

Fig 4. 5: Nitrogen pool (%) in each component of a Sitka spruce stand at different ages.

4.1.4 Nitrogen removal by harvesting

The whole-tree harvest (WTH) system extracted the greatest amount of N (1745 kg ha^{-1}) in the 30 year old Sitka spruce stand while the SOH system exported 1246 kg ha^{-1} (Table 4.5). Nitrogen removal increased over time in the three types of harvesting. Moreover, the difference in N removal between WTH, SBH and SOH also increase with stand age (Fig 4.6).

Table 4. 5: Nitrogen removal (kg ha^{-1}) in three different harvesting scenarios in a Sitka spruce chronosequence between 9 and 45 year old. SOH, only-stem harvesting, SBH, stem and branch harvesting, WTH, whole-tree harvesting. Mean and standard deviation are reported.

		Nitrogen removal (kg ha^{-1})		
Age	N pool (kg ha^{-1})	WTH	SBH	SOH
9.0	225.4 ± 38.1	186.9 ± 32.7	93.7 ± 17.9	42.0 ± 9.7
14.0	668.9 ± 206.9	517.9 ± 154.4	342.9 ± 112.9	170.0 ± 40.6
21.0	1034.4 ± 264.9	875.0 ± 238.8	744.6 ± 200.9	383.3 ± 112.5
30.0	1745.4 ± 194.4	1611.3 ± 146.1	1415.4 ± 183.1	652.2 ± 52.6
45.0	1586.8 ± 240.1	1264.6 ± 210.8	1020.0 ± 181.5	700.7 ± 127.1

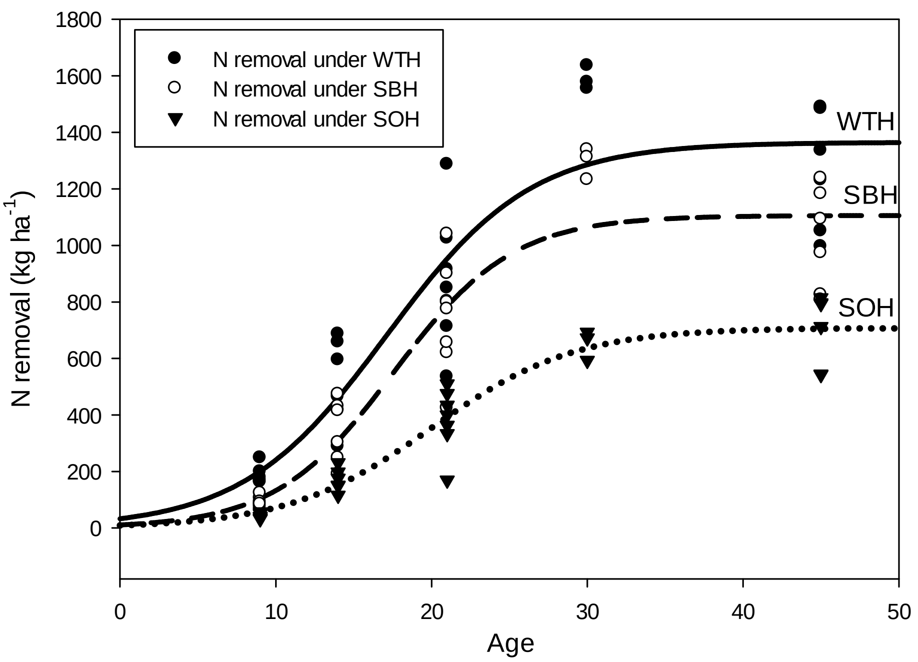

Fig 4. 6: Comparison N removal (kg ha^{-1}) in and between three different harvesting scenarios in a Sitka spruce chronosequence between 9 and 45 years old. Dotted line: stem and branch harvesting (SOH); Dashed line: only-stem harvesting (SBH); Continuous line: whole-tree harvesting (WTH).

4.2 Nutrient pools in lodgepole pine and Sitka spruce

4.2.1 Nutrient concentrations

Analysing the nutrients separately, it was observed that the concentration of each element varied between trees. It was also shown that these elements have different concentrations depending on the tree component (Table 4.6).

- Nitrogen concentration was the highest nutrient concentration in all the tree components in both species, especially in needles (10.17 mg g^{-1} and 13.56 mg g^{-1} in lodgepole pine and Sitka spruce respectively). Stemwood contained the least concentration of N (1.19 mg g^{-1} in lodgepole pine and 1.39 mg g^{-1} in Sitka spruce).
- Phosphorus concentration was the lowest in all the tree components of both species. The maximum concentration remained in needles (1.06 mg g^{-1} in lodgepole pine and 1.18 mg g^{-1} in Sitka spruce) and it was very low in stemwood (0.02 mg g^{-1} in both species).
- Potassium concentration was greater in needles (5.03 mg g^{-1} in lodgepole pine and 6.09 mg g^{-1} in Sitka spruce) but little in the other tree components. Roots and branches contained the second highest potassium concentration (values below 2 mg g^{-1}).
- Magnesium concentration was the second lowest in all the tree components in both species. The greatest Mg concentration in Sitka spruce and lodgpepole pine were 1.07 mg g^{-1} and 1.12 mg g^{-1} respectively in needles.
- Calcium concentration was the second highest in all the tree components in both species. The largest Ca concentration in Sitka spruce was 4.42 mg g^{-1} in needles and in lodgepole pine was 5.83 mg g^{-1} in stembark.
- In general, the largest nutrient concentration was in needles and the lowest was in stemwood.

The distribution of the nutrients was similar in both Sitka spruce and lodgepole pine. Significant differences were found in nutrient concentration between species, although not in all the tree components: Mg and P concentration were different between species only in needles and branches; Ca concentration varied according to the species in needles, branches and stemwood; and K and N concentrations were different between species in all the tree components except stembark (Table 4.6).

In most cases, P and Ca concentration were slightly greater in lodgepole pine than Sitka spruce while K, Mg and N concentrations were slightly higher in Sitka spruce (Fig 4.7). Branches were an exception, as the greatest P and Ca concentrations were found in Sitka spruce branches whereas the largest K, Mg and N concentrations were found in lodgepole pine branches.

The concentrations of each nutrient were correlated (Table 4.7). Needles and stembark concentrations of nutrients were highly correlated with each other, except Mg concentration which was not correlated. Correlation among nutrient concentration was poor in branches and deadwood. Only Ca and P and K and P were correlated in these components. There was also high correlation between Ca and P in roots and between Ca and Mg in stemwood. Concentrations of nutrient were in general strongly correlated among Ca and P and K and P in all the components. At contrast, Mg was the least correlated element with the others.

Table 4. 6: Summary of nutrient concentration (mg g^{-1}) in the different components of Sitka spruce and lodgepole pine. Mean and standard deviation are reported.

		Nutrient concentration (mg g^{-1})				
		Ca	**Mg**	**K**	**P**	**N**
Lodgepole pine	Deadwood	1.47 ± 0.32	0.54 ± 0.12	0.21 ± 0.03	0.09 ± 0.01	3.70 ± 0.66
	Branches	3.69 ± 0.76	0.71 ± 0.24	1.67 ± 0.43	0.37 ± 0.09	5.54 ± 1.53
	Needles	4.42 ± 0.85	1.12 ± 0.39	5.63 ± 2.13	1.06 ± 0.22	10.17 ± 3.87
	Roots	1.45 ± 0.30	0.90 ± 0.36	1.16 ± 0.35	0.25 ± 0.15	4.21 ± 1.16
	Stembark	2.57 ± 0.70	0.73 ± 0.19	0.59 ± 0.15	0.15 ± 0.05	3.38 ± 0.73
	Stemwood	0.52 ± 0.06	0.20 ± 0.02	0.20 ± 0.03	0.02 ± 0.01	1.19 ± 0.28
Sitka spruce	Deadwood	2.37 ± 1.09	0.32 ± 0.11	0.21 ± 0.03	0.15 ± 0.05	4.05 ± 1.30
	Branches	3.36 ± 0.73	0.58 ± 0.23	1.55 ± 0.33	0.34 ± 0.06	4.86 ± 0.98
	Needles	4.97 ± 1.28	1.07 ± 0.52	6.09 ± 2.13	1.18 ± 0.32	13.56 ± 3.35
	Roots	2.69 ± 0.61	0.40 ± 0.13	1.30 ± 0.23	0.31 ± 0.06	4.05 ± 0.79
	Stembark	5.83 ± 0.97	0.46 ± 0.07	1.50 ± 0.34	0.38 ± 0.04	4.22 ± 0.48
	Stemwood	0.48 ± 0.06	0.07 ± 0.01	0.22 ± 0.05	0.02 ± 0.01	1.39 ± 0.20

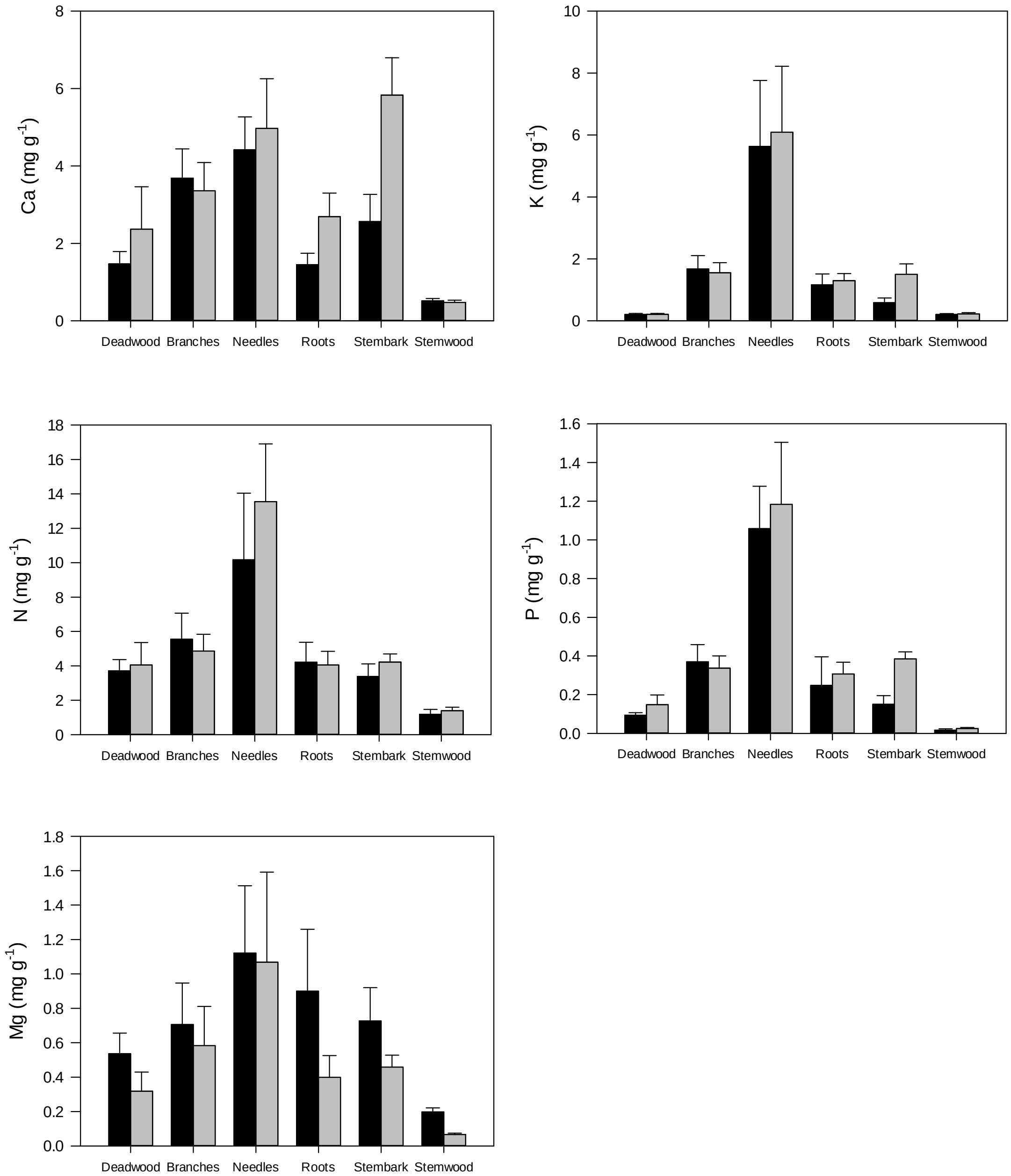

Fig 4. 7: Nutrient concentration (mg g^{-1}) among Sitka spruce and lodgepole pine species in each tree component. Black column represents Sitka spruce. Grey column represents lodgepole pine.

