Universiteit Utrecht

Master thesis

Sustainable forestry residue parameters

Lucy Buck
3212793
l.buck@students.uu.nl

Master thesis
30 ECTS

Utrecht University
3-7-2013

Supervisors:
Birka Wicke
Vassilis Daioglou

Executive Summary

Energy demand is growing and could potentially be aided by using more forestry products in energy production. One option is forestry residues, those parts of the tree that generally remain on the field after harvest. In order to investigate the possibilities of the forestry residue option, several potentials are calculated in the course of the research. These potentials are theoretical potential, which is all aboveground biomass excluding the merchantable stem, and the sustainable potential, the aboveground biomass excluding some fraction that is used to protect biodiversity and nutrient cycling.

The potentials are calculated for combinations of management options and biomes. The management options are clearcut (natural and semi-natural forests) and plantations. The five biomes that are distinguished are boreal forest (BF), cool conifer forest (CC), temperate mixed forest (TM), temperate deciduous forest (TD) and warm mixed forest (WM). Only two of the biomes have enough plantations to be valuable for research and these are temperate deciduous plantations (TDM) and warm mixed plantations (WMP).

The method that is used to calculate the potentials is based on branchiness, which is the ratio of crown mass to stem mass. This is a measure of the amount of residues produced based on the amount of wood taken out of the forest for timber production. The branchiness is calculated for different genera that are combined into plant functional types (PFTs). These PFTs are then combined to form the biomes. Branchiness is then used in combination with the production of stemwood to determine the theoretical amount of residues that can be produced during final harvest.

Within wood production there are more harvest stages then just harvest, another is thinning. Thinning is the process of removing some trees such that better wood will be produced at final harvest. During thinning, which can be done in multiple stages, trees are removed and they can also produce residues. Thinning stages, thinning branchiness, thinning fractions and the final production are used as an approximation for the amount of thinning residues. These thinning residues need to be added to the residues from harvest to arrive at a full total potential.

Once all the residues accrued over the lifetime of the forest are combined, that value is divided by the rotation length of the stand in order to produce the theoretical potential. The theoretical potential is highest in the TDP and WMP (1367 and 3109 kg/ha/yr respectively) since they have high production. For clearcut, the BF, CC and TD produce similar amounts of residues at the high end of the results (663, 638 and 649 kg/ha/yr respectively). The WM clearcut produces the least amount of residues (456 kg/ha/yr) due to lower branchiness and production. The BF and CC forests produce the most residues compared to the other clearcuts over their lifetime, but their lifetime is longer and therefore this is obscured in the theoretical potential.

The sustainable potential was calculated using a number of guidelines. The most important guidelines were that at least 10 tonnes of residues per hectare should remain in the forest and that all foliage should be retained also. Leaving an amount of residues in the forest will aid nutrient cycling and biodiversity, it will keep the soil in a good shape and assist with water holding capacity.

The percentage of the total final harvest residues that was foliage was calculated and compared to the percentage of residues from final harvest that were equal to 10 tonnes of residues. The highest of these percentages was deduced from the final harvest residues to determine sustainable final harvest levels. For thinning, all leaves should also remain in the forest and therefore thinning residues were deduced by the percentage of residues that is leaves. These two reduced residue amounts are added and divided by the rotation length. The resulting value is the sustainable potential.

Sustainable potential was again highest in plantations (TDP: 937 kg/ha/yr and WMP: 1958 kg/ha/yr) as these have the most residues to begin with. WM clearcuts have the lowest sustainable potential (281 kg/ha/yr), while BF and TD clearcuts have the highest potential (471 and 468 kg/ha/yr respectively). Technical limits of recovery are such that the sustainable potential is achievable.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

b	Branchiness (kg_{crown} / kg_{stem})
BDT	Boreal deciduous tree
BEC	Boreal evergreen conifer
BF	Boreal forest
CC	Cool conifer
CT	Commercial thinnings
CTC	Cool-temperate conifer
CTR	Complete tree residues
d	Density of wood (kg/m^3)
DBH	Diameter at breast height
DCNR	Department of Conservation and Natural Resources
EEA	European Environment Agency
FAO	Food and Agriculture Organisation of the United Nations
FSC	Forest Stewardship Council
GDD	Growing degree day
ha	Hectare (10000 m^2)
hr	Harvest residues (kg/ha)
Kg	Kilogram
MCPFE	Ministerial Conference on the Protection of Forests in Europe
Mg	Megagram or tonnes (1000 kg)
MNP	Milieu- en Natuurplanbureau (Netherlands Environmental Assessment Agency)
n.a.	Not applicable
p	Production ($kg_{stemwood}$ /ha)
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
PCT	Pre-commercial thinnings
PFT	Plant functional type
pv	Production volume ($m^3{}_{stemwood}$ /ha)
rl	Rotation length (years)
RQ	Research question
sfh	Sustainable fraction of harvest (%)
SFM	Sustainable Forest Management
sft	Sustainable fraction of thinning (%)
SOC	Soil organic carbon
SOM	Soil organic matter
SRC	Short rotation coppice
t	Tonne (1000 kg)
tb	Thinning branchiness (kg_{crown} / kg_{stem})
TD	Temperate deciduous
TDP	Temperate deciduous plantation
TDT	Temperate deciduous tree
tf	Thinning fraction (% of trees removed per thinning)
TM	Temperate mixed
TP	Theoretical potential
tr	Thinning residues (kg_{crown}/ha)
ts	Thinning stages (amount of stages)
UNECE	United Nations Economic Commission for Europe
WCED	World Commission on Environment and Development
WM	Warm mixed
WMP	Warm mixed plantation
WTE	Warm-temperate evergreen
WTR	Whole tree residues
WTRS	Whole tree residues + stump
yr	Year

1. Introduction

1.1. Background

Forests have many functions; they provide ecosystem services and form part of the landscape (Duncker et al., 2012). Moreover, they supply an important commodity in the form of industrial roundwood for commercial purposes and fuelwood (Scarlat, Blujdea, & Dallemand, 2011). In many developing countries, biomass is primarily used for energy, often produced unsustainably since it is not being replaced (Goldemberg & Teixeira Coelho, 2004; Siry, Cubbage, & Ahmed, 2005). However, interest in biofuels and biomass for energy production is increasing, also in developed countries (Duku, Gu, & Hagan, 2011; Stupak et al., 2007). Reasons for this include the growing global population and associated energy use, fluctuating fossil fuel prices and predicted climate change (Duku et al., 2011; Siry et al., 2005).

In order to keep the impacts from using more energy from exacerbating the problems associated with climate change, the fuels used have to be sustainable. The sustainability of biomass rests on the assumption that the carbon emitted during burning was taken up from the atmosphere during the lifetime of the plant, and can be taken up again by new vegetation (Stupak et al., 2007). However, the carbon neutrality of wood is being questioned (Holtsmark, 2011; McKechnie, Colombo, Chen, Mabee, & MacLean, 2011; Schlamadinger, Spitzer, Kohlmaier, & Lüdeke, 1995) as it can take longer than a rotation cycle for trees to take up the carbon from the harvested trees, thereby leaving a carbon debt (Holtsmark, 2011).

Using the by-products such as residues for energy is not as controversial. The land on which they are produced is already in use. Moreover, the land that would be required for energy crops is decreased. Inputs of residues are reduced and production processes are already implemented (Gregg & Smith, 2010). Much of the forest biomass is currently unused, including, trees that are too small to harvest with machines, abandoned residues, rotten and crooked trees and dead standing trees (Andersson et al., 2002). By utilising these unused sources, more energy can be produced. However, using residues can also increase the harvest of trees due to increased demand for residues (Holtsmark, 2011).

Nevertheless, next to energy production, residue removal has other benefits. These include decreasing the risk of forest fires, a healthier forest, recreation purposes, improving aesthetics and it advances the growth of trees in early stand development (Grebner et al., 2011; Malinen, Pesonen, Maatta, & Kajanus, 2001; Polagye, Hodgson, & Malte, 2007; Wilkerson & Perlack, 2011). On the other hand, some other ecosystem services are disturbed when logging occurs. Biomass removal can lead to soil degradation as nutrients are not returned to the soil upon harvest and erosion can occur (Flaspohler et al., 2011; Gregg & Smith, 2010; Malinen et al., 2001; Stupak et al., 2007; Wilkerson & Perlack, 2011; Woods, 2007). Moreover, biodiversity can decrease and habitats are disrupted or destroyed (Flaspohler et al., 2011; Stupak et al., 2007).

While much research has been done on forestry and agricultural residues, the problem remains that there is not a single definition for it. Moreover, differences in the types of limitations, data and scope can impact the potentials for forestry residues (Smeets & Faaij, 2006). Since this may become an important source of renewable energy feedstock, it is necessary to produce a consistent definition as well as an understanding of how residue removal affects different forests and forest types.

1.2. Research aim

This study will act as a contribution towards a larger PhD project that is being carried out. One of the goals of the PhD project is to determine the potentials of forestry residues and project them into the future. The goal of this thesis is to develop a definition for the theoretical potential, and a method for calculating it. Moreover, it also serves to determine factors related to the sustainability of forestry residues and whether these differ between biomes and between management regimes.

1.3. Research questions

In order to achieve the research aim, a number of research questions (RQs) have been developed that will be answered in the course of this research. This section will list the main research questions and sub questions. The two main research questions (RQ) are numbered 1 and 2 and referred to as RQ1 and RQ2. The sub questions are listed per main research question and given a, b, and c classifications. Figure 1 shows the progression from sub-research questions to research questions.

1. What are the drivers of the theoretical potential for forestry residues and how can these be parameterised?
   - 1.a. Which parts of the forest are considered to be forestry residues?
   - 1.b. How is the parameterisation of the theoretical potentials different for the different biomes?
   - 1.c. How is the parameterisation of the theoretical potentials different for the different management options?
2. What are the drivers of sustainable harvesting of forestry residues and how can these be parameterised?
   - 2.a. What factors influence the sustainable recovery of forestry residues for energy production?
   - 2.b. Based on these factors, how can sustainable recovery of forestry residues in the biomes be parameterised?
   - 2.c. How are these factors parameterised for the different management options?

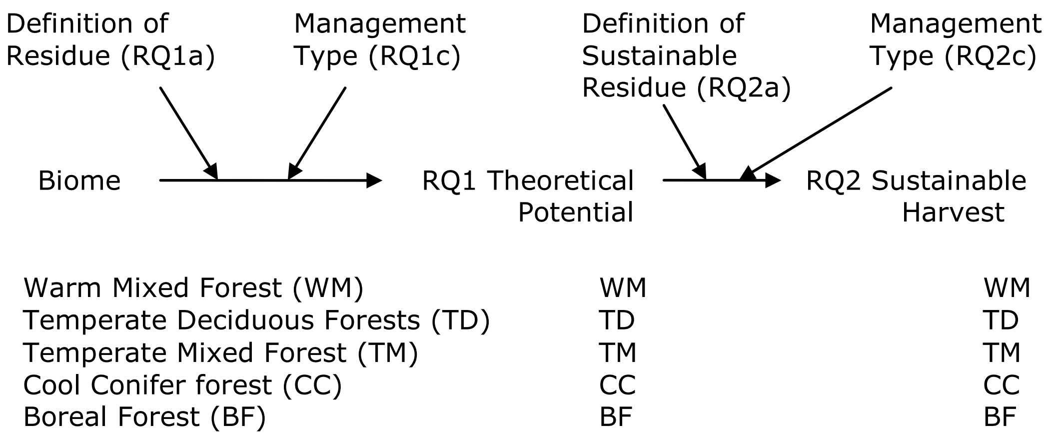

Figure 1. Structure of the research questions.

2. Methodology

The aim of this chapter is to provide the framework on which this research has been based. It will explain the boundaries and assumptions that have been made, give the definitions that will be used throughout the research and describe the procedures that were followed.

2.1. Definitions, boundaries and assumptions

This study will solely look at the aspects that influence the availability and sustainability of forestry residues. Only issues that are directly related to the forest are taken into account. The processes after harvest, e.g. transport and incineration, are not reviewed. It will not provide actual estimates for potentials of energy production from forestry residues.

2.1.1. Forests

Forests are collections of trees with over 10% crown cover, and at least 0.5 ha in size (FAO 1998b in Smeets & Faaij, 2006). Moreover, three different forest types are distinguished: natural forests, semi-natural or regenerated forests and plantations. Natural forests are defined as "forests composed of native species that are managed and utilized but regenerated naturally following their harvest or forests undisturbed by human management" (Siry et al., 2005, p. 553). The Food and Agriculture Organisation of the United Nations (FAO) distinguishes between primary forest, without human activities, and other naturally regenerated forests, where there are human activities present (Food and Agriculture Organisation of the United Nations [FAO], 2010). However, here these are combined into natural forests.

Plantations are forests that are heavily managed and planted specifically for the production of a type of forest product. Industrial plantations are for producing industrial roundwood, while non-industrial plantations can be for wood fuel or soil and water aspects (Smeets & Faaij, 2007; Siry et al., 2005). SRC plantations will be ignored as their primary purpose is to produce wood fuel (Andersen, Towers, & Smith, 2005). Plantations can consist of native or exotic species, which are often chosen for their fast-growing abilities (Siry et al., 2005).

In between plantations and natural forests are semi-natural forests. These are forests with mostly native species planted for timber production but with a very long rotation time, around 100 years (Siry et al., 2005). These will be grouped with natural forests in this research.

2.1.2. Biomes

This thesis is a small part of a larger research into biomass production. The basis of the research is the IMAGE model. The BIOME model of Prentice et al. (1992) is used in the IMAGE model to compute the distribution of 14 natural land-cover types (Van Minnen, Strengers, & Eickman, 2006). However, the biomes determined in Prentice et al. (1992) do not match the IMAGE model. This was the result of renaming some biomes (Alcamo, Leemans, & Kreileman, 1998).

The biomes used in this research are Warm Mixed Forest (WM), Temperate Deciduous Forest (TD), Temperate Mixed Forest (TM), Cool Conifer forest (CC) and Boreal Forest (BF). They are determined by the coldest month temperature, growing degree days (GDD) required, dominant plant functional types (PFT) and hydrological requirements (Prentice at al., 1992). The cold tolerance of plants determines their distribution and therefore the temperature of the coldest month aids in the approximation of the distribution (Prentice et al., 1992). Plants also require a period with temperatures sufficient for growth, which is measured in GDD (Prentice et al., 1992).

The plant functional type is an umbrella term for multiple species of plant that are determined by specific similar characteristics. PFTs are smaller than biomes and can therefore give more detailed information on the nature of the plant life in a specific climate (Prentice et al., 1992). The first variable that influences the PFT is the hydrological requirement of plants, which is the amount of rainfall that falls, which meets the evaporative demand of the plants. This is a measure of growth-limiting drought stress on plants (Prentice et al., 1992). The determinants for the PFTs are listed in Table 1. The biomes are generally composed of multiple PFTs, so some PFTs occur in multiple biomes. The PFTs associated with the different biomes can be found in Table 2.

Table 1. Plant functional types and associated climate aspects (adapted from Leemans & Van der Born, 1994).

Plant Functional Type (PFT)	**GDD**[1]	**Coldest month temperature** (°C)	**Moisture index**[2]
Boreal deciduous trees (BDT)	≥350	<5.0	≥0.65
Boreal evergreen conifers (BEC)	≥350	-35.0 - -2.0	≥0.75
Cool-temperate conifers (CTC)	≥900	-19.0 – 5.0	≥0.65
Temperate deciduous trees (TDT)	≥1200	-15.0 – 15.5	≥0.65
Warm-temperate evergreen (WTE)	None	≥5	≥0.65

[1] Growing degree days on a 5°C base. GDD = (minimum temperature + maximum temperature)/2 - base temperature.
[2] Ratio of actual and potential evapotranspiration.

Table 2. Biomes from the different models, the associated plant functional types, and the regions they occur in (partially adapted from Arets et al., 2011; Leemans & Van der Born, 1994; PBL, 2001).

Biome	**Plant Functional Type (PFT)**	**Regions**
Boreal forest	Boreal evergreen conifers Boreal deciduous trees	Canada, Russia, OECD Europe
Cool conifer	Cool-temperate conifers Boreal evergreen conifers	Canada, Russia, OECD Europe, Japan
Temperate mixed	Temperate deciduous trees Cool-temperate conifers Boreal evergreen conifers Boreal deciduous trees	USA, Eastern Europe, Ukraine, Russia, Korea, Japan
Temperate deciduous	Temperate deciduous trees Cool-temperate conifers Boreal deciduous trees	USA, OECD Europe, Eastern Europe, Turkey, Russia, Korea, East Asia, Japan, Oceania
Warm mixed	Warm-temperate evergreens	USA, Rest South America, Southern Africa, East Asia, Japan, Oceania

Boreal forest

Boreal forests exist in areas where the winters are cold and long, in the uppermost latitudes (Ciesla, 2002). The regions in which boreal forest dominates are Canada, Norway, Sweden, Finland and Russia (Prentice et al., 1992; Planbureau voor de Leefomgeving [PBL], 2001). They are often composed of conifers such as firs, pines and spruces or broadleaved species such as birches, poplars, willows and larches (Boreal forest, 2012; Ciesla, 2002). The trees in these areas mature slowly and therefore the rotation length is long (between 53 and 230 years) (Lamers, Thiffault, Doré, & Junginger, in press).

Cool conifer forest

Cool conifer forests exist in areas where the winters are relatively cold, (-19 to -2 °C), where summergreen trees are limited by the cold temperatures or a growing season that is not warm enough (Prentice et al., 1992). The region in which CC forest dominates is Estonia, although it is also present in large areas of Sweden, Finland, Russia and Canada (PBL, 2001; Prentice et al., 1992). Cool conifer forests are composed of conifers such as spruce, pine, fir, hemlock and douglas-fir (Ciesla, 2002; Prentice et al., 1992).

Temperate mixed forest

Temperate mixed forests exist in areas with moderately cold winters (-15 to -2°C), enough GDD (>1200) and >75% precipitation to satisfy demand (Prentice et al., 1992).

The region in which TM dominates is eastern Europe, however, it is also present in the USA, Korea and Japan (PBL, 2001; Prentice et al., 1992). Many different types of trees exist in TM forests such as spruces, pines, firs, oaks, birches and beeches (Prentice et al., 1992).

Temperate deciduous forest

Temperate deciduous forests exist in areas where the winters are cool, but with enough precipitation for temperate deciduous trees, cool-temperate conifers and boreal deciduous trees. There is also a requirement of enough GDD (>1200) (Prentice et al., 1992). The areas where TD forests are most dominant are in (western) Europe (e.g. Belgium, Croatia and Denmark), the USA, China and Japan (Ciesla, 2002; PBL, 2001; Prentice et al., 1992). TD forests are composed of beeches, oaks, birches and different conifer trees (Ciesla, 2002; Summer green forests, 2013).

Warm mixed forest

Warm mixed forests exist in areas where the coldest months are still warmer than 5°C, and >65% of water demand is satisfied by rainfall (Prentice et al., 1992). The areas were WM forests are most dominant are in Africa, Portugal, Argentina, Australia, New Zealand and Mexico (Ciesla, 2002; PBL, 2001; Prentice et al., 1992). WM forests are composed of different species depending on the location. Forests in the southern hemisphere are mainly *Nothofagus* and *Eucalyptus* (Ciesla, 2002). Other areas have more redwoods and cedars (Ciesla, 2002).

2.1.3. Management

Two management types are taken into account in this research. These management types are the combination of natural and semi-natural forests classed as (semi-)natural forests or 'clearcut' and 'plantations'. The life cycle of the forest, including harvest, is the same for both management types. It starts with a seed, which is either planted (semi-natural and plantations) or naturally regenerated (natural forests). The trees grow and before they are commercially valuable, pre-commercial thinning takes place. Pre-commercial thinning is done by removing small diameter trees, which are not wide enough to be merchantable (Polagye et al., 2007; Richardson, 2002). It is done to prevent wildfires, reduce competition between trees and increase timber value (Burger, 2002; Polagye et al., 2007). They can, however, be used as firewood or bioenergy source (Richardson, 2002).

Next the thinning phase takes place. Thinning is used to increase the timber value of crop trees, since more room is created for other trees (Burger, 2002). The harvested wood can be used as polewood and pulpwood (Richardson, 2002). Lastly, roundwood harvest is the final stage in harvest. During harvest, following a clearcut method, all merchantable trees are harvested (McKechnie et al., 2011). With whole-tree harvesting the above ground biomass is harvested, but stump-root systems are left in the ground (Hakkila & Parikka, 2002). In the case of complete tree harvesting the stump-root systems are also harvested (Hakkila & Parikka, 2002).

Definitions of these harvest stages that occur in both management types are:

- Pre-commercial thinnings (PCT): "Selective cuttings in young stands, felled trees have no value for wood processing industry" (Vis et al., 2010, p. 28).
- Commercial thinnings (CT): "Selective cuttings in middle age and maturing stands, a part of felled trees have value for wood processing industry, mainly as pulpwood" (Vis et al., 2010, p. 28).
- Harvest: Removal of the tree stem from stump to a minimum top stem diameter (Asikainen, Liiri, & Peltola, 2008).

There exists another type of harvest, selective logging, where very few selected trees are removed. However, selective logging is mainly done in tropical forests (Arets et al., 2011) and is therefore also excluded from this research, which concerns higher latitude forests.

The difference between plantation and (semi-) natural forest management stems from a number of aspects. Plantation forests experience more involved management, where the focus is on maximising production and quality of stems (Oosterbaan, Hochbilcher, Nicolescu, & Spiecker, 2009). The species can be exotic or endemic and are harvested with a clearcut method but new trees are planted and management is present (Arets et al., 2011). The species chosen are fast growing and therefore the rotation length is shorter than with natural forests.

There is less management in natural and semi-natural forests. Some thinning management can take place in semi-natural forests. After harvest, regrowth can take place, either assisted or unassisted by humans (Arets et al., 2011). This can be natural regeneration or planted monocultures of specific endemic species (Arets et al., 2011; Schlamadinger et al., 1995).

Table 3. The classification of biomass resources by Batidzirai et al., 2012.

Resource type	**Category**	**Source[a]**	**Description**
Forestry (Woody biomass)	Primary/ direct	Natural and plantation forests	[..] woody biomass harvested from natural forests, plantations and other wooded areas [..]. Fuelwood extracted from forestlands and excess biomass removed from forestlands [..] (see Perlack et al., 2005). Also ‘surplus forest’ growth in natural forests that is not required for fibre production is another resource (see Smeets and Faaij, 2007; Chum et al., 2011).
		By-products	[..] logging residues from conventional harvest operations, thinning and other forest management by-products and land clearing operations (e.g. twigs, branches).
	Secondary/ indirect		[..] primary wood processing industry residues (e.g. sawdust, bark), secondary wood processing mill residues (e.g. trimmings, offcuts) and pulping liquors (black liquor[b]).
	Tertiary/ recovered	End-use materials	[..] urban wood residues e.g. construction and demolition debris, tree trimmings, packaging wastes and consumer durables.

[a] An alternative classification used by FAO in its Unified Bioenergy Terminology (UBET) is also included here for comparison.

[b] Black liquor is a waste product of paper making (kraft pulping) and contains unutilized wood fibre, lignin, and other chemicals. With wood as input, 50% wood is converted into fibre and the remaining residues are black liquor.

2.1.4. Forestry residues

Woody biomass can be retrieved from different places, this research will only use the residues from natural forests, semi-natural forests and timber plantations. Batidzirai, Smeets and Faaij (2012) created a biomass classification (Table 3), which will be used to explain the inclusion of certain biomass parts as residues and the exclusion of others. This research concerns forestry residues and therefore the only parts that are interesting from that point of view are the forestry primary resources.

This means that short rotation coppice (SRC) plantations, such as willow and poplar energy plantations, are excluded from this research, as they are classified as agricultural resource (Andersen et al., 2005; Batidzirai et al., 2012). Moreover, SRC is excluded because the main goal of the plantation is energy production, so the entire harvest is used for energy production. Secondary and tertiary products, such as processing residues and reclaimed wood are also excluded from the research, as they do not directly influence the forest ecosystem.

Forestry residues are defined as those parts of the tree that are not sold as merchantable timber, so unmerchantable stem top, crown and potentially stump(-root system) (Figure 2) (Hakkila & Parikka, 2002). The stump is the part of the tree from where the merchantable stem has been cut off, to the bottom of the taproot, sideroots are the root-system (Hakkila & Parikka, 2002; Young, Strand, & Altenberger, 1964; Zhou & Hemstrom, 2009). Whole tree residues (WTR) include the above ground biomass: crown, unmerchantable stem top and unmerchantable parts of thinning trees. Complete tree residues (CTR) include the below ground biomass as well: crown, unmerchantable stem top, stump-root system and unmerchantable parts of thinning trees (Hakkila & Parikka, 2002; Young, Strand, & Altenberger, 1964) (

Table 4). Lastly, the residues can also be whole tree residues that include stumps, or complete tree residues without roots, which will be the whole tree residues with stump (Vis et al., 2010).

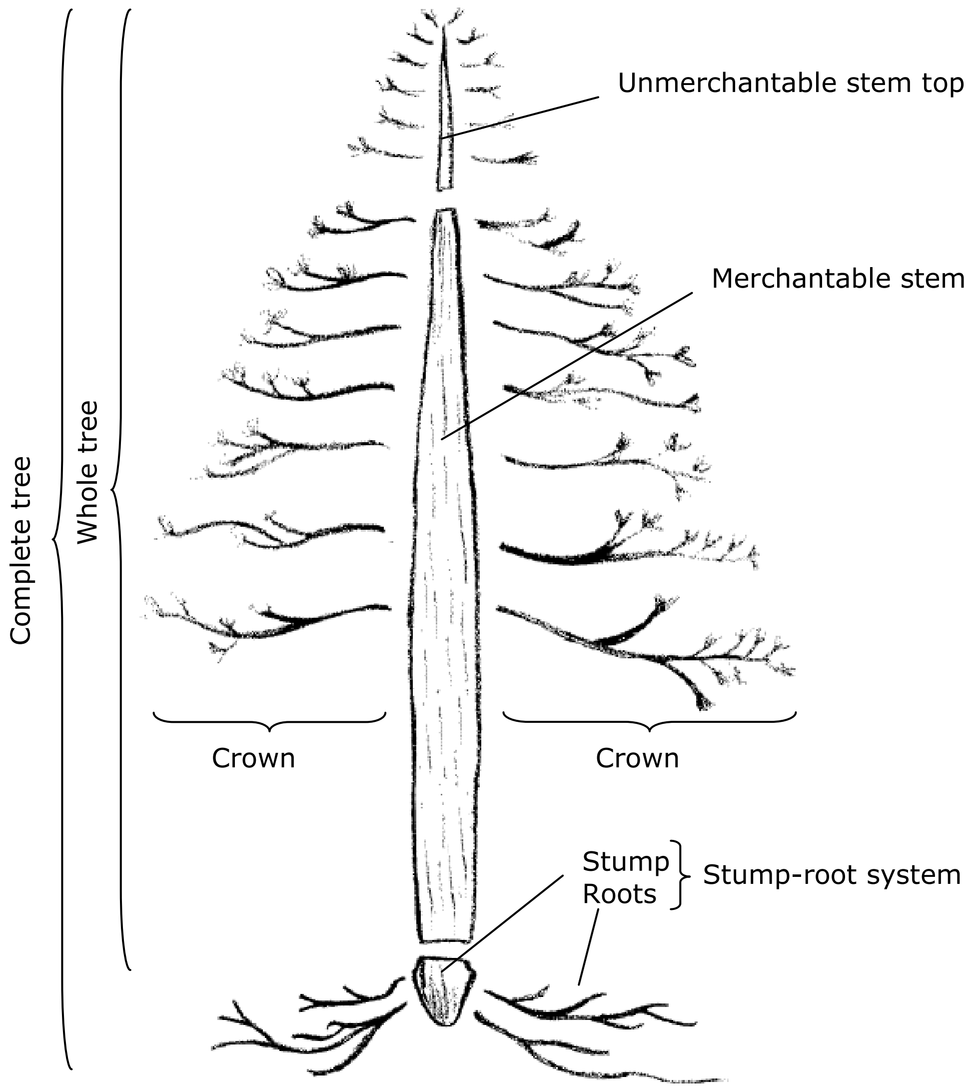

Figure 2. Tree components (redrawn from Hakkila and Parikka, 2002).

The different forestry residues categories are defined as follows:

- WTR: crown, unmerchantable stem top and unmerchantable parts of thinning trees.
- Whole tree residues with stump (WTRS): crown, unmerchantable stem top, stump and unmerchantable parts of thinning trees.
- CTR: crown, unmerchantable stem top, stump-root system and unmerchantable parts of thinning trees.

Different parts of the trees are defined as follows:

- "Stumps: part of the tree stem below the felling cut" (FAO, 2004, p.40), including the taproot (Hakkila & Parikka, 2002).
- "Stemwood: part of the tree stem with branches removed" (FAO, 2004, p. 40), including bark (Vis et al., 2010, p.27).

- "Biomass from pre-commercial thinnings: stems, branches, bark, needles/leaves" (Vis et al., 2010, p. 27).
- "Logging residues: woody biomass by-products that are created during harvest of merchantable timber" (FAO, 2004, p. 37).

Table 4. Harvest and use of different parts of the tree during different harvest stages (based on Poudel et al., 2012; Richardson, 2002).

		Pre-commercial thinning	**Thinning**	**Harvest**
Stump-root system	Root-system	Not harvested	Not harvested	Not always harvested, residue
	Stump	Not harvested	Not harvested	Not always harvested, residue
Bole	Merchantable stem	Not present	Harvested, poles and pulpwood	Harvested, pulpwood and timber
	Unmerchantable stem	Not always harvested, residue	Not always harvested, residue	Not always harvested, residue
	Unmerchantable stem top	Not always harvested, residue	Not always harvested, residue	Not always harvested, residue
Crown	Branches	Not always harvested, residue	Not always harvested, residue	Not always harvested, residue
	Leaves/needles	Not always harvested, residue	Not always harvested, residue	Not always harvested, residue

2.1.5. Sustainability

Sustainable development is defined as ''development that meets the needs of the present without compromising the ability of future generations to meet their own needs'' (World Commission on Environment and Development [WCED], 1987). However, this is still a vague description and definitions of sustainable forest management (SFM) have also been created. SFM is ''the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic, and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems'' (Second Ministerial Conference on the Protection of Forests in Europe [Second MCPFE], 1993).

Sustainability thereby consists of three parts: environmental, social and economic sustainability (Batidzirai et al., 2012; Stupak et al., 2011). This research will focus on environmental sustainability. This includes aspects of biodiversity, productivity, regeneration capacity, vitality and other ecosystem functions. (Batidzirai et al., 2012; Second MCPFE, 1993). For a bioenergy fuel to be environmentally sustainable, the system needs to "maintain or improve the quality of forest ecosystems (including soil and water resources, site productivity and biodiversity)" (Lattimore, Smith, Titus, Stupak, & Egnell, 2009, p.1322).

2.1.6. Potentials

This thesis will deal with two different types of potentials. The first is theoretical potential. The theoretical potential of forestry is the maximum wood production potential of the forests (Smeets & Faaij, 2006). For forestry residues the theoretical potential is the full amount of biomass that could be retrieved from the forest, excluding the merchantable stem, so essentially the CTR. However, much of the literature only includes aboveground biomass, which means that the forestry residues' theoretical potential consists of the WTR. Only in some research the stumps are included and there WTRS is used (e.g. Böttcher et al., 2010; Karaj, Rehl, Leis, & Müller, 2010).

For the purpose of this research, the theoretical potential will be the WTR. This is because this research concerns aboveground biomass and stumps are often considered an intermediary since the taproot is part of the stump. Roots are fully belowground.

Moreover, there are limited data on stump removal and the associated environmental impact makes the harvest debated (Asikainen et al., 2008; Hakkila & Parikka, 2002).

The second potential is sustainable forestry residues potential. The removal of residues is linked to many different detrimental environmental consequences (e.g. Burger, 2009; Lattimore et al., 2009; Vis et al., 2010). The sustainable potential concerns the amount of residues that can be removed while not decreasing the quality of the ecosystem (Lattimore et al., 2009). It includes the residues that need to be left in the forest to guard biodiversity and nutrient levels.

2.2. Procedure

This section will describe the procedures that were taken for collecting data and determining definitions. It will start by introducing the formulas that will be used for the calculations and the sections that follow explain the terms used in these formulas.

2.2.1. Theoretical potential

The following formula is used to arrive at the theoretical potential (TP) in the unit of kg ha^{-1} yr^{-1}. All the values used here are different depending on the biome and management type used. In all, 21 values are produced for each formula, a minimum, maximum and mean value for the 5 clearcut biomes and the 2 plantation biomes.

(1) TP = (hr + tr) / rl

Where TP = theoretical potential (kg/ha/yr), hr = harvest residues (kg/ha) (see also (2)), tr = thinning residues (kg/ha), rl = rotation length (years).