Table 4. 7: Correlation coefficients (r) between nutrient concentrations within tree components. (*): correlation is significant at the 0.05 level. (**) correlation is significant at the 0.01 level.

		r				
Component	Nutrient	Ca	Mg	K	P	N
Needles	Ca	1	-0.331	0.499*	0.537**	0.457*
	Mg		1	-0.361	-0.324	-0.449
	K			1	0.845**	0.607**
	P				1	0.524**
	N					1
Branches	Ca	1	-0.062	0.296	0.685**	-0.173
	Mg		1	0.199	-0.093	-0.329
	K			1	0.724**	-0.649
	P				1	-0.38
	N					1
Stembark	Ca	1	-0.414	0.751**	0.706**	0.598**
	Mg		1	-0.558	-0.503	-0.207
	K			1	0.875**	0.453*
	P				1	0.537**
	N					1
Deadwood	Ca	1	-0.062	0.296	0.685**	-0.173
	Mg		1	0.199	-0.093	-0.329
	K			1	0.724**	-0.649
	P				1	-0.38
	N					1
Roots	Ca	1	-0.417	0.167	0.782**	-0.155
	Mg		1	-0.274	-0.093	-0.06
	K			1	-0.06	0.113
	P				1	-0.356
	N					1
Stemwood	Ca	1	0.585**	0.061	0.11	-0.244
	Mg		1	-0.091	-0.337	-0.382
	K			1	0.385	-0.033
	P				1	0.225
	N					1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

4.2.2 Biomass accumulation

The needle and branch biomass was significantly different between species, being higher in Sitka spruce stands than in lodgepole pine (Table 4.8, Fig 4.8. and Fig 4.9). The amount of total biomass per tree was usually similar or even larger in Sitka spruce species (Table 4.8, Fig 4.8 and Fig 4.9) but the amount of biomass (kg ha^{-1}) in lodgepole pine stands was greater than in Sitka spruce stands, especially in NFI 1551 and NFI 2555 sites (Table 4.9 and Fig 4.10).

There was a variation in the amount of biomass between sites of the same species. In Sitka spruce stands, Downs showed less biomass than Cloonagh and Dooary whereas in lodgepole pine stands NFI 1539 had lowest amount of biomass. Large standard error bars (Fig 4.8.1, Fig 4.8.2, and Fig 4.10) are associated with the amount of biomass and the standard deviation (Table 4.8 and Table 4.9) indicated that there was a variation within each of the means.

Table 4. 8: Summary of biomass per component (kg) in a Sitka spruce and lodgepole pine in several stands. Mean and standard deviation are reported.

		biomass $tree^{-1}$ (kg)					
		Needles*	Branches*	Stembark	Deadwood	Roots	Stemwood
Sitka spruce	Cloonagh	43.23 ± 15.92	54.38 ± 17.66	21.12 ± 6.49	23.23 ± 9.88	47.62 ± 16.62	165.23 ± 54.19
	Dooary	41.10 ± 15.52	52.10 ± 17.12	20.28 ± 6.30	22.00 ± 9.67	45.50 ± 15.96	158.10 ± 52.51
	Downs	17.27 ± 12.45	23.95 ± 15.20	9.64 ± 5.86	8.27 ± 6.78	19.45 ± 13.82	72.09 ± 46.46
Lodgepole pine	Glenamoy	11.42 ± 7.09	25.08 ± 19.61	27.92 ± 21.13	±	66.75 ± 51.24	235.25 ± 182.61
	NFI 1412	9.92 ± 4.12	20.50 ± 10.71	22.75 ± 11.52	±	53.75 ± 27.62	189.67 ± 98.88
	NFI 1539	5.15 ± 2.78	8.85 ± 6.53	10.11 ± 7.25	±	23.85 ± 17.19	82.93 ± 60.64
	NFI 1551	7.25 ± 3.26	13.68 ± 7.33	15.39 ± 8.05	±	36.25 ± 19.32	126.86 ± 68.78
	NFI 2555	7.56 ± 3.28	14.28 ± 7.78	16.06 ± 8.53	±	37.72 ± 20.74	132.44 ± 73.33

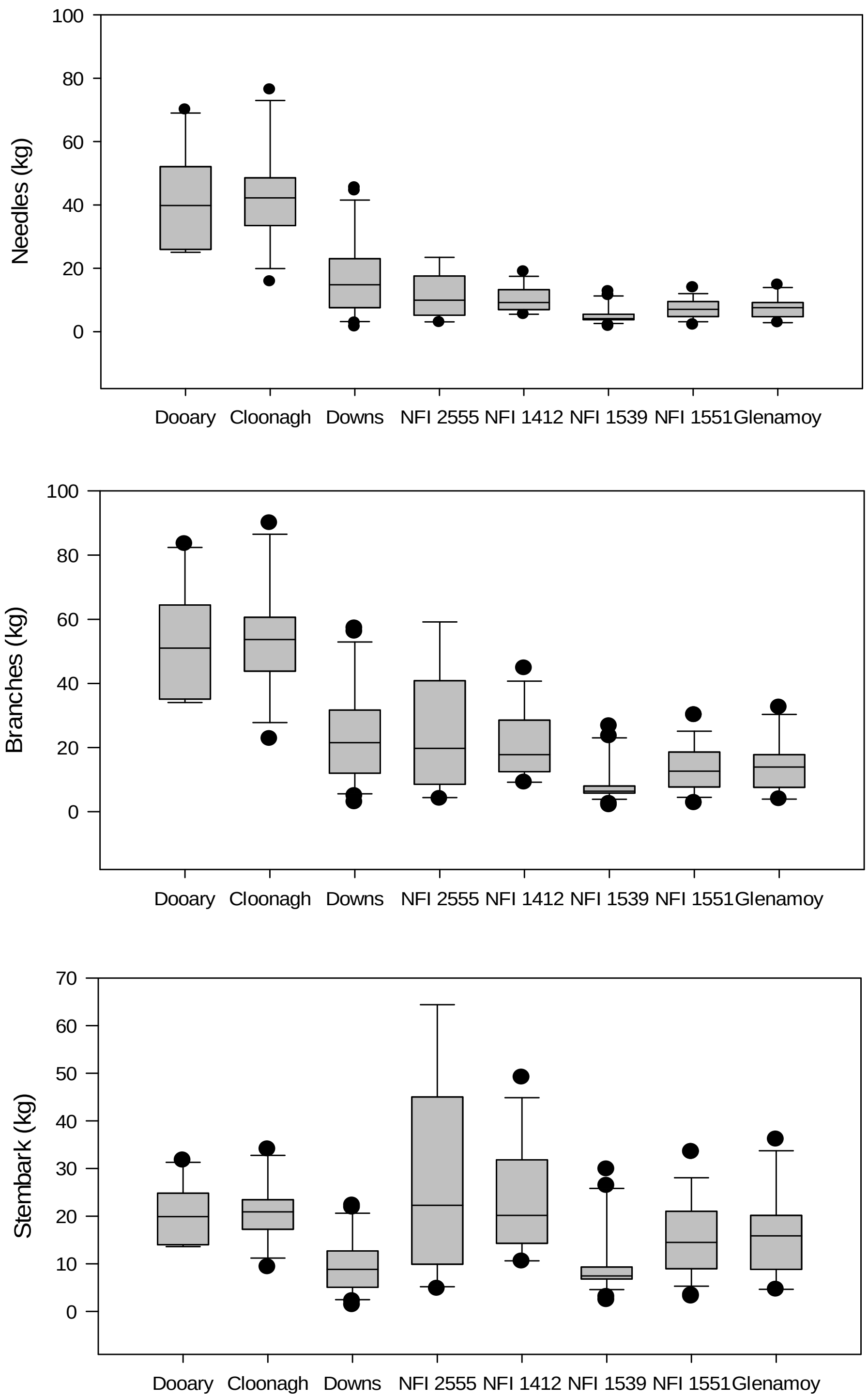

Fig 4. 8: Box plot of tree biomass (kg) in needles, branches and stembark of the studied Sitka spruce and lodgepole pine stands. Standard deviations are indicated by an error bar. Dots are anomalies.