(2) hr = b * p

Where b = branchiness (kg_{crown} / $kg_{stemwood}$; both dried mass), p = production ($kg_{stemwood}$/ha) (see also Formula 3)).

(3) p = pv * d

Where pv = production volume (m^3/ha), d = density of wood (kg/m^3) (0).

(4) tr = p * ts *tf * tb

Where ts = thinning stages (amount of stages), tf = thinning fraction (% of trees removed per thinning), tb = thinning branchiness ($kg_{crown}/kg_{stemwood}$).

The method for determining the values that are used in these formulas follows in the steps below.

2.2.2. Biome

The IMAGE model and Prentice et al. (1993) biomes do not match. The first step was to determine which Prentice biomes mapped onto which IMAGE biomes. The land cover types that correspond with the five used in this research are: taiga (BF), cool conifer forest (CC), cool mixed forest (TM), temperate deciduous forest (TD) and warm mixed forest (WM) (Appendix B)(Table 2) (Leemans & Van der Born, 1994).

Using the different PFTs that were determined for the different biomes, the dominant plants in these PFTs were found in literature (e.g. Ciesla, 2002; Hakkila & Parikka, 2002; Prentice et al., 1992). These PFTs consist of a number of different plant genera, however, only the most prominent genera were taken into account.

After the mapping of the different biomes onto each other was completed, it was possible to use landcover maps to determine the countries in which the different biomes are present. This was done by overlaying a country map onto the landcover maps (Appendix B). The 'biome per country'-distinction is necessary to use data from the FAO, which is only given per country. The FAO provides data on the world's forests, such as the amount of forest, management rights and plants, forest functions and the nature of the forest (FAO, 2010). These data can then be used to answer the research questions. Furthermore, the landcover map of the IMAGE regions was also applied to determine the extent of different biomes into the IMAGE regions (Appendix B)(Table 2) (MNP, 2006; PBL, 2001)

2.2.3. Management

The clearcut and plantation management types will be discussed separately. The values arrived at in 'biome' sections concern clearcut management.

After the biome distribution in the different regions of the IMAGE model was identified by overlaying maps of the IMAGE biome distribution results and a map of countries (PBL, 2001), the countries were then assigned the biomes that were present within their borders. This was extended to determine the biomes present within different regions of the IMAGE model (listed in Appendix B; Arets et al., 2011).

The regions were then connected to the two different management types (clearcut and plantations). Following production data by Arets et al. (2011), it was assumed that no plantations exist in boreal forests. Sweden and Canada, for example, do not report any plantations and Russia's plantations only occupy 1.5% of the total productive forests. All planted forests in BF and CC biomes are therefore considered semi-natural forests. The forests have endemic species and (assisted) natural regeneration in Canada and Sweden (Arets et al., 2011). The situation is assumed to be the same in CC forest. There is only one country with only CC forest (Estonia), all other CC forests occur in close association with boreal forests.

The situation for the temperate biomes is more complicated. More regions have areas of temperate forest and therefore the varying data are difficult to aggregate. Moreover, many of the forests established as plantations have been classified as semi-natural, with the distinction being vague (Brown, 2000). In regions with mainly TM forests, there are areas with plantations, but the species planted are native species, making them semi-natural forests. Since all the countries with TM forests have less than 5% introduced species (Arets et al., 2011; FAO, 2010; PBL, 2001). Therefore, no plantations are assumed to be present in the TM biome.

The most important plantation species worldwide are *Eucalyptus, Pinus, Acacia* and *Tectona* (teak). *Picea*, *Pseudotsuga*, *Swietenia* and *Gmelina* also play an important role in some regions (Kelty, 2006). Tectona, Swietenia and Gmelina are species outside the biomes in this research and therefore excluded (teak, 2013; Lamiales, 2013; mahogany, 2013). However, not all species are equally distributed within plantations in all the areas within a biome. China has plantations of *Acacia* and *Eucalyptus*, Korea has *Pinus* and *Larix* plantations and Oceania has plantations of pines and eucalyptus. Next to that, plantations of *Pseudotsuga, Picea, Populus, Quercus*, *Fagus* and *Betula* are also important in the temperate region (Arets et al., 2011; Brown, 2000). The main plantation species in the warm-mixed region are *Pinus radiata, Eucalyptus* and *Acacia* (Acuña, Espinosa, Cancino, Rubliar, & Muñoz, 2010; Arets et al., 2011; Ouro, Pérez-Batallón, & Merino, 2001; Pérez, Renedo, Ortiz, & Mañana, 2008).

2.2.4. Branchiness

The next step was to determine the branchiness, which is the ratio of crown mass to stem mass of the different dominant tree genera in the PFTs (Hakkila & Parikka, 2002). Another term used to represent the same thing is the logging residue generation factor, which is the ratio between the amount of residues generated and the amount of wood harvested (Smeets & Faaij, 2007). The branchiness was calculated by looking at biomass data in literature, such as ratio of crown to stem (from e.g. Standish et al., 1985) and using biomass estimation equations coupled with diameter at breast height (DBH) (from e.g. Lamson, 1987; Raile, 1982; Zhou & Hemstrom, 2009). Included in stem mass are stem wood and stem bark. Included in crown mass are foliage and branches.

The data were retrieved for different plant species. The mean was taken of the branchiness values for different species within the same genera. The highest and lowest value of the individual species was taken to be the range of the branchiness within that genus. From the data available, the choice was made to use the dried biomass data. The reason for this is that biomass needs to be dried before it can be used for energy production.

By taking the mean of the different genera within a PFT, the mean branchiness for the PFT was determined. The range was the highest and lowest individual species value within the PFT. The mean branchiness of the biome was determined by taking the mean of the mean branchiness of PFTs within that biome. Again, range was highest and lowest individual species value. For WM plantations (WMP), no data were available to calculate the branchiness for *Acacia.* Therefore, *Acacia* was excluded and WMP branchiness was calculated for *Eucalyptus* and *Pinus* (Acuña et al., 2010; Ouro et al., 2001; Pérez et al., 2008).

Although the rotation lengths may be shorter in TD plantations, there are few data available to determine the branchiness of the genera (*Pinus, Eucalyptus, Picea, Populus, Pseudotsuga, Quercus, Fagus* and *Betula*) at those ages. Therefore, it was chosen to take the branchiness at natural forest age as an approximation for plantation branchiness, except for *Eucalyptus, Picea* and *Pinus* since those are available (Acuña et al., 2010; Ouro et al., 2001; Pérez et al., 2008).

2.2.5. Production

In order to determine the available residues, production values of roundwood can be used in combination with branchiness (Formula 2). Production volumes, the amounts of stemwood produced in an area, were determined for the different biomes by using the data from Arets et al. (2011) on production volumes in the different IMAGE regions. These data was available for clearcut and productive plantations. However, the data were available for regions, not for biomes and it was also not possible to separate these. Therefore, the data was used as they were. Those areas that had the same biome and other literature sources were combined and averaged to provide an approximation of the production volume in that biome.

For (semi-)natural forests, the values for clearcut in the IMAGE regions that were present in that biome were combined with additional data on production volumes in different regions from different sources sorted per biome (e.g. Arets et al., 2011; Hakkila, 2004; Kellomäki, 2012; Liu, Ruel, & Zhang, 2007; Mangoyana, 2011; United Nations Economic Commission for Europe [UNECE] & FAO, 2011)(Appendix C). For plantations, the value for productive plantations in the IMAGE regions that were present in that biome was used as an approximation for production volume (Appendix C).

2.2.6. Density

Density of wood is used to derive values for production (Formula 3). The starting values are production volumes while the outcome of the research will be in kg, therefore a conversion factor was needed. The density of wood also varies per species, therefore it was not possible to use a single conversion factor for all volumes (0). Data on the density of different species were found in literature. The mean was taken per genera and the highest and lowest individual values form the range of the densities per genera.

2.2.7. Thinning residues

Thinning is another source of forestry residues. Therefore, the amount of thinning residues needs to be added to the amount of residues from final harvest in order to determine the full theoretical potential of forestry residues (Formula 1). There is no set recipe for thinning since it depends on the stand density, tree species, site quality, thinning methods and the desired result (Juodvalkis, Kairiukstis, & Vasiliauskas, 2005). Generally 2-4 thinning stages are performed in boreal forests and a similar number in temperate forests (Andersson et al., 2002; Hakkila, 2004; Juodvalkis et al., 2005; Malinen et al., 2001; Thomas, Halpern, Falk, Liguori, & Austin, 1999).

In order to calculate thinning residues, some variables are needed. First is thinning fraction, which is the amount of trees that is removed during thinning. It varies significantly depending on the thinning method chosen and the requirements for the final product of the forest. The data were found in literature for both management types and the different biomes.

Thinning branchiness is also determined from literature, if information is available. If there were no data available, the branchiness at final harvest is used as an approximation. For the amount of thinning stages a low, medium and high intensity management option is used. It is assumed that the stages, fraction and branchiness of thinning for CC forests is similar to BF forests, the main branchiness change occurs in the PTF that is present in both biomes. Moreover, these biomes are often treated as being similar. The same thinning fraction was assumed for TM, TD and WM forests. There were very limited data available to calculate the thinning fraction. The results were later compared to literature.

2.2.8. Rotation length

The final variable that is necessary for the theoretical potential is the rotation length. The rotation length differs per biome and management type. Rotation length for BF and CC forests was assumed to be the same. Again, since boreal forest and cool conifer forest exist in close proximity and few data are available for cool-conifer forest while more is available for boreal forest. The rotation length for boreal forest was determined by taking the mean of a number of different sources (Arets et al., 2011; Bernier & Paré, 2013; Holtsmark, 2011; Lamers et al., in press; Poudel et al., 2012).

Rotation lengths for temperate and warm-mixed forests were deduced from data from Arets et al. (2011) on rotation lengths. These rotation lengths were given for hardwood and softwood species (Table 5). Softwoods include: *Abies, Larix, Picea, Pinus, Pseudotsuga, Sequoia, Thuja* and *Tsuga* (Bunnell & Houde, 2010; Zhou & Hemstrom, 2009). Hardwoods include: *Betula, Eucalyptus, Fagus, Nothofagus, Populus, Quercus* and *Salix* (Arets et al., 2011; Zhou & Hemstrom, 2009). Combining the wood type with the species in PFTs leads to the dominant wood type in a PFT (Table 6). These could then be combined to determine the dominant wood type in the biome (Table 6). The recovery cycle was taken as the minimum rotation length, and rotation cycle values as maximum rotation length. These were then combined with values from other publications to produce a mean rotation length, the highest and lowest individual value portray the range of rotation lengths (Arets et al., 2011; Nunery & Keeton, 2010; Peckham, Gower, Perry, Wilson, & Stueve, 2013).

Table 5. Recovery times (time after harvest needed to recover to a stage where harvesting is possible again in a sustainable way) and rotation cycles (used/ prescribed in the concerning region). Values are based on the author's expert judgement from Arets et al. (2011).

Management	**Climate**	**Region**	**Forest type**	**Recovery time** (years)	**Rotation cycle** (years)
Clearfelling	Boreal (BF/CC)	All	All	50	100
	Temperate	All	Softwoods	40	80
	Temperate	All	Hardwoods	70	130
	Warm Mixed	Oceania and Southern Africa	Softwoods	<40	<80
Plantation	Temperate		Softwoods	20	40
	Temperate		Hardwoods	20	40
		China	Softwoods	30	
		China	Hardwoods	30	

Table 6. Type of wood in different PFTs (left) and biomes (right) (based on Arets et al., 2011).

PFTs	
BEC	Softwood
BDT	Mostly hardwood
CTC	Softwoods
TDT	Hardwoods
WTE	Half softwood – half hardwood

Biomes	
BF	Half softwood – half hardwood
CC	Softwood
TD	Half softwood – half hardwood
TM	Mostly hardwood.
WM	Half softwood – half hardwood

The rotation length also differs for the two biomes with plantations. In the WM biome, the *Pinus* and *Eucalyptus* plantations have a rotation length of between 20-40 years (Acuña et al., 2010; Arets et al., 2011; Ouro et al., 2001). For TD plantations this value is higher, between 25 and 80 years. Optimum rotation length for pine in Lithuania was between 55 and 80 years (Brown, 2000). Continuous cover plantations usually have rotation lengths of 25 years and longer (Arets et al., 2011; Brown, 2000). For example, *Pseudotsuga* has a rotation length of 30-60 years (Arets et al., 2011).

2.2.9. Calculations

Lastly, the calculations are performed using the data gathered. The formulas 1, 2, 3 and 4 are used to calculate the theoretical potential for forestry residues. The sensitivity of the results is calculated by applying the formulas to the minimum and maximum values in the ranges of the variables. This produces in the minimum and maximum theoretical potential. The sensitivity is also investigated by varying one of the variables , while keeping the others at the mean value, and determining the effect on the theoretical potential.

2.2.10. Sustainable potential

For the calculation of sustainable potential (SP) only formula 1 is adapted (see Formula 5), formulas 2 to 4 are used in their original form.

(5) SP = ((hr * sfh) + (tr * sft)) / rl

Where SP = sustainable potential (kg/ha/yr), sfh = sustainable fraction harvest (% of residues removed), sft = sustainable fraction thinning (% of residues removed).

The sustainable fraction values are needed to incorporate the requirements for sustainability into the sustainable potential. Aspects that are captured by the sustainable fraction variables are e.g. the retention of residues and foliage. The sfh was calculated by taking the maximum of full foliage retention (based on Appendix D) and 10-tonne residue retention and subtracting it from 100%. The sft was calculated based on leaving all foliage residues in the forest. However, there was no data available for the amount of leaves at thinning ages, so final harvest leave fractions were used as an approximation. The variables were combined following formula 5 to produce the sustainable potential. The calculations were only performed on the mean values due to time constraints.

3. Theoretical potential

The aim of this section is to provide the answers to the first research question and its sub questions. This will be done by elaborating upon the elements that make up the research questions. It will start by explaining the drivers and will continue with the parameterisation of said drivers. A conclusion and answer to the first research question will then be proposed in the last section.

3.1. Drivers

The theoretical potential of forestry is the maximum wood production potential of the forests (Smeets & Faaij, 2006). For forestry residues, there are different ways to define the theoretical potential. Moreover, different variables impact the potential, including tree species and harvesting system (Smeets & Faaij, 2006). This will be explained in the following sections.

3.1.1. Biome

The amount of residues that can be generated from one tree depends on a number of factors. Firstly, not all tree species have the same stem to residues fraction. The species present in an area depend on the biome they are in. The branchiness is a function of stand density, site fertility, genetic factors, age and location (Claveau, Messier, & Comeau, 2005; Hakkila & Parikka, 2002). The branchiness therefore differs throughout the lifetime of the tree as the stem mass increases relative to the amount of foliage and dead branches (Hakkila & Parikka, 2002).

With a higher stand density, the trees produce less crown and fewer residues will be produced (Oosterbaan et al., 2009). Higher fertility can allow a larger crown as the nutrient-rich parts of the tree are the crown (Nurmi, 1999). Genetic factors include species reactions to different circumstances, e.g. shade tolerant species will have a greater crown, which also makes location important (Claveau et al., 2005). The variation in and between species is high, although some general comments can be made on genera with greater crowns and smaller crowns (Claveau et al., 2005).

The biomes have different plant species that make up the bulk of the forest. By determining the branchiness of these species, an estimate can be made of the amount of residues as a percentage of removed stem mass. Do note that the value for the branchiness includes all leaves, needles, twigs, branches and other pieces of above-ground biomass, and it may not be technically feasible to remove all of this from the forest. For example, harvest is limited to 85% of logging residues, 60% of thinning residues and 95% of roundwood in Sweden, because of technical reasons (Eriksson & Gustavsson, 2010). However, technical limitations are not taken into account in the calculations for theoretical potential.

3.1.2. Management type

For natural and semi-natural forests, the amount of residues is that of the biome, including thinning residues. For plantations, an adapted branchiness is used, that takes into account the effects of stand density and management.

Management can have large impacts on the amount of residues that can be produced. The stand density in managed forests can be very different from that in natural forests. Fewer trees are planted, such that fewer branches and a large diameter butt log can be produced (Oosterbaan et al., 2009). The stands are usually more uniform in nature, with a monoculture of the tree species (e.g. Bauhus, Van Winden, & Nicotra, 2004; Kelty, 2006). However, mixed-species plantations also occur that address issues such as limited biodiversity and risk of disease outbreak (Bauhus et al., 2004).

Management aims for the decrease of natural branchiness, as fewer branches are linked to better wood quality (Oosterbaan et al., 2009). Therefore, management techniques can be implemented such as pruning (Oosterbaan et al., 2009), which produces some residues in the short term, but reduces them in the long term. However, there are no data on the biomass removed during pruning for forestry. There are estimates available for fruit trees, however, these are agricultural crops and no not fall within the dimensions of this research (Vis et al., 2010). Therefore, it will not be taken into account in this research. However, it may be an additional source of biomass for energy.

3.1.3. Thinnings

Thinning is employed in temperate, boreal and cool conifer forests (Dymond, Titus, Stinson, & Kurz, 2010; Egnell & Leijon, 1997; Juodvalkis et al., 2005; Nave, Vance, & Swanston, 2010; Thomas et al., 1999). The removal from thinning depends on a number of factors. Firstly, the age at which the thinning is performed since this impacts the branchiness of the trees. It also influences the inclusion or exclusion of stemwood from residues. If the stemwood is large enough it can be sold as polewood (Richardson, 2002). Second, the amount of times thinning is performed increases the amount of residues produced (Andersson et al., 2002; Hakkila, 2004). Third, the thinning fraction, the amount of trees that is removed during the thinning stage, influences the amount of residues produced (Andersson et al., 2002; Ulvcrona, Claesson, Sahlen, & Lundmark, 2007). Lastly, the biome is of influence because it determines the branchiness of the forest.

The age of the thinning matters as younger trees have a higher proportion of leaves to stem mass, although a lower overall mass (Hakkila & Parikka, 2002). If trees are thinned early in their life, proportionally more residue will be produced, although not in absolute sense (Hakkila, 2004). In pre-commercial thinning, the stems are not large enough to be merchantable and the entire tree can be harvested and used for energy production (Richardson, 2002). Pre-commercial thinning is performed when trees are still short and thin, in Sweden, for example, the age of the trees is between 14 and 23 years (Ulvcrona et al., 2007). During commercial thinning the stemwood is used for poles and pulpwood so the same residues are left as with final harvest, but less of them (Richardson, 2002).

3.2. Parameterisation

This section will deal with the parameterisation of the aspects discussed in section 3.1. It follows a similar approach as section 2.2, where the variables in the formulas are determined first.

3.2.1. Biome

The values obtained from different sources have produced a picture of the branchiness for different tree genera and biomes. Table 7 shows the results from the research into branchiness of tree genera. Table 8 lists the final values for biomes, do note that biomes consist of a combination of PFTs as listed in Table 2.

Table 7. Mean and range of branchiness of the different PFTs, determined from main tree genera in those PFTs, for (semi-)natural forests. Genera name in *italics*, common name in brackets.

PFT	Plant genera	Branchiness dried (kg_{crown} /kg_{stem})	Sources	PFT dried
Boreal evergreen conifer (BEC)	*Abies* (Fir)	0.464 (0.327-0.577)	1	0.386 (0.176-0.600)
	Picea (Spruce)	0.418 (0.283-0.600)	1,2,3	
	Pinus (Pine)	0.275 (0.176-0.406)	1,3	
Boreal deciduous trees (BDT)	*Betula* (Birch)	0.286	1	0.244 (0.145-0.422)
	Larix (Larch)	0.145	1	
	Populus (Poplar)	0.313 (0.203-0.422)	1	
	Salix (Willow)	0.234 (0.222-0.246)	4,5	
Cool-temperate conifer (CTC)	*Picea* (Spruce)	0.418 (0.283-0.600)	1,2,3	0.289 (0.176-0.600)
	Pinus (Pine)	0.275 (0.176-0.406)	1,3	
	Pseudotsuga (Douglas fir)	0.255 (0.182-0.327)	1	
	Tsuga (Hemlock)	0.207 (0.205-0.210)	1	

Temperate deciduous tree (TDT)	*Quercus* (Oak)	0.196 (0.185-0.207)	4,5	0.240 (0.185-0.286)
	Betula (Birch)	0.286	1	
	Fagus (Beech)	0.237	4,6	
Warm-temperate evergreen (WTE)	*Eucalyptus* (Eucalyptus)	0.191	7	0.219 (0.120-0.347)
	Nothofagus (Southern beeches)	0.216 (0.205-2.227)	8,9	
	Sequoia (Redwood)	0.12	10	
	Thuja (Cedar)	0.347	1	

1 Standish et al., 1985; 2 Hakkila, 2004; 3 Hakkila & Parikka, 2002; 4 Zhou & Hemstrom, 2009; 5 World Agroforestry Centre, 2013; 6 Lamson, 1987; 7 Pérez et al., 2009; 8 Donoso et al., 2010; 9 Silva, 1997 in Donoso et al., 2010; 10 Busing & Fujimora, 2005.

Table 8. Mean and range of branchiness in different biomes based on the different PFTs.

Biome	**Branchiness** (kg_{crown} /kg_{stem})	**PFTs**	**Sources**
Boreal forest	0.315 (0.145-0.600)	BEC, BDT	1,2,3,4,5
Cool conifer forest	0.338 (0.176-0.600)	CTC, BEC	1,2,3
Temperate mixed forest	0.290 (0.145-0.600)	TDT, CTC, BEC, BDT	1,2,3,4,5,6
Temperate deciduous forest	0.258 (0.145-0.600)	TDT, CTC, BDT	1,2,3,4,5,6
Warm mixed forest	0.219 (0.120-0.347)	WTE	1,7,8,9,10

1 Standish et al., 1985; 2 Hakkila, 2004; 3 Hakkila & Parikka, 2002; 4 Zhou & Hemstrom, 2009; 5 World Agroforestry Centre, 2013; 6 Lamson, 1987; 7 Pérez et al., 2009; 8 Donoso et al., 2010; 9 Silva, 1997 in Donoso et al., 2010; 10 Busing & Fujimora, 2005.

3.2.2. Management type

The species composition in plantations is assumed to be different from (semi-) natural forests. Therefore, the branchiness for plantations had to be calculated separately. The different sources have produced new values for the branchiness of plantations. These can be found in Table 9.

Table 9. Mean and range of branchiness in plantations in the different biomes.

Biome	**Branchiness** (kg_{crown} /kg_{stem})	**Species**	**Sources**
Temperate deciduous plantation	0.268 (0.135-0.600)	*Betula, Eucalyptus, Fagus, Picea, Pinus, Populus, Pseudotsuga, Querqus*	1,2,3,4,5,6,7
Warm mixed plantation	0.219 (0.135-0.354)	*Eucalyptus*, *Pinus*	1,3,7

1 Standish et al., 1985; 2 Hakkila, 2004; 3 Hakkila & Parikka, 2002; 4 Zhou & Hemstrom, 2009; 5 World Agroforestry Centre, 2013; 6 Lamson, 1987; 7 Pérez et al., 2009.

3.2.3. Production

The biome and management type also influence the stemwood production and thereby the amount of residues that are produced. Appendix C shows the difference in the volume of roundwood production in different regions in the world per hectare. The final values that are used to calculate theoretical potential can be found in

Table 10. To calculate the production in kg, the values are multiplied by the densities of the biomes (0).

Table 10. Mean and range of production volume in different biomes and under different management strategies.

Biome	**Management**	**Production volume** (m^3/ha)	**Sources**
Boreal forest	Clearcut	223 (80-442)	1,2,3,4,5
	Plantation	*n.a.*	*n.a.*
Cool conifer forest	Clearcut	223 (80-442)	1,2,3,4,5
	Plantation	*n.a.*	*n.a.*
Temperate mixed forest	Clearcut	212 (111-357)	1,6
	Plantation	*n.a.*	*n.a.*
Temperate deciduous forest	Clearcut	214 (40-422)	1,6
	Plantation	233 (113-501)	1
Warm-mixed forest	Clearcut	179 (40-357)	1
	Plantation	340 (65-930)	1

1 Arets et al., 2011; 2 Hakkila, 2004; 3 Kellomäki, 2012; 4 Liu et al., 2007; 5 Mangoyana, 2011; 6 UNECE & FAO, 2011.

3.2.4. Thinnings

In order to calculate the thinning residues some variables need to be mentioned. First, the branchiness varies over the life of the tree. For example, the branchiness of Scots pine at 30 years (first thinning) is 0.42, at 50 years (late thinning) this is 0.24 and at 80 years (final harvest) it is 0.18 (Hakkila & Parikka, 2002). With spruce, a similar picture emerges, although there is a higher overall branchiness: at 30 years 0.47, at 50 years 0.39 and at 80 years at 0.40 (Hakkila & Parikka, 2002). During pre-commercial thinning, much of the stem mass is also removed and used as residues. This is beneficial because stemwood is a better energy source than leaves and branches (Hakkila, 2004).

Thinning itself also has an influence on the results of the final harvest. The level of thinning in young stands influences the volume increment, with light thinning leading to a higher volume increment (Juodvalkis et al., 2005). Thinnings are also an important tool in plantations, which can help redistribute the growth potential over the plantation to optimise yields, quality and economic returns (Lesch & Scott, 1997).

The calculation of thinning residues used for this paper is based on the final production of stemwood (

Table 10). Next to that are the thinning stages. On average 2-4 thinnings are performed during the rotation of a forest (Andersson et al., 2002; Hakkila, 2004; Juodvalkis et al., 2005; Malinen et al., 2001; Thomas et al., 1999). The low thinning scenario was set at 2 thinnings, the medium thinning at 3 and the high thinning at 4 thinning stages. Some natural forests have no management at all and no thinnings or other interventions are performed (FAO, 2010). However, thinning residues are seen as an important part of the bioenergy potential from forestry. Therefore, the choice was made to include a minimum number of thinnings that is not negative. Table 19 is available to show the theoretical potential from only harvest residues.

Many different values have been cited in literature concerning thinning residues. For example, in Sweden, Norway and Finland, countries with boreal forest and cool conifer forest, the amount of residues produced during a thinning stage is around 20-70 m^3/ha (9200-32200 kg/ha)[1] (Andersson et al., 2002). This value is in agreement, albeit somewhat higher at the top end, with the residue production values of Hakkila, 2004 (Table 11). It is, however, somewhat higher than the values from Helmisaari et al. (2011) and Jacobson et al. (Jacobson, Kukkola, Mälkönen, & Tveite, 2000), where the minimum produced amount was 4600 kg/ha and 4590 kg/ha respectively, although the average was 11288 kg/ha and 11079 kg/ha respectively. The mean stem mass removed in these two instances was 55 and 56 m^3 respectively.

Table 11. Thinning and harvest residues produced in a typical management regime of a southern Finnish forest stand. Lower values refer to Scots pine and higher values to Norway spruce (adapted from Hakkila, 2004).

Treatment	**Stand age** (years)	**Yield of timber** (m^3/ha)	**Forestry residues** (m^3/ha)	**Residue production ratio** ($m^3_{residues}/m^3_{stem}$)
Pre-commercial thinning	10-20	-	15-50	
1st commercial thinning	25-40	30-80	30-50	1-0.625
2nd commercial thinning	40-55	50-90	20-40	0.400-0.444
3rd commercial thinning	50-70	60-100	20-40	0.333-0.400
Final harvest	70-100	220-330	70-130	0.318-0.394
Total during rotation		360-600	155-310	0.431-0.517

The values used for thinning fraction and branchiness can be found in Table 12. The only values that were changed for branchiness were pine and spruce in the PFTs (based on Hakkila & Parikka, 2002; Helmisaari et al., 2011; Jacobson et al., 2000). This had an impact on the BEC and CTC PFTs and the branchiness for both types of plantations. All the other numbers within PFT calculations were kept the same.

Table 12. Variables for the calculation of thinning residues. Mean and range of thinning fraction and thinning branchiness.

Biome	**Manage-ment**	**Thinning fraction** (% of trees removed)	**Source**	**Thinning branchiness** ($kg_{crown}/kg_{stemwood}$)	**Source**
BF	Clearcut	0.303 (0.215-0.390)	1,2	0.415 (0.227-0.774)	1,2,3
	Plantation	*n.a.*	*n.a.*	*n.a.*	*n.a.*
CC	Clearcut	0.303 (0.215-0.390)	1,2	0.415 (0.227-0.774)	1,2,3
	Plantation	*n.a.*	*n.a.*	*n.a.*	*n.a.*
TM	Clearcut	0.260 (0.100-0.500)	13,14,15	0.314 (0.145-0.774)	3,4,5, 6,7,8
	Plantation	*n.a.*	*n.a.*	*n.a.*	*n.a.*
TD	Clearcut	0.260 (0.100-0.500)	13,14,15	0.272 (0.145-0.347)	3,4,5, 6,7,8
	Plantation	0.299 (0.100-0.540)	13,14,15, 16,17,18	0.292 (0.135-0.774)	1,2,3,4, 6,7,8,9
WM	Clearcut	0.260 (0.100-0.500)	13,14,15	0.219 (0.120-0.347)	4,9,10

[1] Values expressed in kg/ha have been recalculated using 0.

					11,12
	Plantation	0.348 (0.220-0.540)	16,17,18	0.384 (0.135-0.774)	1,2,3,9

1 Helmisaari et al., 2011; 2 Jacobson et al., 2000; 3 Hakkila & Parikka, 2002; 4 Standish et al., 1985; 5 Hakkila, 2004; 6 Zhou & Hemstrom, 2009; 7 World Agroforestry Centre, 2013; 8 Lamson, 1987; 9 Pérez et al., 2009; 10 Donoso et al., 2010; 11 Silva, 1997 in Donoso et al., 2010; 12 Busing & Fujimora, 2005; 13 Rummer et al., 2005 in Polagye et al., 2005; 14 Tritton, Martin, Hornbeck, & Pierce, 1987; 15 Juodvalkis et al., 2005; 16 Ganjegunte, Condron, Clinton, Davis, & Mahieu, 2004; 17 Balboa-Murias, Rodríguez-Soalleiro, Merino, & Álvarez-González, 2006; 18 Lesch & Scott, 1997.

3.2.5. Rotation length

Lastly rotation length is required to be able to calculate the theoretical potential of residue production per year. This section is split up in the two management types.

Natural forests

Rotation length in boreal forests is between 53 and 230 years (), although harvest takes place when maturity is reached, between 70 and 120 years (). Other values are also mentioned, such as 70-120 years, 106-113 years, 120 years and 80-100 years(Bernier & Paré, 2013; Holtsmark, 2011; Lamers et al., 2013; Magnani et al., 2007; Poudel et al., 2012; Storaunet and Rolstad, 2002 in Lamers et al., 2013). The average rotation length for boreal forests is therefore put at 107 years.

For TM forests, the rotation lengths of the forests are between 70-130 years (Arets et al., 2011). Peckham et al., (2013) indicate that temperate mixed forests have a rotation time of 70 years. However, Nunery & Keeton (2010) state that this is between 80 and 120 years. This leads to a mean value of 94 years for TM forest rotation lengths.

For TD forests the picture is mostly the same, with one change. In TD forests there are also softwoods present. The rotation lengths for softwoods are shorter than for hardwoods according to Arets et al. (2010). They state that softwoods have rotation lengths of 40-80 years. Adding these data to the original temperate forest data leads to a mean rotation length of 84 years in TD forests.

For WM forests the values for temperate forests are used from Arets et al. (2011). Since there are both softwoods and hardwoods in WM forests, both rotation lengths are taken. This results in a mean rotation length of 80 years (see also Table 14).

Plantations

The picture is different for plantations, here the rotation lengths are shorter. The temperate deciduous rotation lengths for plantations were derived from Arets et al. (2011) and Magnani et al. (2007). The rotation lengths that these sources provide are respectively 25-80 and 40-50 years. Therefore, the mean rotation length for TD plantations is calculated at 49 years. In WM forests, it is even shorter. Arets et al. (2011) state that these plantations rotate once every 20-40 years, the mean value used for WM forests is 30 years.

3.3. Theoretical potential

The theoretical potential was calculated using formulas 1,2,3 and 4. Table 13 shows the values that were used to produce the harvest and thinning residues that can be found in Table 14.

Table 13. Parameters of the theoretical potential of forestry residues, including the low and high values of the range between brackets.