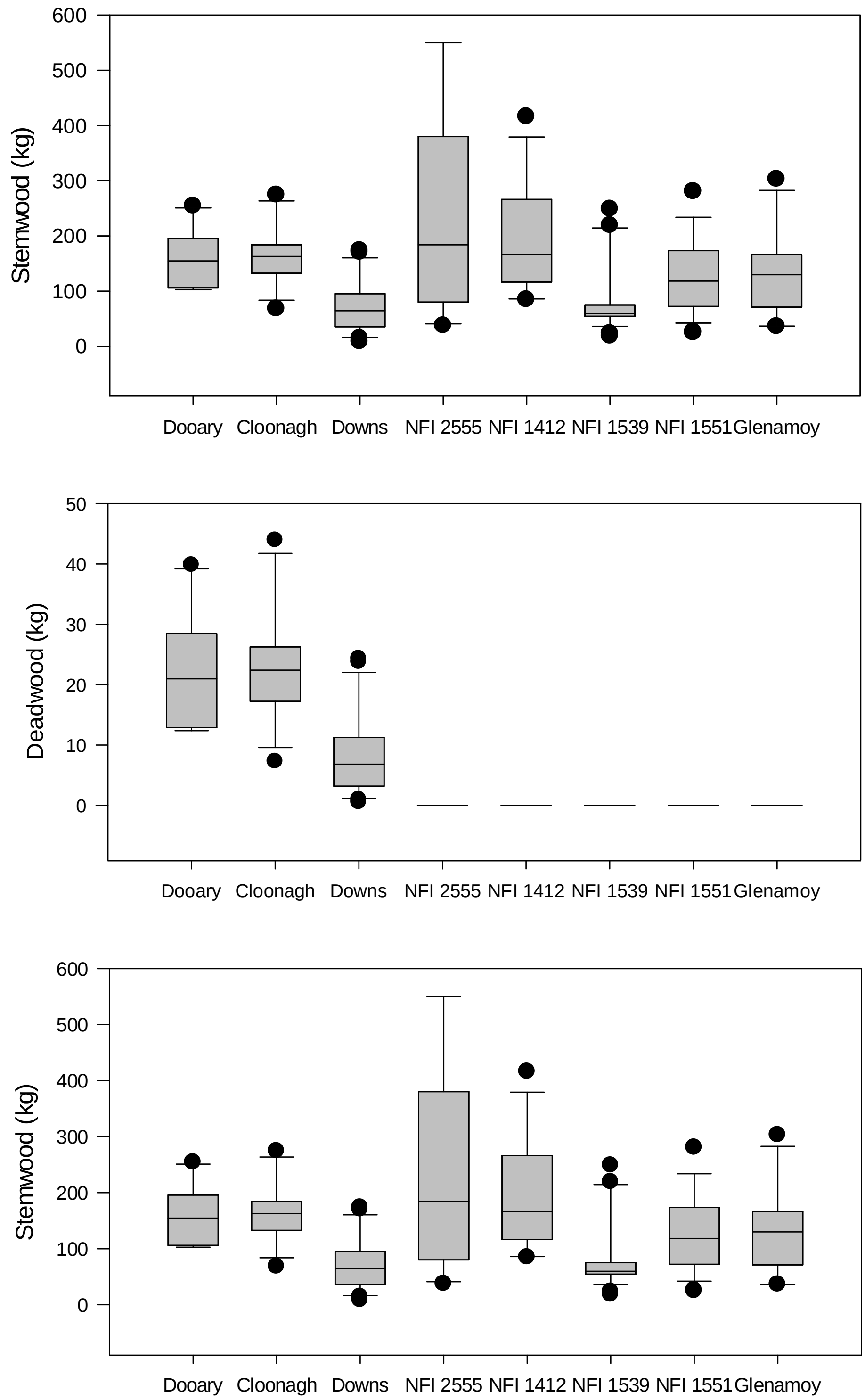

Fig 4. 9: Box plot of tree biomass (kg) in roots, deadwood, stemwood of the studied Sitka spruce and lodgepole pine stands. Standard deviations are indicated by an error bar.

Table 4. 9: Summary of biomass per component (kg ha^{-1}) in a Sitka spruce and lodgepole pine in several stands. Mean and standard deviation are reported. (calculated based on a data in Table 4.8 and stocking from Table 3.2).

		Biomass (kg ha^{-1})					
		Needles	Branches	Stembark	Deadwood	Roots	Stemwood
Sitka spruce	Cloonagh	56252 ± 20819	70779 ± 22984	27460 ± 8436	30254 ± 12663	61795 ± 21500	214772 ± 70434
	Dooary	55356 ± 20908	70117 ± 23082	27273 ± 8468	29564 ± 12693	61014 ± 21596	212661 ± 70739
	Downs	37944 ± 27395	52615 ± 33658	21218 ± 12892	18486 ± 14945	42860 ± 30506	158534 ± 102347
Lodgepole pine	Glenamoy	13496 ± 5914	25507 ± 14188	28993 ± 15607	±	68015 ± 37244	238375 ± 132073
	NFI 1412	11976 ± 4846	24380 ± 12769	27403 ± 13849	±	64667 ± 33330	227534 ± 118674
	NFI 1539	10293 ± 5617	17745 ± 13006	20441 ± 14411	±	47638 ± 34246	166106 ± 121179
	NFI 1551	20297 ± 8834	38038 ± 20675	43294 ± 22830	±	101492 ± 54361	355541 ± 192554
	NFI 2555	19533 ± 12314	42952 ± 33422	47669 ± 36050	±	113311 ± 87062	400258 ± 310415

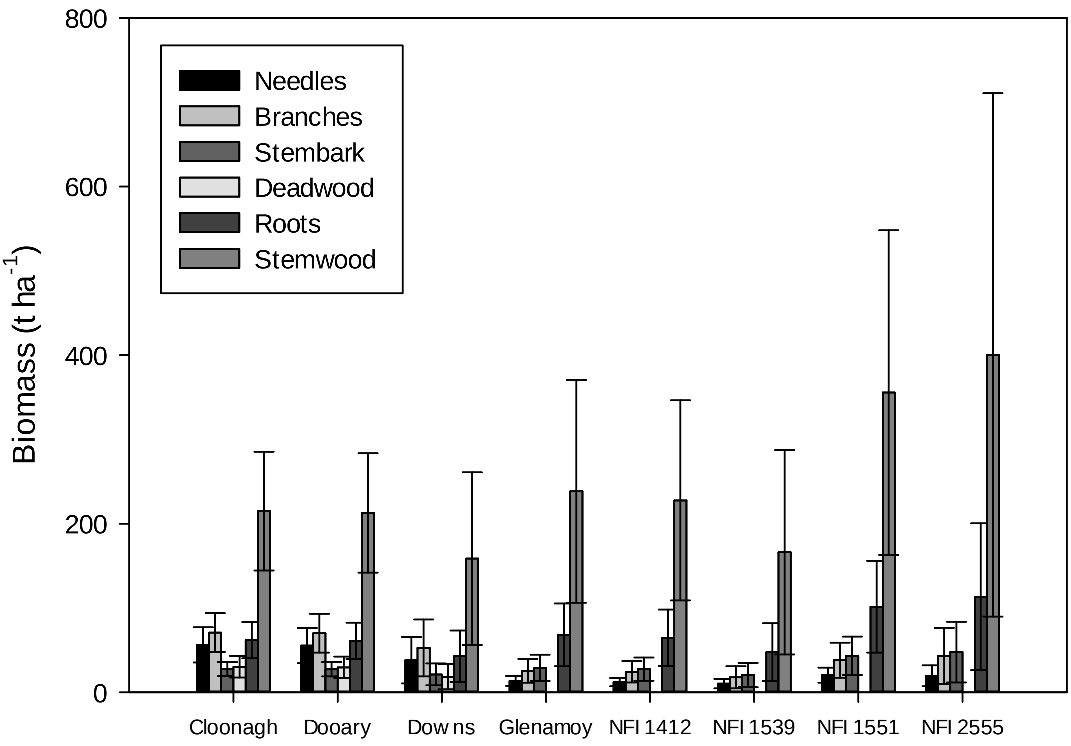

Fig 4. 10: Total biomass (tons ha^{-1}) in each component of a tree of the studied Sitka spruce and lodgepole pine stands. Error bars are the standard deviation.

4.2.3 Nutrient accumulation

Significant differences in nutrient pools were found between species in stembark, branches and needles. In roots and stemwood there were only significant differences between species in the Mg pool (Table 4.10). The most abundant nutrient pools in both species were Ca and N and the smallest was P (Table 4.10). The K pool was also high, especially in Sitka spruce stands (Table 4.10). Nutrient pools in Sitka spruce stands were usually higher than in lodgepole pine stands in needles, branches and stembark (Table 4.10). An exception was identified in stembark where the Mg pool was larger in lodgepole pine stands (Table 4.10). Nutrient pools in roots and stemwood were larger in lodgepole pole stands (Table 4.10).

All Sitka spruce stands had the greatest amount of nutrients in needles followed by branches, roots, stemwood, stembark and deadwood (Table 4.10 and Fig 4.11). This distribution of each nutrient per component was similar in the three studied sites (Fig 4.11). Nevertheless, in lodgepole pine stands, nutrient pools varied according to the studied stand, especially in roots (from 250 to 500 kg ha^{-1}) and in stemwood (between 230 and 550 kg ha^{-1}) (Fig 4.12 and Fig 4.13).

Table 4. 10: Summary of nutrient pools (kg ha^{-1}) per component in mature Sitka spruce and lodgepole pine stands. Mean and standard deviation are reported.

		Nutrient pool (kg ha^{-1})					
		Needles	Branches	Stembark	Deadwood	Roots	Stemwood
Sitka spruce	Ca	223 ± 90	205 ± 44	144 ± 20	70 ± 18	158 ± 49	91 ± 14
	Mg	47 ± 16	38 ± 8	12 ± 0	10 ± 2	27 ± 12	13 ± 1
	K	272 ± 119	99 ± 20	33 ± 10	6 ± 2	66 ± 28	42 ± 7
	P	55 ± 22	22 ± 3	10 ± 1	4 ± 2	18 ± 5	4 ± 1
	N	544 ± 114	317 ± 34	114 ± 14	91 ± 32	261 ± 111	345 ± 132
Lodgepole pine	Ca	63 ± 24	101 ± 41	78 ± 33	- ± -	105 ± 39	133 ± 58
	Mg	15 ± 8	19 ± 12	22 ± 8	- ± -	66 ± 32	49 ± 20
	K	80 ± 28	46 ± 20	18 ± 5	- ± -	81 ± 43	51 ± 19
	P	15 ± 5	10 ± 5	5 ± 2	- ± -	19 ± 9	4 ± 1
	N	139 ± 64	150 ± 58	103 ± 48	- ± -	321 ± 153	297 ± 129