Biome	**Management**	**Branchiness harvest - b** (kg_{stem}/kg_{crown})	**Production volume - pv** ($m^3_{stemwood}/ha$)	**Density - d** (kg/m^3)
BF	Clearcut	0.315 (0.145-0.600)	223 (80-442)	460 (350-714)
	Plantation	*n.a.*	*n.a.*	*n.a.*
CC	Clearcut	0.338 (0.176-0.600)	223 (80-442)	429 (350-512)
	Plantation	*n.a.*	*n.a.*	*n.a.*
TM	Clearcut	0.290 (0.145-0.600)	212 (111-357)	510 (350-977)
	Plantation	*n.a.*	*n.a.*	*n.a.*
TD	Clearcut	0.258 (0.145-0.600)	214 (40-422)	542 (390-977)
	Plantation	0.268 (0.135-0.600)	233 (113-501)	542 (390-977)
WM	Clearcut	0.219 (0.120-0.347)	179 (40-357)	523 (315-833)
	Plantation	0.219 (0.135-0.354)	340 (65-930)	523 (315-833)

Table 13 continued. Parameters of the theoretical potential of forestry residues including the low and high values of the range between brackets.

Biome	**Management**	**Thinning stages – ts** (number of times thinning is performed)	**Thinning fraction - tf** (fraction of trees removed)	**Thinning branchiness - tb** ($kg_{crown}/kg_{stemwood}$)	**Production - p** ($kg_{stemwood}/ha$)
BF	Clearcut	3 (2-4)	0.303 (0.215-0.390)	0.415 (0.227-0.774)	102639 (28000-315588)
	Plantation	*n.a.*	*n.a.*	*n.a*	
CC	Clearcut	3 (2-4)	0.303 (0.215-0.390)	0.415 (0.227-0.774)	95559 (28000-226304)
	Plantation	*n.a.*	*n.a.*	*n.a*	
TM	Clearcut	3 (2-4)	0.260 (0.100-0.500)	0.314 (0.145-0.774)	108080 (38850-348789)
	Plantation	*n.a.*	*n.a.*	*n.a*	
TD	Clearcut	3 (2-4)	0.260 (0.100-0.500)	0.272 (0.145-0.347)	115997 (15600-412294)
	Plantation	3 (2-4)	0.299 (0.100-0.540)	0.292 (0.135-0.774)	126296 (44070-489477)
WM	Clearcut	3 (2-4)	0.260 (0.100-0.500)	0.219 (0.120-0.347)	93646 (12600-297381)
	Plantation	3 (2-4)	0.348 (0.220-0.540)	0.384 (0.135-0.774)	177875 (20475-774690)

Table 14. Harvest and thinning residues, rotation length and resulting total forestry residue potential including the low and high values of the range in brackets.

Biome	**Management**	**Harvest residues - hr** (kg/ha)	**Thinning residues - tr** (kg/ha)	**Rotation length - rl** (year)	**Theoretical forestry residue potential - TP** (kg/ha/yr)
BF	Clearcut	32331 (4060-189353)	38632 (2740-381168)	107 (53-230)	663 (128-2481)
	Plantation			*n.a.*	
CC	Clearcut	32299 (4928-135782)	35967 (2740-273330)	107 (53-230)	638 (145-1779)
	Plantation			*n.a.*	
TM	Clearcut	31343 (5633-209273)	26471 (1127-539925)	94 (70-130)	615 (97-5763)
	Plantation			*n.a.*	
TD	Clearcut	29927 (2262-247376)	24610 (452-286132)	84 (40-130)	649 (68-4104)
	Plantation	33847 (5949-293686)	33144 (1190-818572)	49 (25-80)	1367 (286-13903)
WM	Clearcut	20508 (1512-103191)	15997 (302-206382)	80 (40-130)	456 (45-2381)
	Plantation	38955 (2764-267268)	54303 (1216-1295158)	30 (20-40)	3109 (199-39061)

Table 14 shows that there are differences between biomes and management types. For the clearcut biomes, the highest latitude forests produce more residues during harvest and thinning in absolute terms. However, this effect is obscured by the longer rotation lengths in the theoretical potential. Since BF and CC forests have longer rotation lengths, the residue production per year will be lower, even though they produce more residues during harvest. The WM clearcut biome produces the least amount of residues which can be explained mostly by the low branchiness, so less residues are produced per tree, and also a lower production occurs in that biome.

In contrast, WM plantations are the most productive, residue wise. The highest branchiness and production volumes are found in the WMPs. In general, plantations are assumed to produce more residues than clearcut management. This is because plantations use faster growing species that ensure a shorter rotation length. With a shorter rotation length, more residues are produced per year. This was found in this research also.

4. Sustainable potential

The sustainable potential of forestry residues depends on the severity of the negative effects of removal of biomass. Extracting forestry residues in a sustainable manner has a dual purpose. These are to "maintain or improve the quality of forest ecosystems (including soil and water resources, site productivity and biodiversity)" and "reduce excessive pollution" (Lattimore et al., 2009, p.1322). A secondary benefit would be the generation of a primary energy source in the form of forest residues. The aim of this chapter is to identify the drivers that limit the removal of forestry residues to maintain sustainability criteria. Furthermore, these are parameterised and recommendations are listed.

4.1. Drivers

This section will first describe the aspects that influence environmental sustainability that have been identified from literature. For example, next to harvest system and tree species, the maximum amount of residues that should be recovered from the forest is also part of the sustainable potential. Residues could be used to protect against soil depletion or erosion and the decrease of biodiversity (Smeets & Faaij, 2007). Next, the applicability of these and other drivers is assessed per biome and management type.

4.1.1. Environmental drivers

Removal of forestry residues is thought to impact a number of forest systems and functions. These can broadly be distinguished in the following categories: soil, hydrology, site productivity and biodiversity (Lattimore et al., 2009). There is some overlap between these categories, as some aspects influence multiple systems.

Soil

Soil is an important part of the forest ecosystem. It is the medium that holds the nutrients and water required for plant growth and supplies habitat for important forest species (Burger, 2002). Soil has multiple properties, including physical, chemical and biological properties, which can be influenced by the removal of forestry residues from a harvest site. Physical properties include moisture, structure, temperature and erodability. Chemical properties include soil organic matter, soil organic carbon, nutrients, toxins, pH and salinity. Finally, the biological properties include soil biota and soil regenerative properties (Lattimore et al., 2009).

Soil moisture, the amount of water in the soil, is influenced by removing residues, because residues left on the field will start to decay and decaying logging residues can hold a lot of water (Graham et al., 1994). Reducing soil moisture is detrimental because it could act as a limiting factor for plant growth (Kellomäki, Peltola, Nuutinen, Korhonen, & Strandman, 2008). Moreover, soil moisture depends in part on soil structure, which can also be compromised from retrieving logging residues (Burger, 2002).

Soil structure, another aspect of the soil, can be influenced from the harvest of residues. Soil structure can be altered because entry or re-entry with heavy machinery into the forest to collect the residues compacts the soil (Hakkila & Parikka, 2002). Often logging residues are used under the machinery to provide a buffer against compaction, with WTR collection this is no longer possible (Asikainen et al., 2002; Graham et al., 1994; Lamers et al., in press). However, soil compaction should be avoided because it influences the moisture, air and heat balance, and can disturb the extent and rate of plant root growth (Richardson, 2002).

The temperature of the soil is also an important aspect of soil processes. An increase in soil temperature is associated with increased organic matter deposition, leaching loss of nutrients, nitrogen mineralisation and nitrification. Removal of logging residues raises the soil temperature and thereby could have an effect on the afore mentioned processes (Mahendrappa, Pitt, Kingston, & Morehouse, 2006).

Increasing the susceptibility of soils to erosion is another important side effect of harvesting residues. In stem-only harvesting the residues are left on the forest floor, where they help stabilise soil. Removing the residues leads to some disruption and removal of topsoil (Burger, 2002; Lamers et al., in press). Also, natural dams that the logging residues and down wood form are removed and more erosion is possible (Graham et al., 1994; Grigal, 2000). This effect is even greater on steep slopes with a greater potential for surface erosion. With erosion, soil is removed from its original location and deposited elsewhere. Not only does this remove an essential part of the growing medium for plants, including nutrients and organic matter, it also can have a detrimental effect on streams where the soil may end up. Moreover, the water-holding capacity of the soil is diminished with the erosion of topsoil layers (Grigal, 2000).

Soil organic matter (SOM) is one of the components of soil. It has many functions that are of importance to plants. It holds the food and energy source for soil organisms, influences soil temperatures, and increases soil water-holding capacity and infiltration. For plants it holds the nutrients that allow them to grow, especially nitrogen and phosphorus. It also impacts the structure of the soil, the balance of water and air and these factors influence root growth and soil organisms. SOM is replenished by plant and animal detritus. The effect of harvest on SOM depends on the amount of biomass and forest floor removed, which is dependent on the harvesting method. More removal of biomass and forest floor means less SOM is available (Burger, 2002; Lattimore et al., 2009).

Another of the chemical properties of soils is the amount and concentration of soil organic carbon (SOC). SOC is used in the soil as a source of energy for nutrient-recycling activities performed by heterotrophic soil organisms (Nave et al., 2010). SOC is influenced by harvesting (Eriksson et al., 2007; Nave et al., 2010). Removing additional biomass in the form of residues can lead to a decrease in SOC, as less material is added to the soil (Eriksson et al., 2007). Harvesting leads to the loss of a substantial proportion of carbon stocks in the forest floor (the upper layer of the soil). The effects of this in the long term are unknown (Nave et al., 2010).

As mentioned previously, soils house the nutrients that the plant needs to grow. In conventional harvesting, the nutrients from the harvested stemwood are taken out of the cycle while the residues are left in the forest, decay there and can thereby recycle their nutrients through the system (Graham et al., 1994). While some of the removed nutrients can return via atmospheric deposition, such as nitrogen, some others have a low atmospheric concentration and therefore do not have sufficient deposition, such as phosphorus, potassium and calcium (Grigal, 2000). Next to atmospheric deposition, weathering also can replenish nutrients. The extent of nutrient influx is therefore dependent on the bedrock (European Energy Association [EEA], 2006). Removal of logging residues exacerbates the nutrient removal from the system and could thereby impact productivity. However, actual effects are difficult to quantify and vary significantly per forest area (Grigal, 2000). Moreover, forests also recycle nutrients during the lifetime of the trees. Many nutrients are returned to the soil via litterfall, root turnover and mortality. Therefore, the harvest removes only a small part of the total biomass production (Raison, 2002). The effect of the nutrient removal is also dependent on the type of soil that is present; shallow, coarse-textured, low nutrient soils will be more susceptible to nutrient depletion than others (Grigal, 2000).

Removal of logging residues can also have an effect on the soil by means of acidification (Hall et al., 1993; Lamers et al., in press; Wikström, 2007). More acidic soils will have a lower nutrient availability (EEA, 2006). While removal of stem also leads to acidification, this effect is worse with the removal of logging residues (Augusto et al., 2002; Wikström, 2007). The neutralisation effect of biomass decomposition is removed for a larger part, which decreases the pH of the soil. This can lead to the additional release of harmful aluminium ions that are toxic to the root system of the plant. Moreover, beneficial nutrients such as calcium, potassium and manganese begin to leach out below a pH of 5 (Hall et al., 1993).

Biological properties of the soil can also be altered by harvest and logging residue removal. Harvest can influence the communities that grow in the forest, by altering the species composition and age-class distribution (Grigal, Rosillo-Calle, Williams, & Woods, 2000). Moreover, as forestry residues slowly become part of the soil ecosystem, they serve as a food source for soil biota (Vis et al., 2010). Soil biota play an important role in the soil because they decompose the logging residues. Reduced activity of soil biota could therefore lead to reduced nutrient recycling rates and aeration. Whole tree harvesting is expected to have a high risk of causing this reduced soil biota activity (Lamers et al., in press). Lamers et al., (in press) also state that whole tree harvesting can have a potential risk by changing the substrate and microclimate, which can have an effect on soil biota. This would be caused by compaction, drying and waterlogging of the soil (Lamers et al., in press).

Soil fertility, another part of soil biological properties, is "the capacity of the soil to produce a large harvest" (Augusto, Ranger, Binkley, & Rothe, 2002, p. 234). It is a complicated concept that is based on the amount, availability and concentration in solution of plant nutrients (Burger, 2002). It is influenced by different site aspects including the type of soil, tree species, nutrient input and output fluxes (Augusto et al., 2002; Burger, 2002).

Soil fertility is influenced by organic matter content, therefore, it will be influenced by the removal of residues. This problem is increased when more residues are removed over shorter rotation times. However, forests may not experience soil fertility problems as much as agricultural systems. The residues are more woody and therefore sustain soil organic matter and fertility better, if these are spread out. However, spreading does not occur with whole tree harvest and could therefore still pose a problem without adequate management (Vance, 2000). Moreover, some intensive management techniques, such as ploughing and removing the logging debris can lead to a loss of soil fertility (Ouro et al., 2001).

Soil regenerative capacity, the ability of the site to produce new life, is decreased by compaction, moisture imbalance and nutrient loss (Lattimore et al., 2009). Whole tree harvesting can then influence the regenerative capacity, since there is a potential risk of compaction and nutrient loss. This can be caused by machinery use and exposure of the soil from the removal of deadwood, down wood or slash (Lamers et al., in press; Lattimore et al., 2009).

Hydrology

Harvesting of biomass from the forest has effects on the hydrology of the forest ecosystem. As mentioned above, harvest can have effects on soil moisture due to soil compaction (Grigal, 2000). This compaction has a number of effects on water in the forest system, including influencing the water table and creating the possibility of waterlogging, where the soil is saturated by groundwater and hinders air getting into the soil, which is required by many soil organisms (Burger, 2002; EEA, 2006; Lal et al., 2011). However, harvest also leads to decreased evapotranspiration and therefore increased runoff (Grigal, 2000). The soil is more directly exposed to rainwater if logging residues are removed, and thus more susceptible to erosion (EEA, 2006).

There would also be more associated nutrient movement, however, reviews demonstrated that export of nutrients is rare (Grigal, 2000). Water is stored, captured and hindered by the residues and deadwood and thereby reduce water run-off on slopes. With the removal of residues and deadwood, their regulatory function is disturbed since they help regulate water flows through the ecosystem. They also act as filters for water quality (EEA, 2006; Graham et al., 1994).

Site productivity

Site productivity is "the cumulative increment of trees on an area basis" (Farrell et al., 2000, p. 9). This is thus the amount of additional biomass that can be produced per area. Important aspects for site productivity are regeneration and soil quality (Lattimore et al., 2009). Regeneration is the sprouting of seeds to produce new trees.

Residues can impact regeneration in a number of ways. First, lots of residues can delay establishment of stands by a year (Hakkila, 2004). However, limited amounts of slash can have a positive effect on recruitment of pine and Douglas-fir seedlings (Harrington, Slesak & Schoenholtz, 2013; Prévosto & Ripert, 2008). It can also help protect seedlings from (livestock) damages (Graham et al., 1994). Moreover, if easily decomposable slash is left in the forest, it releases more nutrients during the first stages of stand development. The trees can then grow more in height compared to whole tree harvesting (Mahendrappa et al., 2006).

In order to maintain site productivity, soil quality needs to be sufficient. Soil quality is influenced by SOM, nutrient availability and soil biota (Lattimore et al., 2009). These are affected by nutrient concentrations. Therefore, organic matter removed during harvest need to be sustained (Vance, 2000). Otherwise, growth reduction in the years after whole-tree harvesting could take place (Egnell & Leijon, 1997; Hakkila, 2004; Jacobson et al., 2000; Mahendrappa et al., 2006). Kukkola & Mälkönen (1994 in Egnell & Leijon, 1997) report growth reductions of 10% over 10 year for Norway spruce, and Jacobson et al., report 5% and 6% growth reduction during 10 years for pine and spruce stands respectively (2000). If residues are removed in order to speed up stand establishment this could lead to detrimental effects in the longer term because of growth reductions (Hakkila, 2004). Not all studies have shown growth reductions after residue removal, so the extent of the problem is dependent on local conditions (Grigal, 2000).

Productivity is also dependent on the local soils. Forests are usually established on lands that are already less fertile, so erosion has the potential to worsen some of the properties of soils. Therefore, erosion, which leads to soil water holding capacity decrease often influences productivity more in shallow soils or soils with heavy clay subsoils. Fertility decline is more important in other soil types (Vance, 2000).

Biodiversity

Biodiversity is found to be an important aspect of the forest and an important indicator in the sustainability of forest use. However, it is impossible to measure the impact of management decisions on all species living in the forests. Therefore, indicators are used to portray biodiversity. Some of the attributes that support high levels of biodiversity are: abundance of deadwood, density of large-diameter trees, number of tree species, and number of habitats (Duncker et al., 2012). For a more complete list of sustainability indicators for woody biomass see Lal et al. (2011).