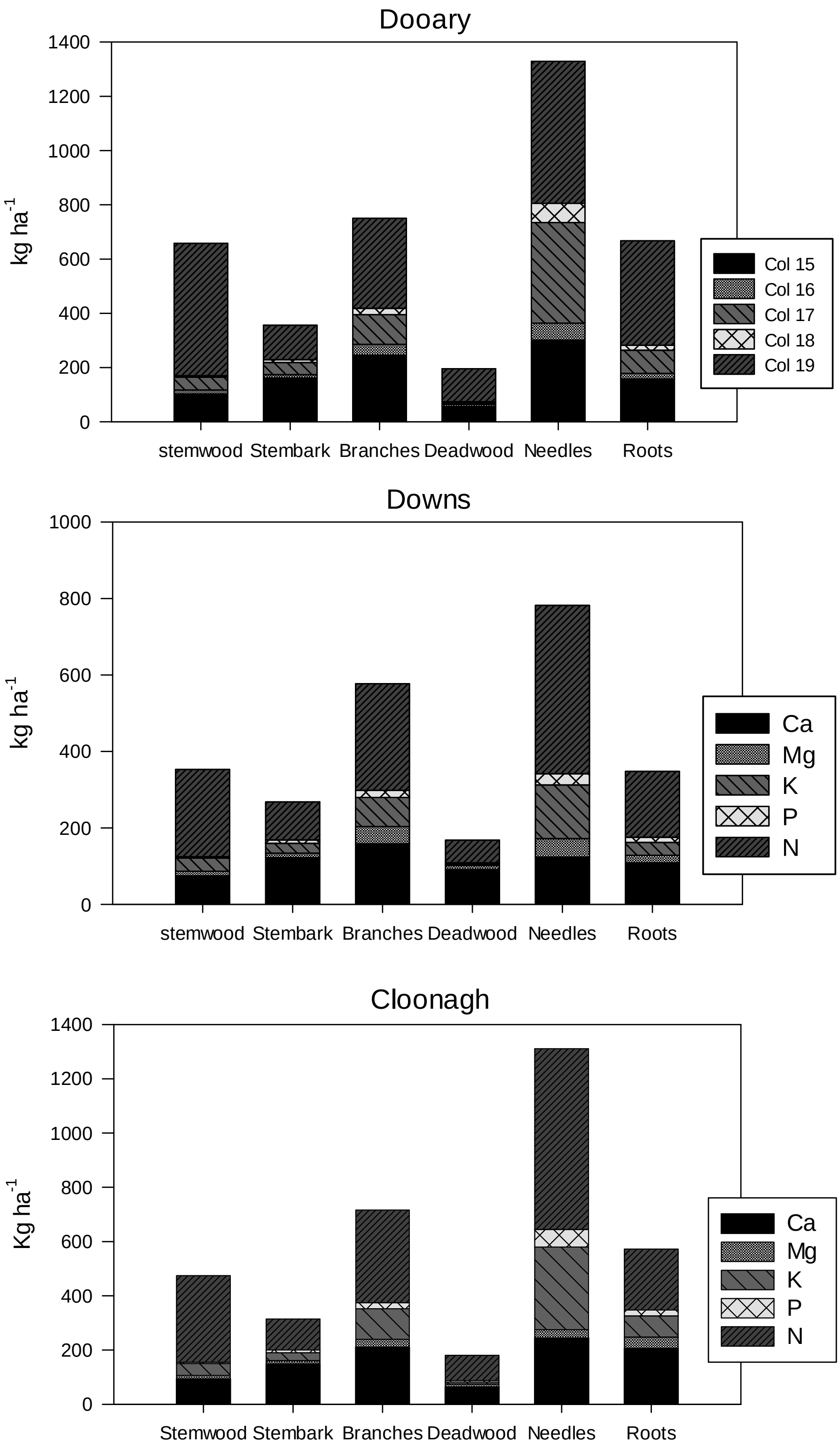

Fig 4. 11: Summary of nutrient pools (kg ha^{-1}) in different tree components in the three Sitka spruce study stands.

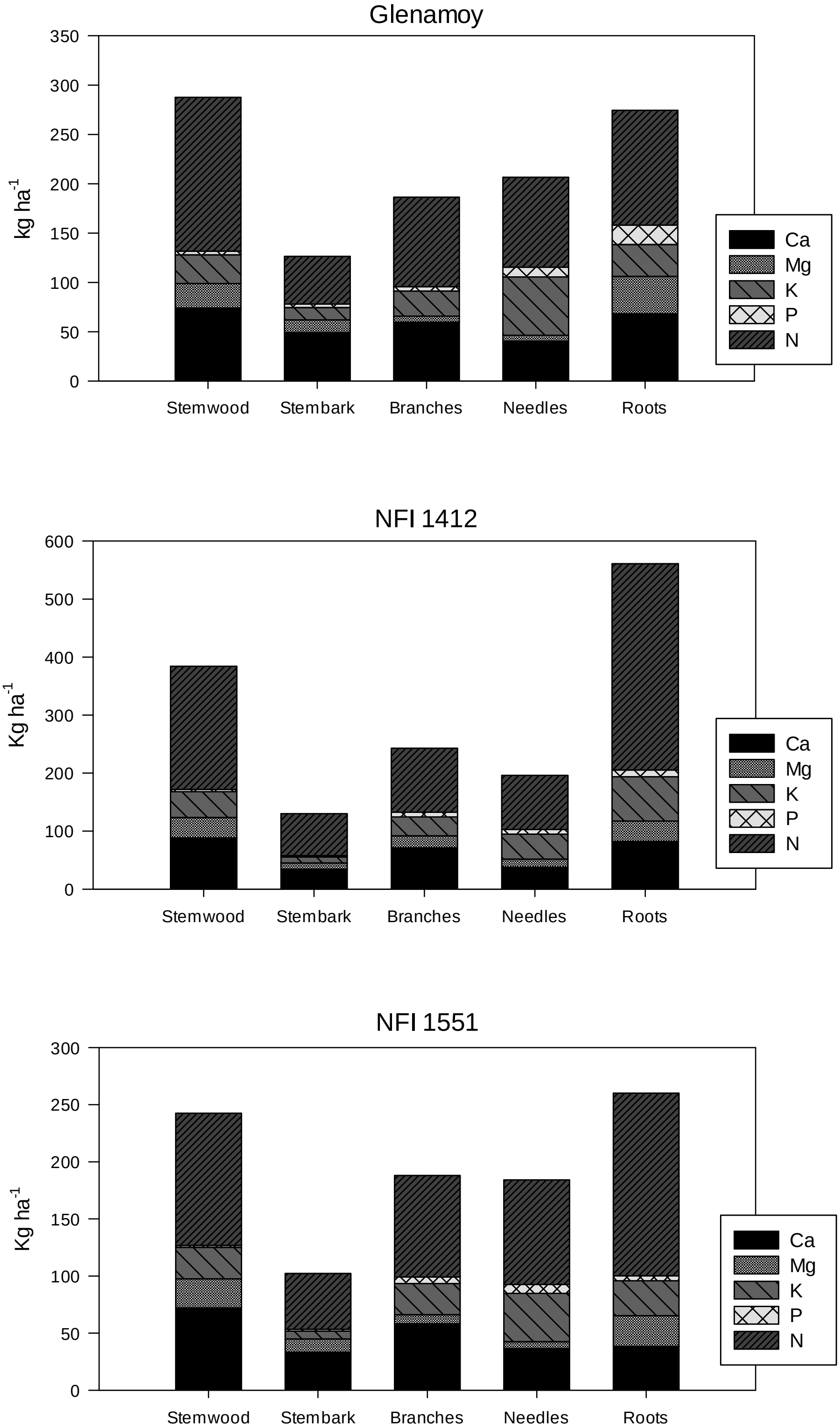

Fig 4. 12: Summary of nutrient pools (kg ha^{-1}) in different tree components in three lodgepole study stands.

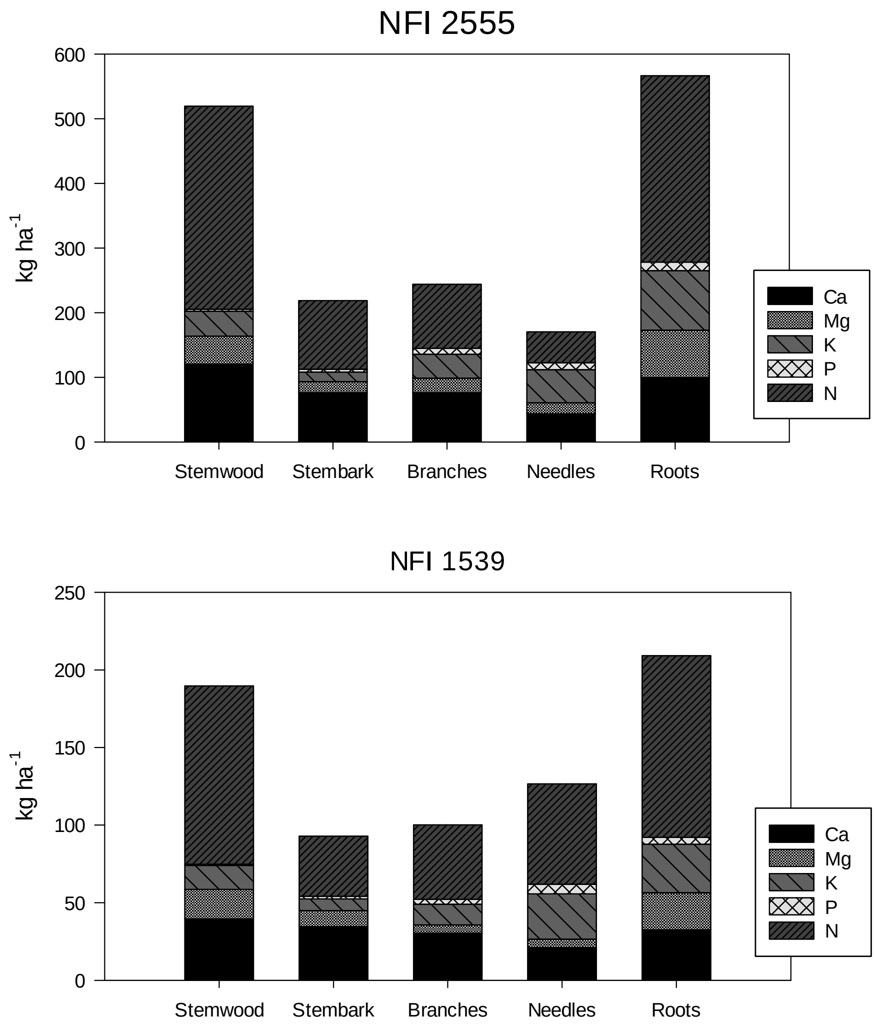

Fig 4. 13: Summary of nutrient pools (kg ha^{-1}) in different tree components in two lodgepole study stands.

4.2.4 Nutrient removal by harvesting

Nutrient pool removal in both Sitka spruce and lodgepole pine stands showed variation depending on the harvesting system. The highest nutrient removal was under WTH system, followed by SBH and SOH (Table 4.11, Fig 4.14). Although in Sitka spruce stands there were significant differences between all the nutrient pools and the type of harvesting, in lodgepole pine stands there were only significant differences between type of harvesting and K and P pools.

Nutrient removal, in general, was higher in lodgepole pine stands than in Sitka spruce stands across the three harvesting systems (Fig 4.14). Nitrogen removal was the highest in both species but also the most abundant in the studied sites. The highest element removed in lodgepole pine stands was Ca (78%) and in Sitka spruce stands was Mg (80%), and both under WTH system (Fig 4.14).

Table 4. 11: Comparison of nutrient removal (kg ha^{-1}) in three different harvesting scenarios in mature Sitka spruce and lodgepole pine stands. SOH, only-stem harvesting, SBH, stem and branch harvesting, WTH, whole-tree harvesting. Mean and standard deviation are reported.