The forest consists of several different types of woody biomass. There are the living standing trees, hollow trees, very large trees, stumps left over from harvest, down wood that is removed from the trees by e.g. wind, snow, droughts and pathogens, deadwood, snags (standing dead trees), slash (forestry residues) and undergrowth (Angelstam, Mikusinski, & Breuss, 2002; Bunnell & Houde, 2010, Thomas et al., 1999). Most of these provide distinct habitats for different species and removal of them will therefore have an effect on the biodiversity of the forest (Angelstam et al., 2002; Bunnell & Houde, 2010, Lal et al., 2011;)

Deadwood is important for forest biodiversity as it provides a habitat for many species (Angelstam et al., 2002; Bunnell & Houde, 2010; EEA, 2006). For plants, deadwood is an important habitat aspect. Logs, roots, stumps and branches create microclimates that can be important for different plants. Moreover, nutrients and moisture are influenced by deadwood. It also facilitates mycorrhizal relationships and create areas where plants can establish, although deadwood is not often the limiting factor for establishment (Bunnell & Houde, 2010).

Moreover, invertebrates, fungi, mosses, liverworts and lichens use the deadwood for habitat. With the reduction of deadwood by means of residue collection, many insect and fungi species are negatively impacted. This could further influence the entire food chain since fungi are often at a low trophic level. They also influence decomposition, nutrient recycling and the growth of crop trees. Next to that mycorrhizal fungi that could be essential for tree productivity disperse from deadwood (Bunnell & Houde, 2010).

However, deadwood is not only a habitat. It provides sheltered areas for reproduction, microclimates, runways and lookout posts, foraging sites, access routes for predators, the substrate on which food (fungi and invertebrates) grows and it creates diversity in the landscape. For amphibians and reptiles it can be used for breeding and as cover. Birds require deadwood for foraging sites and nesting sites (Bunnell & Houde, 2010).

For deadwood size matters. The use of the down wood by organisms depends on the size, distribution and decay state of the down wood. The size, and especially diameter, influences the amount of time a piece of wood will spend in the forest (Bunnell & Houde, 2010). While small deadwood is important for some species, other species depend on large deadwood (Bunnell & Houde, 2010; EEA, 2006). Large animals cannot find shelter in small wood and therefore require greater pieces. Larger logs also encourage greater richness if they are in the right decay stage. However, the smaller pieces are required by some fungi and insects (Bunnell & Houde, 2010).

The amount of decay also influences which species will make use of the down wood. Recently dead wood is used for cover by small vertebrates while more decayed wood is used by insects and as nesting site for small mammals and amphibians. Natural succession of decay allows for foraging of different species on different types of fungi. Although there is variability in decay succession, there is suggestion that the range of decay classes should be present in the forest to sustain the entire range of biodiversity (Bunnell & Houde, 2010).

The distribution of down and deadwood is also important. The effect of removing or piling down wood from a site has a greater impact on poorly dispersing species, who cannot find accommodation in the now empty landscape (Bunnell & Houde, 2010). Moreover, residue extraction affects the composition of the species present because the habitat is homogenised and the soil is more disturbed (EEA, 2006).

The challenges associated with estimating amounts and distributions appropriate for maintaining biodiversity are threefold: scale – the combination of amount and distribution can lead to there being enough deadwood but not enough in certain areas -, the transient nature of deadwood – the habitat is constantly changing and pieces may last or disappear -, and the variation within stand types. The resulting conclusion is that because of the variation in response, it is difficult to estimate threshold values for down and deadwood. Moreover, the relations found between biodiversity and amount of dead and down wood are often weak and confused (Bunnell & Houde, 2010).

There are also differences between biomes when it comes to down wood. Some species of tree decay much slower than others and therefore have a higher likelihood of hollows, e.g. *Sequoia*, *Pseudotsuga*, ponderosa pine (*Pinus ponderosa*) and western redcedar (*Thuja plicata)*. Bark thickness and the opportunities it provides for e.g. hiding places for salamanders and substrate for cryptogams, also differ per species. *Picea, Tsuga* and *Pseudotsuga* have 10, 20 and 30 years of stable bark surface respectively (Bunnell & Houde, 2010).

The age of the trees is also a factor in biodiversity. Older trees hold species that thrive in late succession, by removing these trees, the habitat for those species gets lost. Moreover, older trees produce deadwood with specific qualities for certain organisms (EEA, 2006). Old growth forests also have a greater likelihood of harbouring rarely detected fungal species (Bunnell & Houde, 2010). Moreover, old trees are identified as an important forest quality for many plants, invertebrates and vertebrates. Retaining old trees is barely compatible with managing forest stands and therefore the threat to species that depend on old trees is large. Some species also require areas that occasionally catch fire, which also does not fit with management plans (Angelstam et al., 2002).

With biodiversity as an important indicator of sustainability, measures have been taken to try and protect biodiversity. The 10% criterion is a measure designed to help protect biodiversity, it proposes to protect at least 10%, in some countries 12%, of forest area at a national level (Smeets & Faaij, 2007). This is thought to help biodiversity by limiting interference in certain stretches of forest. However, Soulé and Sanjayan (1998) state that when only 10% of the land is protected that may not be enough to ward of major extinction events. It is feared that countries will believe 10% is enough and stop there with biodiversity measures. Still, if 10% of the land area would be protected this would be a major achievement (Soulé & Sanjayan, 1998).

There are guidelines for biodiversity protection. For example, in Europe, foliage and roots should be left on site, the wood supply area should be decreased by 5% in each member state such that there is more protected area and 5% of wood volume should be set aside as retention trees to provide large diameter trees and deadwood (EEA, 2006). In Austria, deadwood should be left in the forest if there is no comprehensive danger. In Sweden deadwood should remain untouched unless there is danger of insect pests (Stupak et al., 2007)

4.1.2. Other drivers

However, next to environmental factors, there is also the aspect of technical recovery. Not all residues can be recovered due to technical limitations (Smeets & Faaij, 2007), e.g. needles that fall off are not worth recovering. Moreover, residues from steep slopes are more difficult and therefore expensive to recover (Scarlat et al., 2011; Zambelli et al., 2012). Some of the hills are too steep for access (Smeets & Faaij, 2007). Furthermore, there are many protected forests in the world, where logging is not permitted, and therefore no residue recovery may take place (Smeets & Faaij, 2007).

The building of roads, landings and other access points to the forest can also have an effect on the ecosystem. It influences the productivity of the forest because it can increase erosion, it takes part of the area out of production, changes relative productivity on the sides of the road and disrupts hydrologic flow paths (Grigal, 2000).

4.1.3. Management

Industrial wood plantation growth rates are much higher than those for natural or semi-natural forests, this means that their rotation length is also much shorter. Siry et al., (2005) determined industrial plantations to consist of species with growth rates of 5 m^3/ha/yr or more and a rotation length of less than 30 years. However, because this rotation length is much shorter, it reduces the pressure on natural forests. The demand for timber can more easily be satisfied from industrial plantations, as they supply wood quicker (Siry et al., 2005).

Nevertheless, there are critics who are negative about the role of plantations in forest products production in the future. Plantations require additional inputs to maintain productivity in the form of nutrients (Siry et al., 2005). The biodiversity in plantations is often lower than in natural forests (Siry et al., 2005) XXX, because they are composed of one or a few species of trees and weed management can be present (Brown, 2000). There is also the risk that natural forests are converted to plantations. Natural forests grow slower and are therefore not as profitable as plantations, leaving them vulnerable to harvest and replacement with plantations (Siry et al., 2005).

Forest management leads to a limitation of tree age, which reduces the amount of woody debris in the forest. Moreover, maintaining large trees does not comply with the goals of managed forest and by removing the older and larger trees, habitat is lost. However, there are often more small stems, branches and twigs on the ground of managed forests and these can also have habitat functions. There are less large pieces of down wood (Angelstam et al., 2002). Moreover, stand age at the time of harvest is important since there is a lower average nutrient content in older stands (Augusto et al., 2002).

Piling is the process of stacking or gathering the residues or logs in a pile. This is thought to be a prerequisite for effective harvesting of residues (Asikainen et al., 2011). While piling makes sense economically, because it is easier to gather the residues after they have dried in the forests, it is more ambiguous for biodiversity (Andersson et al., 2002; Bunnell & Houde, 2010). Some organisms, like small mammals, use piles of residues, however, the real benefit is unclear. Moreover, some organisms disperse from residues and having residues that are only present in a piled stack will limit the distribution. If residues are more spread out, they create more diversity and microclimates in the landscape that can be beneficial for different types of organisms (Bunnell & Houde, 2010). There is increased leaching of nitrogen under piles, which can lead to productivity losses (Egnell & Leijon, 1997).

4.1.4. Comparison to the FSC standard

In order to see what is considered important for sustainability in other systems, a summary of the Forest Stewardship Council (FSC) criteria and indicators was made.

The FSC has 10 principles; 1: compliance with laws, 2: workers' rights and employment conditions, 3: indigenous peoples' rights, 4: community relations, 5: benefits from the forest, 6: environmental values and impacts, 7: management planning, 8: monitoring and assessment, 9: high conservation values, and 10: implementation of management activities (Forest Stewardship Council [FSC], 2012) . There used to be a different 10th principle, concerning plantations, however, this was changed in the newer version (Forest Stewardship Council [FSC], 1996). Of the 10 current principles, the 5th, 6th and 9th address specific environmental issues (FSC, 2012).

Aspects of environmental sustainability include: "5.2 The Organization shall normally harvest products and services from the Management Unit at or below a level which can be permanently sustained." (FSC, 2012, p. 16). Principle 6: "The Organization shall maintain, conserve and/or restore ecosystem services and environmental values of the Management Unit, and shall avoid, repair or mitigate negative environmental impacts." (FSC, 2012, p. 17).

As can be seen, these criteria and indicators are still quite vague and no actual recommendations are made. This will also increase the difficulty for forest owners to use these guidelines and create a sustainable forestry business. However, the fact that some criteria are available does mean that progress is being made to reach a sustainable forest industry.

4.2. Parameterisation

The parameterisation of sustainability criteria is very dependent on the local situation. For example, the type of soil and bedrock has an impact on the amount of nutrients that can be replenished by weathering, and thereby on the amount of nutrients that can be taken out during harvest (EEA, 2006). Soil types are not uniform over the entire biome and therefore it is difficult to accurately indicate how much nutrients can be removed. Moreover, long-term effects of whole tree harvesting are difficult to determine as this method is fairly new and effects can be obscured (e.g. Andersson et al., 2002; Jacobson et al., 2000; Lamers et al., in press; Nave et al., 2010). The variability within the biomes makes parameterisation over the whole biome difficult. This following section will deal with some of the methods that should limit environmental impacts of forestry residue harvesting and thereby make it more sustainable.

4.2.1. Biome

Many of the elements in the categories discussed in section 3.1.1 (soil, hydrology, productivity and biodiversity) overlap and one measure can have effects on one or more of those categories. Therefore, certain practices are discussed here that can influence the sustainability, however, they will not directly be classified according to the same categories as in section 3.1.1.

Harvest

In order for harvest to be sustainable, there should not be more taken out of the forest than is produced. This means that the annual fellings of wood should not be greater than the net annual increment (how much wood is produced per year) in order to be sustainable (Vis et al., 2010). However, harvest is generally less than the annual increment, in inter alia Europe, so this is not yet a problem (Asikainen et al., 2008; Hakkila, 2004; Zanchi, Pena, & Bird, 2012).

Retention

Estimates have been made on the amount of residues that should be left in the forest in order to have sustainable bioenergy production. Reasons for maintaining some residues in the forest include: carbon and nutrient cycling processes, biodiversity, soil organic matter, fungi, soil protection, hydrologic processes and productivity (Bunnell & Houde, 2010; Burger, 2002; EEA, 2006; Etcheverry et al., 2004; Gregg & Smith, 2010; Grigal, 2000; Vance, 2000). Figure 3 shows a histogram of the retention values. There are a few outliers at the top (75 and 100%) and at the bottom (0 and 10%). Most of the values are between 20 and 50%. This would mean that between 50 and 80% of the residues can be taken out of the forest. However, it is interesting to see where the values of the outliers come from.

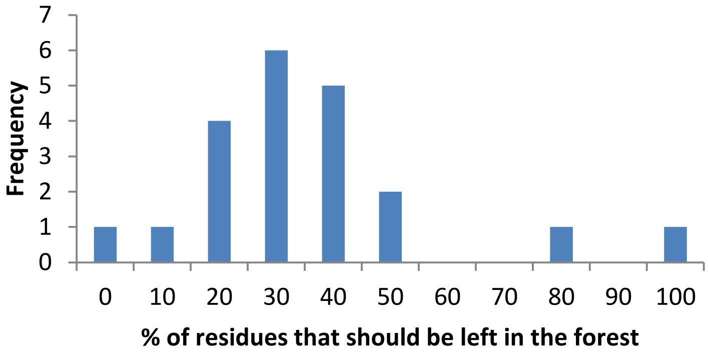

Figure 3. Histogram representing literature for the percentage of residues that should be left in the forest.
Based on: Batidzirai et al., 2012; Bauen, Woods, & Hailes, 2004; Bunnell & Houde, 2010; Dymond et al., 2010; EEA, 2006; Eriksson & Gustavsson, 2010; Etcheverry et al., 2004; Gregg & Smith; Karaj et al., 2010; Lal et al., 2011; Lamers et al., in press; Paré, Bernier, Thiffault, & Titus, 2011; Perlack et al., 2005; Smeets & Faaij, 2007; Titus, Maynard, Dymond, Stinson, & Kurz 2009; Vis et al., 2010).

On the high side of the outliers, Etcheverry et al. (2004) stated that 100% of the branches and foliage should be left in the forest to maintain the carbon and nutrient cycling processes, and also to serve as habitat for animals. Many other sources agree that residues should be left, but all is not necessary (e.g. Bunnell & Houde, 2010; Karaj et al., 2010).

The potential for forestry residues according to Bauen et al. (Bauen, Woods, & Hailes 2004) is 25% of the theoretical potential. This was recalculated to imply that 75% of the residues should be left in the forest. Bauen et al. (2004) do not assume full clearcut, as 40% of the standing biomass is left on site. Half of the roundwood would be available as residues. However, no environmental reasons are giving for mentioning this value (Bauen et al., 2004).

The lowest outliers include the Pennsylvania Department of Conservation and Natural Resources (Pennsylvania DCNR) (2008), which released guidelines that stated that 10% of whole tree harvesting slash should be left at the site. However, the amount of whole tree harvests must be limited and slash should be retained on areas harvested conventionally (Pennsylvania DCNR, 2008). In practice this means that most of the residues produced will be left in the forest.

Lastly, the 0% retention as mentioned by Titus et al. (Titus, Maynard, Dymond, Stinson, & Kurz 2009) was not clearly defended in the original sources (Mabee, Fraser, McFarlane, & Saddler, 2006; Wetzel, Duchesne, & LaPorte, 2006). It does not seem to be the case that environmental criteria were taken into account in the production of this value.

However, there have also been a few numerical values, Graham et al. found that 10 to 20 Mg/ha of fresh coarse woody debris is needed for the optimum amount of organic matter (1994). Gregg & Smith state 20 Mg of logging residues should be left at the site for maintaining soil organic matter and fungi (2010). This value is equivalent to about 25% of the aboveground residues from 40-year-old rotation of Japanese Cedar according to Nishizono et al. (2005, in Gregg & Smith, 2010). Table 14 shows the results of final harvest from this research, where the mean values for the biomes during clearcut are between 20.5 Mg and 32.3 Mg. This would mean that in the warm-mixed forest almost all the residues should be left on the forest floor when following Gregg & Smith’s high value of 20 tonnes (2010). For the lower value of Graham et al. (1994), 49% of the residues should be left in the WM biome and about 31% in the BF and CC biomes. The warm-mixed clearcut produced less harvest residues than the other biomes because of low production and branchiness.

Table 15. Percentage of residues that should be left in the forest based on the 10 and 20 tonne retention from Graham et al., 1994, ranges between brackets (minimum residue production-maximum residue production).

Biome	**Management**	**Harvest residues** (kg/ha)	**Residues left (10 tonne)** (% of total harvest residues)	**Residues left (20 tonne)** (% of total harvest residues)
BF	Clearcut	32331 (4060-189353)	31 (100-5)	62 (100-11)
	Plantation	*n.a.*	*n.a.*	*n.a.*
CC	Clearcut	32299 (4928-135782)	31 (100-7)	62 (100-15)
	Plantation	*n.a.*	*n.a.*	*n.a.*
TM	Clearcut	31343 (5633-209273)	32 (100-5)	64 (100-10)
	Plantation	*n.a.*	*n.a.*	*n.a.*
TD	Clearcut	29927 (2262-247376)	33 (100-4)	67 (100-8)
	Plantation	33847 (5949-293686)	30 (100-3)	59 (100-7)
WM	Clearcut	20508 (1512-103191)	49 (100-10)	98 (100-19)
	Plantation	38955 (2764-267268)	26 (100-4)	51 (100-7)

The mean values found for 10 tonnes retention of forestry residues from clearcut fit well within the retention of 20-50% as found in Figure 3. However, it must be noted that the values found in these biomes are below the 25% of a rotation as mentioned by Nishizono et al. (2005, in Gregg & Smith, 2010). Moreover, using the minimum values for harvest residues as found in this research, none can be removed in any biome for energy purposes. At the highest value, almost all residues can be taken out (Table 15).

Moreover, not only residues that transition into deadwood should be maintained. Snags should also be maintained as some species use the bark piles at their foot, they can be important for the next rotation and they play a role in biodiversity (Angelstam et al., 2002; Bunnell & Houde, 2010; Lal et al., 2011; Lamers et al., 2013; Richardson, 2002). Some large and old trees should also be maintained as they provide large stumps and logs preferred by some wildlife, can house endemic species and benefit biodiversity (Angelstam et al., 2002; Bunnell & Houde, 2010; Dekker, Turnhout, Bauwens & Mohren, 2007; EEA, 2006).

EEA (2006) proposed that 5% of standing volume is to be retained during harvesting as individual and small groups. Retention of living trees can improve the deadwood and mature tree situation as there is sustained provision of deadwood (Bunnell & Houde, 2010; EEA, 2006). However, fresh, finer coniferous material from logging residues is usually abundant in the landscape and its removal will presumably only seldom pose a risk to saproxylic organisms, and therefore does not need as much attention to its retention (Stupak et al., 2007).

Retaining living wood can be in groups or individual trees, both have their advantages. Groups are preferred by mosses, while individual trees are preferred by fungi (Bunnell & Houde, 2010). However, there is no best method, since different species prefer different treatments. Therefore, both types should be retained on site (Bunnell & Houde, 2010).

Foliage

Suggestions have been made that leaves and needles should be left in the forests (EEA, 2006; Etcheverry et al., 2004; Nurmi, 1999). Foliage is the part of the tree and residues that has the highest concentration of valuable nutrients. Therefore, leaving them should improve the nutrient balance and reduce the possible nutrient deficiency effect (Nurmi, 1999; Perlack et al., 2005; Roos, 2002; Stupak et al., 2007). Moreover, leaving the leaves (and some branches) should prevent growth decrease after thinning and harvest residue removal (Helmisaari et al., 2011).

A way to ensure leaves remain is harvesting in the season when foliage has dropped (for broadleaves) since those nutrients are then already on the forest floor (Andersson et al., 2002; Richardson et al., 2002). Another option is topping trees during thinning, this means leaving the top of a tree (e.g. 3 meter for a pine) in the forest, hereby less needles are recovered (52% less) while overall whole-tree recovery is only reduced by 8% (Hakkila, 2003). Another method is to leave the residues to dry in the forest. Much of the foliage will fall off during drying (Nurmi, 1999).

After drying, when removing the residues from the forest the crane should shake the residues such that foliage falls off and is spread over a larger area (Hakkila, 2002). Additionally, drying has additional benefits such as a higher calorific value for the residues and less combustion problems because of ash and alkali metal content (Hakkila, 2004; Nurmi, 1999). However, a disadvantage of drying in the forest is re-entry of machinery into the forest to retrieve the residues. This can lead to soil compaction and this has negative effects on productivity (Burger, 2002). Furthermore, the cost of the resulting fuel from residues can be higher because there is reduced biomass recovery, a delay in harvesting schedule and logistical disadvantages (Hakkila, 2003).

Leaves and needles are a fairly large part of the crown, between 8% (for *Fagus*) and 45% (*for Abies*)(Appendix D). On average the percentage of the crown that is foliage is 26%, based on the data used in this research (e.g. Standish et al., 1985). This means that the theoretical potential for biome and management combinations should be reduced by a certain percentage according to Table 16.

Table 16. Percentage of residues that is foliage and the percentage of residues that should be removed to keep the 10-tonne guideline in the different biomes and management types (based on Standish et al., 1985; Pérez et al., 2009; World Agroforestry, 2013; Donoso et al., 2010; Busing & Fujimori, 2005).

Biome	**Foliage in residues** (%)	**10-tonne retention guideline** (% of residues)
BF	27.3	31*
CC	36.3*	31
TM	25.5	32*
TD	21.2	33*
TDP	25.2	30*
WM	31.5	49*
WMP	37.0*	26

*The percentage used as shf.

Stump and roots

Stumps can also be included in residues. If they are removed from the forest, they can also supply energy. Stump-root systems of spruce and pine have the same mass as 22-25 percent of the stem mass (Eriksson & Gustavsson, 2008; Hakkila, 2004; Nilsson & Thörnqvist, 2004). The energy content in the stump can be higher than that of the crown and therefore could become as cost-effective in the near future (Eriksson & Gustavsson, 2008).

Removal of stumps has its benefits and disadvantages. Benefits include creating the possibility of allowing mechanical planting and extermination of root rot fungus in the soil (Eriksson & Gustavsson, 2008; Hakkila, 2004; Stupak et al., 2007). Also, stump removal will inhibit damage caused by pine weevils and other pest species (Eriksson & Gustavsson, 2008; Wiser, Allen, Benecke, Baker, & Peltzer, 2005).

Nevertheless, not all negative environmental consequences are clear yet (Nilsson & Thörnqvist, 2004). However, some concerns have been identified. Stump removal could lead to long-term production losses and influence biodiversity (Nilsson & Thörnqvist, 2004). Stump harvest affects biodiversity because some species make use of stumps such as grouse, lynx, vascular plants and larger vertebrates (Angelstam et al., 2002; Bunnell & Houde, 2010). For example, different communities of vascular plants settle on and around stumps than do on the forest floor. Therefore, removal of stumps will influence the species composition (Bunnell & Houde, 2010). Moreover, stumps can provide a large amount of coarse woody debris that is used by many species (Graham et al., 1994).

Stump removal can also create a high risk of erosion, especially on slopes (Lamers et al., in press; Lattimore et al., 2009). Moreover, it can cause instability and bring up undesirable soil materials (Lattimore et al., 2009). The soil is also exposed with stump harvesting and this can lead to nutrient exports and leaching (Lattimore et al., 2009; Stupak et al., 2007). The amount of soil nitrogen and carbon may thereby be decreased, but this is uncertain (Eriksson et al., 2007; Lattimore et al., 2009; Poudel et al., 2012; Vis et al., 2010). However, with the increased nutrient export, additional fertilisation and ash recycling will become necessary (Eriksson & Gustavsson, 2008; Eriksson & Gustavsson, 2010).

There are many negative environmental effects of removing stumps. Therefore, recommendations have been made by the Swedish Forestry Agency that stump harvest should not be performed on sensitive lands and be limited to 10% of regeneration felling area. Moreover, only coniferous stumps should be removed (Nilsson & Thörnqvist, 2004). Other research states that a maximum of 33% (or 20-40%) can be removed, although no stump harvest on slopes is permitted (Asikainen et al., 2008; Böttcher et al., 2010). Stumps and roots are left in the ground during thinning to contribute to the soil carbon stock (Poudel et al., 2012). Also, there are social values playing a role, since stump and root harvesting spoils the landscape in the short term (Nilsson & Thörnqvist, 2004).

The problems associated with biodiversity and unknown long-term effects leads to the recommendation that stumps should be left in the ground after harvest. Especially since the intensity of the effects of stump harvest are very dependent on the local situation, and it is difficult to aggregate that over a large area. Moreover, with the environmental problems and social problems it is advised to leave the tree roots in the ground (EEA, 2006).

Handling residues

Forestry residues are often stored in the forest for a period of time. Piling is an often used method for this. The residues are put in a pile and positioned such that machinery will not disturb it and to facilitate air drying (Acuña et al., 2010; Andersson et al., 2002). Drying is beneficial since foliage will fall off and the resulting fuel will produce less ash and have a higher calorific content (Andersson et al., 2002; Nurmi, 1999). In order to get rid of the foliage that is still attached to residues after drying in the forest has taken place, the crane should shake the residues to spread out the foliage over a greater area than that created by the pile (Hakkila, 2002). Piling can also lead to reductions in SOM and proliferation of pest species (Bunnell & Houde, 2010; Lattimore et al., 2009).

Next to aggregating the residues, they can also be dispersed over the forest. Dispersal has colonisation benefits for species that do not disperse as well themselves, residues can then act as stepping stones. Also, there are more microclimates created that can harbour different types of biodiversity. However, there is a greater risk of harmful insect outbreaks (Bunnell & Houde, 2010).

Residues are also often used as mats to protect the soil from machinery (Asikainen et al., 2011; Dymond et al., 2010; EEA, 2006; Lattimore et al., 2009). This alleviates the physical damage that can be done by machinery such as rutting, compaction and forest floor scraping (Dymond et al., 2010; Grigal, 2000; Lamers et al., in press). However, if they are used, they cannot be collected to be used for energy anymore (Asikainen et al., 2011). Still, it is advised to use some of the residues as a mat, even though this reduces the sustainable potential of forestry residues for energy.

Productivity

Removing residues has an effect on the productivity of the stand. It can save time as regeneration can take place earlier (Hakkila, 2004). However, it also protects new recruits and therefore some should be maintained as mentioned before (Graham et al., 1994). Moreover, removing residues will also remove nutrients. This could be remedied by returning nutrients that were removed during harvest (Vance, 2000). This could be done by using fertilisation (Asikainen et al., 2002; Stupak et al., 2007; Wikström, 2007). Finally, recycling of ash is another option to return nutrients to the forest, although nitrogen is not replaced this way (Hakkila, 2003; Eriksson & Gustavsson, 2010; Wikström, 2007). The nitrogen is assumed to be compensated for by atmospheric deposition (Wikström, 2007). However, additional nutrients are sometimes only assumed to be necessary in poor sites, as the nutrient levels should be sufficient when sustainable harvest levels are applied (EEA, 2006).

Forests do not require as high soil nutrient concentrations as annual cropping systems because forests have a longer growing season and more extensive rooting systems. Therefore, they are less susceptible to SOM changes (Vance, 2000). The problem remains that with SOM decrease comes additional erosion and therefore productivity decline. Still, trees have a longer lifetime than agricultural crops. Through litterfall, mortality and root turnover, much biomass is returned to the soil in the form of organic matter (Burger, 2002; Lattimore et al., 2009). There is not yet a clear overall picture of the effects of harvesting of forest residues on SOM (Eriksson et al., 2007; Grigal, 2000; Lattimore et al., 2009).

Protected status

The 10% criterion states that 10% of the forest area should be protected. The FAO have data on the protected status of forests for the countries of the world (FAO, 2010). Of the 70 countries in which forests classified in the five biomes from this research were present, 37 countries had assigned a protected status to less than 10% of their total forest area (FAO, 2010) (Appendix C). If those countries with only a small part of their forest area in one of the biomes were excluded, 31 out of the 59 remaining countries had not reached the 10% criterion, and 33 had not reached the 12% criterion (FAO, 2010) (Appendix C).

Carbon

One of the reasons for limiting the use of logging residues for energy purposes and leaving them in the soil is the change in carbon release. When residues are left in the forest they decompose and slowly release their carbon to the atmosphere over a number of years. If the residues are burned that carbon is released immediately. There is less dead wood and litter and a decrease of soil carbon. The effect of this is compared to the carbon that would be released if fossil fuels would not be substituted with bioenergy. However, the use of easily decomposable forestry residues from sustainable forests for energy can produce greenhouse gas benefits from the beginning of their use (Lattimore et al., in press; Zanchi et al., 2012).

4.2.2. Management type

Many of the abovementioned aspects also apply to plantations. However, there are some differences that are explained here.

Retention

The retention for plantations was assumed to be similar to those in Graham et al. (1994). Table 15 shows the values for plantations. These are in the same range as those found for clearcut, although the warm-mixed plantations produce more residues and therefore have less percentage retention compared to clearcut biomes. This is striking because the variation between the clearcut and plantation in the warm-mixed biome is so large, it represents the highest and the lowest retention value. This is mainly due to the assumed production volumes. The highest production volumes are from warm-mixed plantations, while the lowest are for warm-mixed clearcut (Table 12 and Table 13). Also in plantations the minimum value does not allow any residues to be taken out of the forest, while maximum values allow almost all residues to be removed.

Productivity

The aspects of fertility that are present in the (semi-)natural forests are also applicable to plantations. However, because of the shorter rotation period, the effect of removing many nutrients could be exacerbated. There is less litterfall, mortality and root turnover because the lifetime is shorter. In cases where there is no fertilisation, the trees depend on nutrient cycling for their nutrients. Moreover, while there is limited calcium and magnesium weathering, of which fast growing stands require a high uptake (Ouro et al., 2001).

Soil fertility in plantations may be maintained by planting mixed species of nitrogen-fixing and non-nitrogen-fixing tree species. This way soil fertility can be maintained without as much fertiliser input (Bauhus et al., 2004). Moreover, using mixed species in a plantation can be facilitative, where one type of tree benefits of the growth of the other type of tree (Kelty, 2006).

4.2.3. Guidelines

Many guidelines have been proposed that should help maintain sustainability in the forest system. Some will be mentioned here (Table 17). Do note that this is not an exhaustive list as there are many guidelines proposed per forested country. For extensive lists of guidelines for wood and residue removal see e.g. Lattimore et al. (2009) and Lamers et al. (in press).

Table 17. Guidelines for forestry residue removal.

Category	**Guideline**	**Source**
Harvest	Annual fellings should not exceed net annual increment	1
Retention	Retain 20-50% of residues in the forest	Table 15
	Retain 10-20 tonnes of residues in the forest	2
	Sustain 50% of naturally occurring amounts of down wood at the landscape level	3
	Sustain a range of size and decay classes of down wood, including large pieces	3
	Provide both aggregate (piles) and dispersed down wood	3
	Retain some live wood	3,4
	Retain some snags	3
Foliage	Leave foliage on site	4,5
	Harvest broadleaves in winter	6,7
	Top thinning trees (leave 3 meter top behind)	8
	Dry residues in the forest	5
	Shake dried residues to disperse foliage	9
Stumps and roots	Leave roots on site	4
	Never harvest stumps on slopes	10,11
Handling residues	Limit amount of machinery passes in forest	11,12, 13
	Leave residues to form a mat to protect the soil	4,11,1 3,14
Productivity	Use ash fertilisation where nutrient limitation is suspected	4,15
Protection	Reduce wood supply area in countries with 5%	4
	Give 10% of forest area protected status, where no harvest is allowed	16
Management	Leave a proportion of the stands unmanaged	3
	Mix management styles	3
	Plant multiple species in plantations	17,18

1 Vis et al., 2010; 2 Gregg & Smith, 2010; 3 Bunnell & Houde, 2010; 4 EEA, 2006; 5 Nurmi, 1997; 6 Andersson et al., 2002; 7 Richardson et al., 2002; 8 Hakkila, 2003; 9 Hakkila, 2002; 10 Lamers et al., in press; 11 Lattimore et al., 2009; 12 Dymond et al., 2010; 13 Grigal, 2000; 14 Asikainen et al., 2011; 15 Wikström, 2007; 16 FAO, 2010; 17 Bauhus et al., 2004; 18 Kelty, 2006.

Table 18. Sustainable forestry residue potential and difference from theoretical potential

Biome	**Management**	**Harvest residues** (kg/ha)	**Thinning residues** (kg/ha)	**Rotation length** (years)	**Sustainable residue potential** (kg/ha/yr)	**Difference from theoretical residue potential** (%)
BF	Clearcut	22331	28085	107	471	29
	Plantation					
CC	Clearcut	20574	22911	107	406	36
	Plantation					
TM	Clearcut	21343	19721	94	437	29
	Plantation					
TD	Clearcut	19927	19393	84	468	28
	Plantation	23185	22704	49	937	32
WM	Clearcut	10508	11965	80	281	38
	Plantation	24541	34211	30	1958	37

In all but the CC forests and plantations, more residues are needed to satisfy the 10-tonne guideline and therefore additional branches should be left. This then contributes to satisfying the requirements for size ranges of down wood. The branches that are left should be placed in the path of the machinery to serve as a protective mat against soil disruption. In the forests, the debris that falls should be left.

In the CC forests and plantations, just leaving the foliage is sufficient to satisfy the 10-tonne guideline. However, there are more than 10 tonnes of foliage and therefore, more residues need to be left there. Some of these should also be branches, however, this was not taken into account in the calculation since there is no estimate of branches that should be left.