			Nutrient removal (kg ha^{-1})		
		Nutrient pool	WTH	SBH	SOH
Sitka spruce	Ca	891 ± 186	529 ± 217	403 ± 131	235 ± 34
	Mg	147 ± 10	117 ± 32	89 ± 28	25 ± 1
	K	518 ± 182	300 ± 159	146 ± 46	75 ± 17
	P	113 ± 31	58 ± 35	28 ± 12	14 ± 2
	N	1672 ± 357	997 ± 402	700 ± 229	459 ± 145
lodgepole pine	Ca	519 ± 173	406 ± 143	339 ± 121	230 ± 85
	Mg	187 ± 69	116 ± 39	99 ± 32	78 ± 24
	K	300 ± 86	209 ± 65	125 ± 39	75 ± 20
	P	55 ± 17	36 ± 11	21 ± 7	9 ± 3
	N	1110 ± 308	749 ± 206	600 ± 195	438 ± 165

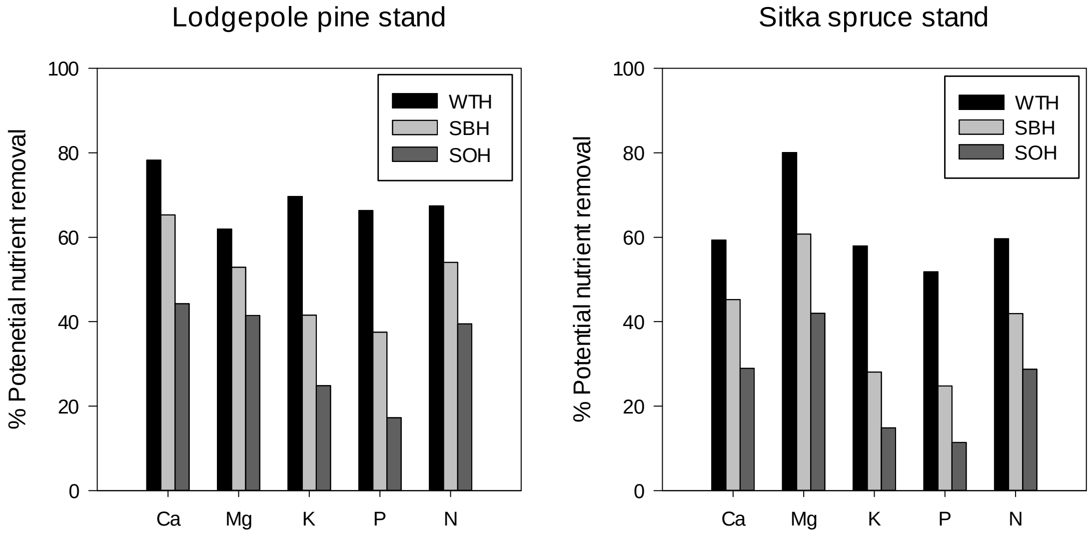

Fig 4. 14: Comparison of nutrient removal (%) between mature Sitka spruce and lodgepole pine stands in three different harvesting scenarios in. SOH, only-stem harvesting, SBH, stem and branch harvesting, WTH, whole-tree harvesting.

4.3 Nutrient removals in stemwood and harvest residue

4.3.1 Nutrient concentrations

The nutrient concentration in green and brown Sitka spruce harvest residue under different treatments was similar regarding the proportion of nutrient concentration. Nitrogen was the most predominant, followed by Ca, K, Mg, S and P (Table 4.12). Although nutrient concentration was significantly different neither among treatment nor among material, Table 4.12 indicated some differences. Harvest residue under ARD and DRR treatments had usually more nutrient concentration than NRD (Fig 4.15). Furthermore, green material contained more nutrients than brown material under ARD and DRR treatments, while it was the opposite under NRD treatment (Fig 4.15).

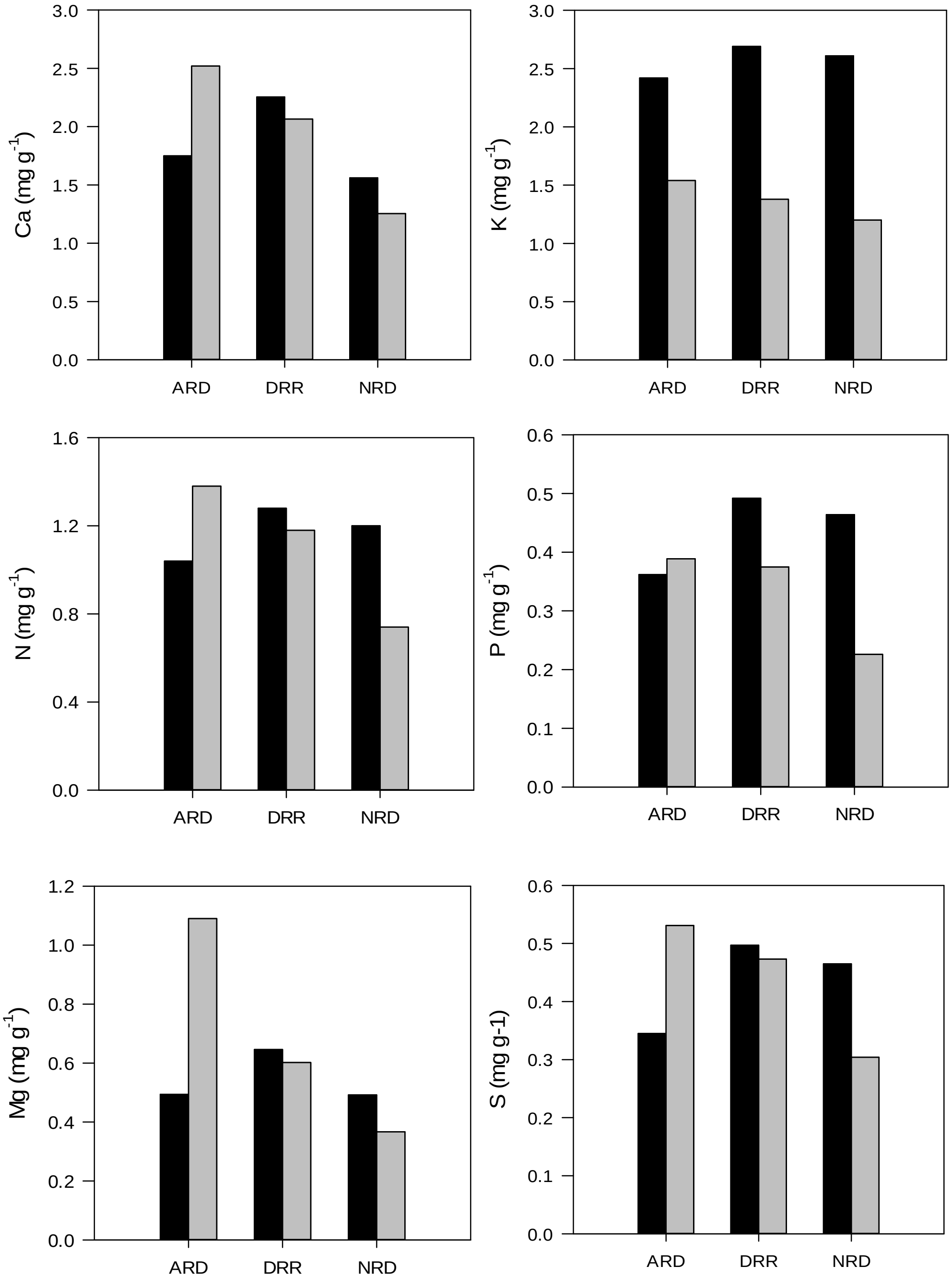

Fig 4. 15: Difference of nutrient concentration (mg g^{-1}) between green (after harvesting) and brown (seven months after harvesting) material in Sitka spruce harvest residue under three different treatments (ARD: All Residues Driven upon. DRR: Driving on Residues Reduced. NRD: No Residues Driven on). Black column represents Green material. Grey column represents brown material.

Table 4. 12: Summary of nutrient concentration (mg g^{-1}) in Sitka spruce harvest residue under three different treatments. ARD: All Residues Driven upon. DRR: Driving on Residues Reduced. NRD: No Residues Driven on .Green: brash after harvesting. Brown: brash 7 months after harvesting.

Treatmenet	Material	Nutrient concentration (mg g^{-1})					
		Ca	Mg	K	P	N	S
ARD	Green	3.50	0.49	2.42	0.36	5.20	0.35
	Brown	5.04	1.09	1.54	0.39	6.90	0.53
DRR	Brown	4.13	0.60	1.38	0.38	5.90	0.47
	Green	4.51	0.65	2.69	0.49	6.40	0.50
NRD	Green	3.12	0.49	2.61	0.46	6.00	0.47
	Brown	2.51	0.37	1.20	0.23	3.70	0.30

4.3.2 Nutrient accumulation in brown material

The major nutrient content in Sitka spruce harvest residue under the three different treatments is N pool (between 106.19 kg $ha^{-1}$and 117.30 kg ha^{-1}), followed by Ca (between 72.04 kg ha^{-1} and 85.68 kg ha^{-1}) (Table 4.13). Both of them were a great part of the total nutrient pools. Sulphur and P pools, in turn, were the lowest, followed by Mg and K pools (Table 4.13).

Table 4.13 and Fig 4.16 show that, in general, nutrient pools in harvesting residues under ARD treatment was usually the greatest, while it was lowest under NRD treatment. Nevertheless, there were exceptions. K pool was the highest in NRD treatment (34.44 kg ha^{-1}) as compared with the K pool in ARD and DRR treatments (26.18 kg ha^{-1} and 26.634 kg ha^{-1}respectively). The highest S and P pools were under DRR treatment (9.12 kg ha^{-1} and 7.23 kg ha^{-1}), although they were similar than those under ARD (9.02 kg ha^{-1} S pool and 6.61 kg ha^{-1} P pool).

Table 4. 13: Summary of nutrient pools (kg ha^{-1}) in Sitka spruce harvest residue under three different treatments. ARD: All Residues Driven upon. DRR: Driving on Residues Reduced. NRD: No Residues Driven on.

	Nutrient pool (kg ha^{-1})					
Treatment	Ca	Mg	K	P	N	S
ARD	86	19	26	7	117	9
DRR	80	12	27	7	114	9
NRD	72	11	34	6	106	9

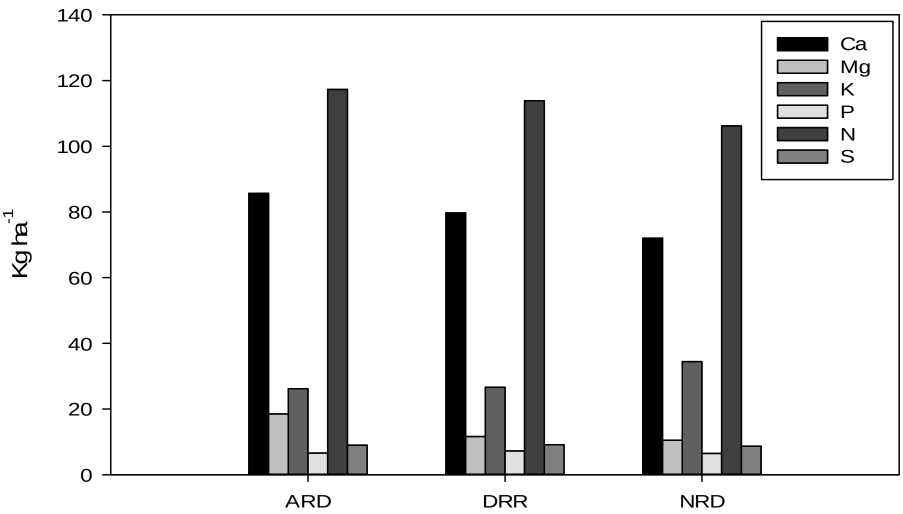

Fig 4. 16: Summary of nutrient pools (kg ha^{-1}) in Sitka spruce harvest residue under three different treatments (ARD: All Residues Driven upon. DRR: Driving on Residues Reduced. NRD: No Residues Driven on .Green: brash after harvesting)

CHAPTER 5. DISCUSSION

5.1 Biomass accumulation

Knowledge of biomass accumulation in forests is useful for many purposes such as timber production (Röser, 2008), energy (Hendrick and Black, 2009; EIA, 2012) and C stocks (Lunnan *et al.*, 2008; Hendrick and Black, 2009). In this study, biomass accumulation is estimated as a first step towards calculating the nutrient pool in forest biomass.

Many studies have shown that the amount of biomass in each forest depends on several factors such as stand density (Pearson *et al.*, 1984; Tobin and Nieuwenhuis, 2007), site conditions (Cole and Rapp, 1981; Pearson *et al.*, 1984; Tobin and Nieuwenhuis, 2007), stand age (Pearson *et al.*, 1984), yield class and management (Tobin and Nieuwenhuis, 2007). The estimates of stand level biomass for the sites investigated in this study are discussed below:

5.1.1 Lodgepole pine

The comparison of biomass between the stands of this study and other stands located in Ireland or UK was impossible as any information was found in the literature. Trees in America have greater crowns than those in Ireland because Irish forests are very dense and the sunlight does not penetrate as deeply through the canopy, thus the living crown of the trees are reduced (De Kovel *et al.*, 2000; Black *et al.*, 2004). In contrast to this, the needle and branch biomass in the stands that examined in this study was similar to the results obtained by Little and Shainsky (1992) and Monserud *et al.* (2006) (in studies from the west coast of America). Stembark, roots and stemwood biomass in this study (Table 4.9) were higher than those investigated by Little and Shainsky (1992) and Monserud *et al.* (2006). Overall, the total biomass of a lodgepole pine stand (a range between 231,05 tons ha^{-1} and 504,82 tons ha^{-1}) found in this study was higher than the mean that Monserud *et al.* (2006) and Little and Shainsky (1992) estimated (172,500 tons ha^{-1} and 145.800 tons ha^{-1} respectively) for stands in America. The difference of amount of biomass could be due to each study used a different allometric equation and therefore the error is greater. It is also possible that other factors are involved as discussed earlier. For instance, it has been reported that lodgepole pine stands are less productive in sites with bad drainage, low light exposure and no thining (Ní Dhubháin and O'Leary, 2002). Furthermore, the absence of allometric equations for lodgepole pine in Ireland, this study used equations from North America. This may lead to underestimation of relevant factors and generate less reliable results (Black *et al.*, 2004; Tobin and Nieuwenhuis, 2007), and therefore the results should only be generalised with care.

It was evident that NFI 1551 stand had the largest amount of biomass of the lodgepole pine stands (Fig 4.10). NFI 1551 stand had also the highest stocking density and according to Pearson *et al.* (1984), this is an important factor controlling the amount of biomass in lodgepole pine stands. Another stand with a high quantity of biomass is NFI 2555 stand. Although the stocking density is not as high in this case compared with that of NFI 1551 stand, factors such as good drainage might have influenced the growth of the tree (Dhubhain and O’Leary 2002).

5.1.2 Sitka spruce

In this study the total amount of biomass in a mature Sitka spruce (26-32 years old) varied between 151 and 355 kg (Table 4.8, Fig 4.8 and Fig 4.9). Carey and O’Brien (1979) who examined eight trees of 33 year old Sitka spruce, reported values between 38 and 257 kg, and Carey (1980), who examined a 50 year old Sitka spruce, showed values between 225 and 1290 kg in Ireland. Analysing each component of a tree, similar trends were found between these investigators. Overall, it is possible to state that the biomass of each tree component remained within the normal range although they were slightly greater than those reported by Carey and O’Brien (1979). However, the results of this research have shown that the standard deviation was high suggesting a high uncertainly associated with the biomass estimate and that the range obtained by Carey and O’Brien (1979) is also appropriate.

The biomass in the stand "Down" was the lowest of the Sitka spruce sites studied (Fig 4.10). Several factors could be accountable for this low values such as stand age, stand density, yield class and management. It is almost certain that stand age and density were not the reasons as "Down" stand was the densest and oldest stand of all. It may have a lower yield class, and therefore lower standing volume than the other sites. "Down" stand was also the only unthinned stand and this reduces the volume growth of a Sitka spruce (Skovsgaard, 2009; Pinno *et al.*, 2012).

Chronosequence

Biomass in the Sitka spruce chronosequence increased through time in all tree components (Table 4.3 and Fig 4.1). During the first years the growth in needles and branches were greater, but over time, stemwood accounted for a larger proportion of total biomass. Biomass in stemwood and roots was extremely large in comparison to other tree components between the 30 year old and 45 year old Sitka spruce stands. This finding is consistent with the investigation carried out by Tobin and Nieuwenhuis (2007) who also studied this chronosequence. Other investigators found similar trends for other tree species such as Peichl and Arain (2007) for a White pine *Pinus strobus* L. in Canada or Helmisaari *et al.* (2002) for a Scots pine *Pinus sylsvestris* L. chornosequence in Finland.

There is a large difference of total biomass between the 14 year old stand to 30 year old stand (Table 4.3 and Fig 4.1). It might be that the thinning carried out in the 30 year old has impacted the total biomass as it is demonstrated that this management has a positive impact in the height ant basal area growth (Pinno *et al.*, 2012).

Although the trends found here may be considered valid, care should be taken when extrapolating then to other sites as the results may differ under different circumstances or conditions. For example, deadwood decreased from 30 year old stand to 45 year old stand.

5.1.3 Comparison between species

The total biomass in lodgepole pine and Sitka spruce (Table 4.9 and Fig 4.10) and stands was similar to those reported by Ericsson (1994) in a natural forest (between 150,000 and 325,000 kg ha^{-1}), so it is reasonable to think that the climatic and edaphic conditions were not substantially different to affect the production of the stands. Stemwood accounted for the largest proportion of the total biomass for both species in a stand which is usual in a mature stand. Biomass in lodgepole pine stands tended to be greater than in Sitka spruce stands and this finding is in good agreement with Bothwell *et al.* (2001).

Root biomass in this study was equivalent to 10 and 16% of the above-ground biomass in lodgepole pine and Sitka spruce respectively. Olajuyigbe *et al.* (2012a) suggested that roots biomass is equivalent to 20% of the above-ground biomass. However, while this study only quantified coarse roots, Olajuyigbe *et al.* (2012a) also took into account the fine roots. It is also possible that other underlying factors are affecting the root biomass. For instance, Ericsson (1994) affirmed that root system tends to be smaller when the stand is under low light conditions and high soil moisture, which are both characteristics of Irish forests located in peat (Farell, 1985). Moreover, roots are difficult to study and it is expected to have a high variability because they are below-ground and it is difficult to visualize the growth form of the root system of the tree (Helmisaari *et al.*, 2007).

5.2 Nutrient concentrations and pools

Biomass is an important pool of nutrients in forest ecosystems (Cole and Rapp, 1981) and strongly influences the productivity and sustainability of the forests (Johnson *et al.*, 1982). An appropriate knowledge of Sitka spruce and lodgepole pine nutrition is required in order to better manage the stands and to maintain high productivity across successive rotations.

The nutrient content of a tree depends on several factors such as age, location, soil composition, tree species and components of the tree (Cole and Rapp, 1981; Savill and Evans, 1986; Ericsson, 1994; Finer *et al.*, 2003; Palviainen and Finér, 2012; Paré *et al.*, 2013). Information on the relationship between these factors and nutrients contents is not always readily available. Furthermore, Irish published works is very limited. These two factors prevent us having sound basis for decision-making. A discussion about each nutrient is presented below:

5.2.1 Nitrogen

Overall, N concentration of lodgepole pine was the highest in all the tree components, except in stembark where Ca concentration was greater. Needles and branches had higher N concentration than other tree components which is similar to other studies (Kimmins, 1975; Pearson *et al.*, 1987; Little and Shainsky, 1992). In this study, N concentration in needles (Table 4.6) was lower than the value reported by Asam et al. (2014) and Alriksson and Eriksson (1998) (Table 2.5). It was also observed that needles had lower N concentration, and branches and stemwood had higher N concentration (Table 4.6) than those calculated by Jacobson *et al.* (2000) for a general pine and by Paré *et al.* (2013) for a general conifer (Table 2.3).

The nitrogen concentration in Sitka spruce was higher in all the tree components than the values reported by other investigators of other countries (Beaton *et al.*, 1965; Jacobson *et al.*, 2000; Freer-Smith and Kennedy, 2003; Vanguelova *et al.*, 2010; Paré *et al.*, 2013) . Asam *et al.* (2014), Carey (1980) and Carey and O'Brien (1979) studied the N concentration of Sitka spruce under Irish conditions. While this study found a similar N concentration to Asam *et al.* (2014), it was lower than the results obtained by Carey (1980) and Carey and O'Brien (1979).

Overall, the concentration of N in both Sitka spruce and lodgepole pine stands were the highest (13.56 mg g^{-1} and 10.17 mg g^{-1} respectively) in needles. Plants always have high N concentration in needles, especially conifers as they do not have to replace annually the total foliage so do not need as much N as broadleaves to maintain their canopy (Cole and Rapp, 1981). Nevertheless, the concentrations in needles were below the optimum concentrations in both species according to Renou-Wilson and Farrell (2007) and Carter R. (1992) (Table 2.2). Although this could be taken to suggest that there is N deficiency and there are some facts that support this such as Irish soils are usually poor in N or that the N fixation is very low (Taylor, 1991), it should be remembered that this study sampled all years foliage with the objective of estimating potential nutrient removals in harvest, whereas Renou-Wilson and Farrell (2007) and Carter R. (1992) sought to establish the foliar N level below which deficiency occurs.

Bothwell *et al.* (2001) compared the N concentration in the needles of a 11 year old Sitka spruce and lodgepole pine stands and showed that lodgepole pine had a greater N concentration. This finding sustains the view that lodgepole pine needs less N than Sitka spruce to develop, so it remains in needles. Contrary to expectations, this research found that Sitka spruce had higher N concentration than lodgepole pine in needles. It may be that stands of lodgepole pine had much less access to N than those of Sitka spruce. For instance, Little and Shainsky (1992) have conclusively shown that, although the soil has a great N content, it does not necessary have to mean that trees will uptake it all.

A previous investigation suggests that the N content in a temperate forest is usually less than 10,000 kg ha^{-1} (De Kovel *et al.*, 2000). Based on the content of the N pool in a Sitka spruce and lodgepole stand found in this study (around 1700 kg ha^{-1} and 1000 kg ha^{-1} respectively), the statement that De Kovel *et al.* (2000) made is real but not practical, as the range of N content is very large depending on the stand. However, it was not possible to determinate a better approach.

Chronosequence

The chronosequence approach is a useful tool to rapidly obtain information on age-related changes in forests (Black *et al.*, 2009). Although Hellsten *et al.* (2013) did not find any correlation between nutrient concentration and age, the majority of investigators that studied a chronosequence concluded that nutrient content is related to the stage of maturity. However not all of them observed the same trends. According to Pearson *et al.* (1987), nutrient increment rates are positive through time, even in the oldest stands. In contrast, Cole and Rapp (1981) and Ranger and Turpault (1999) determined that during the first years of a stand, the nutrient demand increases over the age and thereafter, once that stand is mature, decreases. De Kovel *et al.* (2000) affirmed that once the tree is at the adult stage, the mean nutrient concentration depends mainly on wood chemistry. Although this study did not enable us to determine this last assumption, it did corroborate the statement of an increasing and thereafter decreasing N concentration, at least in stembark, deadwood and stemwood. Nitrogen concentration in aboveground biomass increased gradually over time until it was reached a specific age (around 30 year old) and then decreased (Table 4.1). Nitrogen concentration in needles, although it was not statistically significant with stand age, still showed a trend. A previous researcher hypothesized that older trees have lower growth rates and therefore they require less N (Fernandez Moya *et al.*, 2013).

It is believed that needles N concentration did not correlate with stand age because the N concentration in the 14 year old stand was lower than expected. This may be due to this site being less productive than the others. However, it should be listed that these results apply to this chronosequence only and additional chronosequences should be sampled if a broader picture is to be achieved. The concentration of N in roots and branches did not correlate with age. More intensive sampling may be required to verify if a trend exits.

5.2.2 Phosphorus

The concentration of P in lodgepole pine examined in this study was low (Table 4.6) compared to the concentrations reported by American, Canadan and Swedish investigators (Kimmins, 1975; Will *et al.*, 1979; Pearson *et al.*, 1987; Little and Shainsky, 1992; Alriksson and Eriksson, 1998; Paré *et al.*, 2013) (Table 2.4) . Nevertheless, the concentration was similar to the values that Asam *et al.* (2014) found, under Irish conditions. The P concentration in this study was very low compared to the P concentration that Jacobson *et al.* (2000) and Paré *et al.* (2013) revealed in a pine and in a conifer (Table 2.3).

In general, P concentration in trees of Sitka spruce in this study (Table 4.6) was lower than that reported elsewhere (Carey and O’Brien, 1979; Carey, 1980; Freer-Smith and Kennedy, 2003; Vanguelova *et al.*, 2010; Asam *et al.*, 2014) (Table 2.5). Phosphorus concentration in this study was also low compared to those found in a spruce and in a Doublas fir (Jacobson *et al*., 2000) and in a conifer (Paré *et al*., 2013) (Table 2.3).

The P concentration found in this study (1.18 mg $g^{-1}$and 1.06 mg g^{-1} in Sitka spruce and lodgepole pine respectively) are lower than those reported by Renou-Wilson and Farrell (2007) and Carter R. (1992), (1.8 mg g^{-1} and 1.5 mg g^{-1} in Sitka spruce and lodgepole pine respectively). While this could be taken to suggest that there is P deficiency in the Sitka spruce and lodgepole pine sites used in this study, it should be remembered that this study sampled all years foliage with the objective of estimating potential nutrient removals in harvest, whereas Renou-Wilson and Farrell (2007) and Carter R. (1992) sought to establish the foliar P level below which deficiency occurs.

5.2.3 Potassium

The potassium concentration in lodgepole pine trees of this study (Table 4.6) was low compared with studies in other countries, especially in stembark and stemwood (Kimmins, 1975; Will *et al*., 1979; Pearson *et al*., 1987; Little and Shainsky, 1992; Alriksson and Eriksson, 1998; Jacobson *et al*., 2000; Paré *et al*., 2013) (Table 2.3 and Table 2.4). Comparing the K concentration found in this study to the values reported by Asam *et al.* (2014) (also under Irish conditions), it is evident that the K concentration is similar in needles and branches. Bringmark (1977) studied the K concentration in Scots pine which was lower than the K concentration of lodgepole pine K in this study.

In general K concentration in Sitka spruce in this study (Table 4.6) was lower than those reported by other investigators in Ireland (Carey and O'Brien, 1979; Carey, 1980; Asam et al., 2014) (Table 2.5). Values for branches (1.55 mg g^{-1}) were extremely low compared to those obtained by Carey and O'Brien (1979) (4.09 mg g^{-1}) and Carey (1980) (3.56 mg g^{-1}). Comparing the K concentration of Sitka spruce tree with Douglas-fir *Pseudotsuga menziesii*, the difference the two species in stembark and stemwood became apparent. While K concentration in Sitka spruce of this study was 1.50 mg g^{-1} in stembark and 0.22 mg g^{-1} in stemwood, the K concentration that Jacobson et al. (2000) reported for Douglas-fir was 3.83 mg g^{-1} and 0.43 mg g^{-1} respectively.

The K concentration was low in both species in all tree components, especially in stembark and stemwood. These two components could have lower K concentration due to the peculiarity of trees having to transfer nutrients from one tree component to another through translocation (Augusto *et al.*, 2000). Having observed the optimal levels of K concentration in needles for both species according to Carter R. (1992) for lodgepole pine tree and Renou-Wilson and Farrell (2007) for Sitka spruce tree (Table 2.2) , it was notable that trees examined in this study had lower K concentration.

5.2.4 Calcium

The calcium concentration in lodgepole pine in this study (Table 4.6) is higher in branches and needles when compared with lodgepole pine in Canadian, American and Swedish sites whereas Ca concentration is lower in stem and bark (Kimmins, 1975; Will *et al.*, 1979; Pearson *et al.*, 1987; Little and Shainsky, 1992; Alriksson and Eriksson, 1998; Paré *et al.*, 2013) (Table 2.4). Asam *et al.* (2014), who also studied lodgepole pine in Ireland, found 1.22 mg g^{-1} in needles while this study found 4.42 mg g^{-1}. Jacobson *et al.* (2000) and Paré *et al.* (2013) studied the calcium concentration for pines and conifers (Table 2.3) and they found similar Ca concentration in all the tree components, except in stembark which was lower.

Calcium concentrations of Sitka spruce trees in this study (Table 4.6) are similar to those reported in several sites around Canada, UK and Ireland (Carey and O'Brien, 1979; Carey, 1980; Freer-Smith and Kennedy, 2003; Vanguelova *et al.*, 2010; Asam *et al.*, 2014) (Table 2.5). However, Ca concentrations in Sitka spruce of this study was lower than that found by Jacobson *et al.* (2000) and Paré *et al.* (2013) for spruces and conifers (Table 2.3). Comparing the Ca concentration of Sitka spruce of this study with that obtained in Douglas-fir by Jacobson *et al.* (2000) (Table 2.3), it was observable that Ca concentration in needles and in branches was less in Sitka spruce but higher in stembark and stemwood. It may be that Ca concentration can differ between species and can reflect adaptation to the type of the soil where trees are located (Paré *et al.*, 2013).

Calcium concentration in mature trees is usually highest in stembark. Whilst the Sitka spruces in this study have demonstrated this, the lodgepole pines appear to have a lower Ca concentration. The Ca concentration in needles of Sitka spruce and lodgepole pine were higher than those reported by Carter R. (1992) and Renou-Wilson and Farrell (2007) (Table 2.2). While this could be taken to suggest that the Ca concentration is optimum in the Sitka spruce and lodgepole pine sites used in this study, it should be remembered that this study sampled all years foliage with the objective of estimating potential nutrient removals in harvest, whereas Renou-Wilson and Farrell (2007) and Carter R. (1992) sought to establish the foliar Ca level below which deficiency occurs.

5.2.5 Magnesium

The Mg concentration in lodgepole pine in this study (Table 4.6) was in accordance with the results reported by other investigators (Kimmins, 1975; Will *et al.*, 1979; Pearson *et al.*, 1987; Little and Shainsky, 1992; Alriksson and Eriksson, 1998; Jacobson *et al.*, 2000; Paré *et al.*, 2013) (Table 2.4). A study carried out by Asam *et al.* (2014) and the results of this study, both under Irish conditions, showed similar Mg concentration in branches (0.71 and 0.72 mg g^{-1} respectively).

The concentration of Mg found in Sitka spruce needles in this study (Table 4.6) was similar to those from Sitka spruce trees in other Irish sites (Carey and O'Brien, 1979; Carey, 1980; Freer-Smith and Kennedy, 2003; Asam *et al.*, 2014) and in the UK (Vanguelova *et al.*, 2010) and slightly higher than in Canada (Paré *et al.*, 2013) (Table 2.5). In general, Mg concentration was higher in Sitka spruce compared with the Mg concentration that Jacobson *et al.* (2000) found in a spruce (Table 2.3). However, Mg concentration was similar or even lower in some components such as stembark and stemwood than the values that Paré *et al.* (2013) discovered in conifers (Table 2.3).

Magnesium concentrations in the needles of both species were within the optimal values that (Renou-Wilson and Farrell, 2007) and Carter R. (1992) reported for Sitka spruce and lodgepole pine (Table 2.2). However, it should be remembered that this study sampled all years foliage with the objective of estimating potential nutrient removals in harvest, whereas Renou-Wilson and Farrell (2007) and Carter R. (1992) sought to establish the foliar Mg level below which deficiency occurs.

5.2.6 Relation between nutrients

The strongest correlations among nutrient concentrations were found in needles and stembark, followed by branches and deadwood (Table 4.7). All these components correlated strongly Ca-P and K-P. Needles and branches also found a correlation between Ca-N, N-P and K-N, although weaker than Ca-P and K-P (Table 4.7). There was little correlation between stemwood and roots. In stemwood there was only a correlation between Mg-Ca, two of the elements that are usually accumulated in permanent plant structures. Roots only showed a correlation between Ca-P. However, this relation was stronger that that of stemwood. The lack of correlation among nutrients suggests that the removal of an element does not imply that there will be an export of another nutrient (Paré *et al.*, 2013).

The correlation among nutrients may be useful to predict the growth of a tree or the nature of nutrient limitation in a site. For instance, Koerselman and Meuleman (1996) suggested that the N:P ratio could detect the nature of nutrient limitation. Jonard *et al.* (2015) also affirmed that high N and S deposition has an affect on P nutrition. This study analyzes the correlation between nutrients (Table 4.7) and compared the results to the investigation carried out by Paré *et al.* (2013). It was found that Mg showed little correlation with other nutrients. This finding was unexpected because Paré *et al.* (2013) suggested that Mg showed the strongest correlation with other elements in all the tree components except for stembark. Furthermore, there were many nutrient correlations in the stembark in this study, whereas Paré *et al.* (2013) found hardly any.

5.2.7 Overview of nutrients in biomass

In general, it was found that nutrient concentrations were higher in the actively growing components of the trees and lower in the structural components. Both tree species showed that needles was the component with the largest nutrient concentrations and stemwood was the component with the lowest (Table 4.6 and Fig 4.7) as previous investigations indicated (Mann *et al.*, 1988; Ericsson, 1994; Ingerslev, 1999; Ranger and Turpault, 1999; Kofman *et al.*, 2007; Tobin and Nieuwenhuis, 2007; Raulund-Rasmussen *et al.*, 2008; Röser, 2008; Palviainen and Finér, 2012; Paré *et al.*, 2013; Zhang *et al.*, 2014).

Nutrient concentration in trees, according to Pearson *et al.* (1987), were identified from the highest to the lowest: N > Ca > K > Mg > P. This trend was found in both lodgepole pine and Sitka spruce (Table 4.6 and Fig 4.7). However, K concentration was higher than Ca concentration in needles. Renou-Wilson and Farrell (2007) and Carter R. (1992) also suggested that K concentration is greater than Ca concentration in needles (Table 2.2)

Needles are usually analysed to know what nutrients are limited in a site. Renou-Wilson and Farrell (2007) presented an indicative table to identify the nutrient limitation of Sitka spruce and the grade of this limitation. Carter R. (1992) proposed similar table for lodgepole pine (Table 2.2). Comparing these tables with the values of this study, it was possible to observe that Mg and Ca concentrations were high (Table 4.6). Meanwhile, K, P and N concentrations were low in both species. These relatively low nutrient levels might be causing a growth reduction as these nutrients are responsible for growth (Na, 2007). However, the stands of this study are mature and it is believed that it is more difficult to assess the nutrient status of mature stands.

Sitka spruce in this study had higher Ca, K, P and N concentrations in needles and stembark (Table 4.6 and Fig 4.7) than lodgepole pine which is in agreement with Palviainen and Finér (2012). It may be that Sitka spruce stores more nutrients in order to use them subsequently. In general, pine is more tolerant of nutrient poor conditions. For instance, Carey and Hendrick (1986) observed that on nutrient-poor peatlands and heathlands in Britain and Ireland, lodgepole pine required less P fertilizer. Therefore, it is possible that, if there is nutrient availability, they make every endeavour to absorb nutrients. However, other studies found that trees absorb all the nutrients available in a stand. This leads to the possibility that Sitka spruce nutrient concentration is greater because these stands have more nutrients available. It is also possible that Sitka spruce stands had less accessibility to Mg as the concentration of this element in Sitka spruce trees is lower than lodgepole pine trees in all the components.

5.3 Nutrient pools and potential nutrient removal in harvest

Nutrient pools and potential nutrient removal in a stand depend on tree species, development stage of the stand and harvesting method (Augusto et al., 2000; Finer et al., 2003; Clarke, 2012; Palviainen and Finér, 2012). This study aims to investigate and discuss this. De Kovel *et al.* (2000) also found that biomass production affects the nutrient pools. Nutrient removal can have a negative impact on the ecosystems in the long term. Forest harvesting exports nutrients and De Kovel *et al.* (2000) and Johnson *et al.* (1982) suggest that the frequency of harvesting might cause the nutrient removal to vary but it was not possible to discuss this statement in this study as there is not enough information available.

- **Do the nutrient pools and potential nutrient removal depend on development stage of the stand?**

This investigation studied the N pool of a Sitka spruce chronosequence and it demonstrated that the more mature a stand is, the larger the available N pool is. For instance, the 9 year old Sitka spruce stand of this study could have 225 kg ha^{-1} while the 45 year old stand could contain 1586 kg ha^{-1} (Table 4.4). In contrast, it was possible to observe that the percentage of N pool in young stands (0.36 - 0.93% of the total biomass) is greater than in older stands (0.22 - 0.29% of the total biomass) of this study. It is likely that all the nutrients are related to the stage of the stand’s development however this research was limited to N.

- **Do nutrient pools and potential nutrient removal depend on tree species?**

This study compared the nutrient pools among mature Sitka spruce and lodgepole pine stands. In general, Sitka spruce stands had greater nutrient pools than lodgepole pine stands (Table 4.10). Comparing the mean between the two species, it was found that

Sitka spruce stands can contain double amount of K, P and Ca pools and slightly less than double of N pool. In contrast, the Mg pool was estimated to be slightly greater in lodgepole pine, although the percentages were similar (0.019 and 0.023 % of the total biomass).

- **Do the nutrient pools and potential nutrient removal depend on the harvesting method?**

The results tended to be the same for all nutrients in lodgepole pine and Sitka spruce stands: nutrient removal was greater under WTH system and lesser under SOH system. Observing in detail the removal of each nutrient it was found that that WTH removed double or almost double the amount of nutrients than SOH from the site (Table 4.5, Fig 4.6, Table 4.11 and Fig 4.14) as Helmisaari et al. (2014) and Luiro et al. (2009) suggested. This probably occurs because small branches contain higher nutrient concentrations than stems (Mann 1988, Helmissari 2014, Luiro 2009) and WTH system removes these components while SOH retains them. As WTH system removes more nutrient amounts, it is hypothesized that the production of the stands under WTH system will be lower than under SOH in the future as Proe *et al.* (1996) stated.

It must also be stated that in this study, deadwood has not been accounted in the nutrient removal of SOH system but it may be included in some cases. Therefore it is useful to take into account that nutrient removal could be greater if deadwood is also removed from the forest.

No significant differences were found between nutrient concentration in a Sitka spruce harvest residue (bundles) and the treatment followed (ARD, DRR, NRD) (Table 4.12). Nutrient concentration in Sitka spruce harvest residue (bundles) was not clearly related to the type of material (brown and green) either (Table 4.12). There was no correlation between the nutrient pool that a bundle contains and how the harvest residues to make bundles have been removed from the sites (Table 4.13 and Fig 4.16). Given that this was limited to one site it should not be applied to other sites and further investigation across a range of sites is recommended.

- **Do nutrient pools and potential nutrient removal depend on other factors?**

The extent of N pool in sites that contain similar species of the same age can vary considerably (more than double). The N removal in the 45 year old Sitka spruce stand after bundling was 0.63% of the total biomass (it is assumed that bundles are made from all tree components except the roots) (Table 4.13) and 0.29% in the 45 year old Sitka spruce stand in the Dooary Sitka spruce chronosequence study (Table 4.5). Nitrogen removal varied greatly when the two different data sources of mature Sitka spruce stands (between 26 and 33 year old) of this study were compared. The range of percentage of potential N removal in the 30 years old Sitka spruce stand in the Dooary Sitka spruce chronosequence study was between 0.40% and 0.46% depending on the harvesting type (Table 4.5) whereas the mean of the other three mature Sitka spruce stands was in the range among 0.18% and 0.25% (Table 4.11). However, the minimum of these stands was 0.08% and the maximum was 0.48% and therefore the range of the 30 year old Sitka spruce stand in the Dooary Sitka spruce chronosequence was within the range of the other mature Sitka spruce stands. In addition to age, species and type of harvesting, the nutrient pools and potential nutrient removal of a site may be affected by other factors such drainage (Savill and Evans, 1986).

Finally, the results are only considered as estimates for many reasons. For instance, this study considered a removal of 100% of harvesting residues according to each harvesting system. However, other investigators who studied stands of Sitka spruce and lodgepole pine stands in Ireland assumed different percentages. Johnson *et al.* (2015) assumed that 70% of branches and needles were available for removal. Mockler (2013) estimated a residual material of 53% in lodgepole pine stands and 44% in Sitka spruce stands. Merilä *et al.* (2014) thought that sparing just 30% of canopy biomass was not enough for the provision of nutrient needs in future rotations. (Pyörälä *et al.* (2012)) proposed to leave 40% of the harvest residues on site. More research should be undertaken in order to determine how much harvest residue must be left on sites to be sustainable and productive in the long term.

CHAPTER 6. CONCLUSIONS

The total biomass in both Sitka spruce and lodgepole pine stands was within the normal range of a forest. NFI 1551 had more amount of biomass than the other lodgepole pine stands probably because its tree density was higher. Regarding Sitka spruce stands, Down site had less biomass than others probably because it was unthinned while the others Sitka spruce stands had not been thinned. This study found significant difference in the amount of tree level biomass between species in needles and branches whereas there was no significant difference in total stand biomass between species. Needle and branch biomass of a tree was greater in Sitka spruce than in lodgepole pine. Root biomass was slightly less than expected.

Although the results can be considered valid and successfully used for other studies, the allometric equations used were not created for Irish forests conditions and future work should involve creating specific allometric equations for Irish forests in different tree development stages.

In general, nutrient concentrations were higher in the actively growing components of the trees and lower in the structural components. Both species showed that needle was the component with higher nutrient concentration and stem the lowest. Nutrient concentration in a tree for both species was identified from large to lesser concentration: N > Ca > K > Mg > P, although K concentration in needles was higher than Ca concentration. The nutrient concentration in needles and branches varied according to the tree species. Sitka spruce had higher nutrient concentrations in needles than lodgepole pine whereas in branches the opposite occurred. Stemwood also presented differences for Ca, K and N. Magnesium presented normal levels of concentration in needles whereas Ca concentration was high and K, P and N concentrations were low. Nutrient correlation in the tree components was different between this study and other investigators. Furthermore, the correlation between nutrients was also different to those studied by other investigators. Nutrient correlation could be a good tool to study the nutrient content but the findings of this study suggest that further study of the issue is still required.

Nitrogen concentration of a tree and age was correlated in stembark, deadwood and stemwood. The N concentration increased over time until it was reached a specific age and then decreased. From 30 year old to 45 year old, N concentration decreased in all the tree components. There was no correlation in needles although it did follow the same trend as the other three tree components while branches and roots did not. There was a significant difference in Sitka spruce biomass and biomass N pool between stands of different age. Biomass in a Sitka spruce chronosequence increased over time in all tree components. When the stand was young, needle and branch biomass increased significantly, but over time, when trees were mature, the increase of stemwood and root biomass was greater. Summing up the results, it can be concluded that trees have a pattern in growth of biomass and nutrient pools.

Nutrient pools and potential nutrient removal were associated with three main factors: age, species and type of harvesting. The findings of this research are quite convincing, and thus the following conclusions can be drawn: the more mature is a stand, the more N pool there is in a site and therefore highest potential N removal; Sitka spruce stands have larger nutrient pools than lodgepole pine stands and therefore Sitka spruce could export greater amount of nutrients; WTH removes double or almost double the amount of nutrients removed by SOH. It has been demonstrated that there is no correlation between the nutrient concentration in a brash bundle and the treatment followed to create this bundle (ARD, DRR or NRD), nor between nutrient concentration and the type of material (brown or green). There is no correlation either between nutrient pool that a brash bundle contains and how the harvest residues to make bundles have been removed from the sites. The results also suggest that other factors besides age, species and type of harvesting might affect the nutrient removal of a site. Further study of the issue would be of interest. Several investigators have suggested different percentages of harvest residues to be retained on field in order to manage the forest sustainably. More research will be needed to verify what amount of harvest residue and what type of it must be left on site.

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APPENDICES

Appendix 1: Location map of the study sites