Sustainable harvest scenario

The aspects of fertility that are present in the (semi-)natural forests are also

From the guidelines an indication can be made of the amount of residues that should be retained in order to comply with sustainability criteria. The basis of the calculation of sustainable forestry residue potential is the 10 tonnes of logging residues that need to be retained. Table 15 shows the percentage of logging residues that needs to be retained in order to reach the 10-tonne residue target.

Table 16 shows that for all but CC forests and WM plantations, retaining the foliage is enough to satisfy the 10-tonne guideline. As all the biomes and management options have less than 50% residue retention based on the 10-tonne guideline, the 20-50% guideline has also been satisfied this way. The problem then is the CC forest and the WM plantation that do not have enough residues to satisfy the leaf retention. The solution to this is to remove more residues than the 10-tonne guideline. However, not only the logging residue foliage needs to be retained, also the thinning foliage needs to stay in the forest in order to reduce the risk of nutrient depletion. The sustainable residue potential that was calculated can be found in

Table 18.

How the guidelines as proposed in Table 17 will be met will be discussed below. First, not more than the annual increment should be harvested. Although this can be difficult to estimate, this is currently generally the case. Next, 20-50% of residues need to be retained in the forest.

Table 18 shows that between 28% and 38% of the theoretical potential is left in the forest to protect against biodiversity loss and problems with productivity. This is nicely in between the 20-50% guideline. Not the full 50% is kept, but over 20% is retained in all cases. Since the sustainable potential was arrived at by using the 10 tonnes guideline, this has also been achieved using the management strategy as proposed here. Between thinning cycles, down wood should be left in the forest and no entry should take place in order to sustain 50% of naturally occurring down wood. Since the naturally occurring down wood is retained, a range of size classes will also be present this way. Moreover, part of the residues produced during final harvest will be used as a mat to protect the soil and can therefore not be used for energy production. They can, however, serve as a source of down wood.

These calculations are all per hectare and thereby do not capture the effect of protected areas. The recommendation remains that at least 10% of the total forest area should be protected and not used for wood production. Doing this will protect more biodiversity, and these areas will certainly adhere to the guidelines as they will not see any management. However, some of the forest area that is used for wood production needs to be sustained to retain some live tree and snags. To do this, patches of forest should not be clearfelled and snags and live trees retained there.

The residues should be dried in the forest. This will also help with retaining all foliage in the forest since they release better from dried biomass. By shaking the residues when they have been dried, the foliage will be spread out more too. The roots and stumps will not be harvested in this scenario. There will be two machine passes per thinning and harvest stage. Once for the thinning/harvesting action, and one at a later time to retrieve the dried residues.

Guidelines that cannot be followed or captured in the sustainable potential are topping off trees, harvest timing, ash fertilisation and mixed management. Topping could be a management option that is easily employed. The harvest time depends on management and demand and is difficult to regulate. Additional ash fertilisation is not captured in the sustainable potential although it can be regulated centrally. The mixing of management styles is difficult to regulate although it should be used.

5. Discussion

The potentials that have been discussed before depend on a number of parameters and assumptions. This section will point out some of these assumptions and the impacts these may have on the potentials. First the theoretical potential, its parameters and the issues that may arise from the assumptions made and data collected are discussed. The same will subsequently be done for the sustainable potential. Next, the influence of management is addressed. A section on costs is added to show further limitations of the research. A comparison to literature is made to show the differences between the results from this thesis and from literature. Lastly, a section on the sensitivity of the results is added to see the influence of the ranges and variables on the theoretical potential.

5.1. Theoretical potential

5.1.1. Branchiness

Many aspects can influence the branchiness, including the species, site conditions, tree age and management. There is great variation within and between tree species on the branchiness (Claveau et al., 2005; Standish et al., 1987). Intraspecies variation can be seen in, for example, the research of Claveau et al., (2005). They measured the total branch mass ratio (BMR) and total stem mass ratio (SMR) for different species of tree, which can give an indication of branchiness. The SMR varied from, for example, 19 to 65% for *Pinus banksiana* (depending on light availability and tree height) and 20 to 95% for *Abies lasiocarpa*. The BMR varied from 5 to 33% for *Pinus banksiana* and 3 to 38% for *Abies lasiocarpa* (Claveau et al., 2005). This shows that there are large variations within species, which leads to variation within genera, PFTs and biomes.

Furthermore, site conditions can have an effect, for example, Claveau et al. (2005) determined that light availability and tree height influenced the SMR and BMR. The branchiness of a tree also differs with age. It is generally higher when the trees are still young and a larger crown is needed to allow growth of the stem (Hakkila & Parikka, 2002). The productivity of the site determines the age at which the trees are mature and large enough for harvest, and therefore site conditions can influence the branchiness. Another aspect is management, if pruning has taken place; some branches will have been taken off to produce a better tree log (Andersson et al., 2002; Oosterbaan et al., 2009; Pérez et al., 2008). This can influence the branchiness at final harvest and thereby the amount of residues that can be produced.

However, many of these elements were not taken into account when calculating branchiness. This was due to limited data availability. Moreover, the variability within tree species is not fully captured by the data that was used for calculating branchiness. Many of the data came from one source that was already relatively old. Moreover, the values used were already averaged in that source (Standish et al., 1987). The data was collected in the USA and therefore may not portray the whole range that could be found in other countries. By using more data from multiple sources and locations, preferably with clearly defined cut off points of the stem top more accurate main values can be determined.

Not all data sources for the branchiness were explicit in the cut off point for the unmerchantable stem, which is the diameter of the stem above which it was considered unmerchantable. Therefore, the values that were used to calculate the branchiness may not measure precisely the same thing. It was not possible to find exactly corresponding values for all tree species with the same cut off point. Therefore, the branchiness values used in this research should only be seen as approximations.

Next to that, the calculation of the branchiness involves some double counting. The calculation of branchiness per biome is based on the branchiness in a PFT. Some of the PFTs have the same species, such as the pine and spruce in both the boreal evergreen conifer and cool-temperate conifer PFTs (Table 7). In the TM biome, spruce and pine are counted twice, as they occur in two of the PFTs used for the calculation. The same is the case for birch, which is double counted in TD forests. A method for solving this could be to eliminate the PFT categories all together and just work with the species present within a biome. However, for either case it is also a consideration that not all species are as prevalent within a biome as others are. In this research this was not taken into account because of data collection difficulties. However, this can have an impact on the amount of residues produced if the species most common have a higher or lower branchiness than the others.

5.1.2. Thinnings

Calculating thinning potentials is complicated by the fact that branchiness changes over the lifetime of the tree and the amount of trees removed influences the amount of residues that can be produced during the next thinning. Furthermore, pre-commercial thinning is not based upon branchiness and the amount of thinning stages is not always prescribed beforehand. Moreover, thinning is dependent on stand origin and forest type and varies a lot (Xu, Li, & Carraway, 2008). All these aspects can influence the thinning potential and not all have been taken into account in this research.

The calculations from thinning residues as used in this research are based on an adapted branchiness that only takes into account changed values of two species. Data limitations restricted the use of more 'young' branchiness data. This means that the effect of age on the branchiness is most likely not taken into account enough. This can only be solved by adding more data and research on this topic.

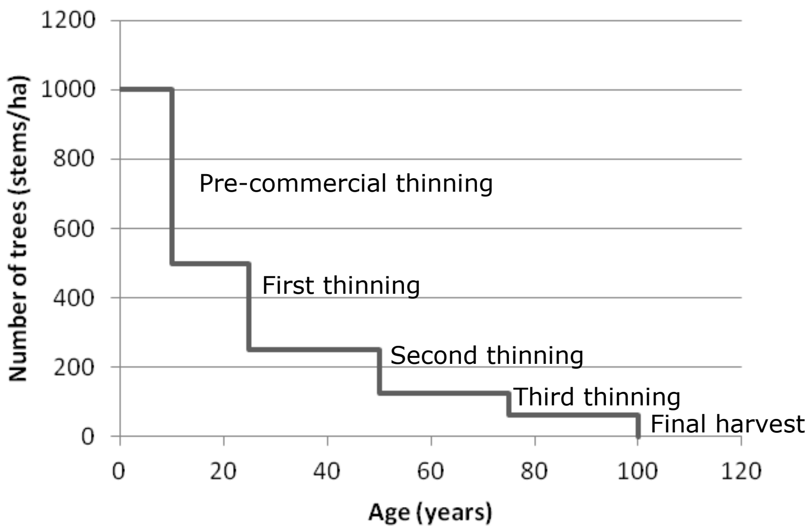

Figure 4. Effect of 50% thinning fraction at different thinning stages on the number of trees remaining in the stand (based on Lesch & Scott, 1997).

The research also used a fixed thinning fraction in order to calculate thinning residues. The problem with doing this is that the thinning fractions are rarely the same at the first and subsequent thinnings (Balboa-Murias et al., 2006; Lesch & Scott, 1997). Moreover, the effect of a similar fraction on a later thinning stage means that fewer trees will be removed (Figure 4). For example, removing 50% of 1000 trees at age 10 during pre-commercial thinning, will remove 500 whole trees that can be used for energy production. However, during the first thinning, only 250 trees will be removed and only the tops and branches of these are fit as residues. This would produce a different amount of residues. However, due to data and time limitation it was impossible to add these complications to the calculation of thinnings. Future estimates can be improved by taking these aspects into account.

Other aspects that can be taken into account are the residues from pre-commercial thinning. Pre-commercial thinning is not based upon branchiness, as the whole tree is residue since the stem is not used for poles or timber on account of its small size. This makes it impossible to estimate the amount of residues that can be produced during pre-commercial thinning using the method employed in this research. Therefore, pre-commercial thinning was not taken into account based on the difficulty of the calculation and the lack of data. Future studies can be improved upon by determining the amounts of residues produced during pre-commercial thinnings.

Other factors that complicate the thinning calculations are the amount and timing of thinning stages. Not every forest has the same amount of thinning stages. Some have no thinnings and management, such as natural forests, while others have more thinning. The same value was assumed in this research throughout the biomes based on literature. However, locally the amount of thinning stages can be variable. Moreover, some management will thin only late in the life of the tree, which then produces more residues than an earlier thinning. Nevertheless, when aggregating over such a large area as a biome, it will be impossible to take the local situations into account.

The local situations also play a role in stand origin and forest type. Some stands will be more productive and therefore have produced more biomass in the years after stand establishment than others. This influences the amount of residues that can be produced. There is no real solution to this problem since the goal of this research was to aggregate over the larger area of the biome. However, more data can help to evaluate the effect of this and how much residues are produced at different ages and in different forests.

Lastly, this research uses the production or stem mass values from the final harvest of the forest. As evidenced in Figure 4, this is based on a much lower amount of stems that is remaining in the forest. It is not likely that the amount of stem mass at final harvest is the same as that at the different thinning stages. Even though the trees grow each year and more stem mass is added, this is not thought to be enough to compensate for the removal of trees during thinning stages. However, due to lack of data this method was thought to be the closest approximation possible in the time allotted for the research.

Most of the problems associated with thinning arise from difficulties with data collection and aggregation over a large range. While the last one is difficult to solve, it can be helped by alleviating the former. More data is needed on the amount of thinning that can be produced during different thinning stages, at different tree ages and in different types of forests. This data can then be used to make clearer indications of the amount of thinning residues that is the most common.

5.1.3. Final harvest

Calculating final harvest potentials is complicated by the fact that branchiness changes over the lifetime of the tree and the amount of trees that is present influences the amount of residues that can be produced. The fact that branchiness differs over the life of a tree has an impact because there also is a variation of age at harvest in different biomes. Next to that were the estimates for production of stem mass in the different biomes.

The data to calculate production was sparse and therefore mainly values from Arets et al. (2011) were used. However, this data concerned different IMAGE regions (Appendix B). The different areas are, in many cases, home to more than one biome. In order to find accurate production values for a biome, the region data would have to be split into the different biomes. However, accomplishing this was not possible due to lack of information. Therefore, the regional production data were used as they were and applied to all the biomes that were present within them.

In addition, not all areas have the same amount of forest and this should also be factored in by taking weighted averages. However, within the timeframe and scope of this research, this was again too difficult. Moreover, the limited data available led to the use of these values for the calculation of production. If more detailed data would have been available, the calculation could have been more accurate.

5.1.4. Theoretical potential

The theoretical potential is based on the sum of the harvest and thinning residues divided by the rotation length. The issues with thinning and harvest residues have been detailed above; however, the rotation length is also variable. The rotation length as used for this research was also based on assumption. For example, in some calculations for rotation length values from Arets et al. (2011) were used. However, these were based on the type of wood, hardwood or softwood. Some of the PFTs were mainly softwoods, while others mainly hardwood or mixes. This complicates the calculation as an average is taken over the different PFTs to produce a biome.

However, there were few other data available and an estimate needed to be made. Solutions could be to eliminate the use of PFTs to calculate values for the biomes, as mentioned before; however, this again produces the difficulty of having to establish the relative prevalence of different tree species within a biome to arrive at an accurate estimate. In order to do this, more data and therefore more research is needed.

5.1.5. Ranges

The main issue with the data that have been collected over the course of this thesis is the fact that most problems associated with removing logging residues depend greatly on the local situation. This is even more so for the extent to which problems could occur. Productivity depends on e.g. soil type, site conditions and local climate (Vance, 2000). These aspects cannot directly be taken into account because the data used in this research are aggregated over many different types of sites and conditions.

The method used to address this problem was to use ranges. The highest and lowest individual values in all variables were taken as the minimum and maximum range. These were taken with the variables as they moved up through the calculations. For example, the lowest value in the boreal summergreen PFT was Larch with 0.145 $kg_{crown\ mass}/kg_{stem\ mass}$. With the combination of different PFTs to form the biomes, Larch remained the lowest minimum value and therefore, the minimum value in the BF, TM and TD forests is 0.145 $kg_{crown\ mass}/kg_{stem\ mass}$. A similar approach was taken with the highest values.

In order to calculate minimum and maximum values for theoretical potential, all the minimum and maximum values were multiplied according to the formulas to produce this potential. The problem with using this approach is that it uses the outliers for the calculation. This will probably over and underestimate the actual potentials. In order to highlight the extent of outliers skewing the results, histograms of the available data points have been provided in Appendix F. The effect of using these high and low values is further discussed in section 5.6.

5.1.6. Above or below ground

Roots are often ignored in estimates of forestry residues (Hakkila & Parikka, 2002; Zhou & Hemstrom, 2009). Although some include them such as Finland and increasingly Sweden who are using stumps for energy purposes (Böttcher et al., 2010; Eriksson & Gustavsson, 2008). However, the primary energy required to use stumps for energy purposes is the highest out of chips, bundles, stumps and small roundwood. The higher energy density ensures that the costs are lower than chips and one type of small roundwood harvest (Eriksson & Gustavsson, 2008). Nevertheless, the value of the energy extracted from stumps is lower than the cost of stump harvesting (Nilsson & Thörnqvist, 2004). While this should decrease in the future and energy prices will rise, which will make stump harvesting and combusting profitable, it is currently not yet cost-effective (Nilsson & Thörnqvist, 2004).

Moreover, a technical and economic problem is that stumps have a high ash content and levels of contamination (Nilsson & Thörnqvist, 2004). To prevent problems during combustion, sifting stump chips has to be done beforehand, which comes at a cost. This is necessary because high ash content and contaminations can lead to sintering boilers, where inorganic materials melt and stick to the boiler. Moreover, stones and other contaminations can harm the comminuting machines, which are used to crush the wood into smaller fragments (Nilsson & Thörnqvist, 2004). Next to that, harvesting stumps and roots is often restricted, e.g. no stump and root harvesting on slopes, and maximum 33% (or 20-40%) in other areas (Asikainen et al., 2008; Böttcher et al., 2010).

If harvesting stumps and roots becomes more accepted, they should be included into the theoretical potential of forestry residues. This is possible by using an adapted branchiness value. The amount of roots and stump can also be expressed as a function of stem mass using, for example, stump equations (Raile, 1982). The stump-root system is about 22-25% of stem mass and this can be added to the value of branchiness already calculated (Eriksson & Gustavsson, 2008; Hakkila, 2004; Nilsson & Thörnqvist, 2004). This value can then be used to calculate the theoretical potential including stumps and roots.

5.1.7. Genera

In total, this research uses 15 tree genera to describe 5 biomes. These biomes cover a large part of the Earth and are composed of more than those 15 species. The genera were chosen based on literature and data availability. However, a better picture could be made if more species were involved in this research, including their relative abundance in the biome. This could help to make weighted averages of the variables used to calculate theoretical potential and thereby provide a more accurate picture.

However, in order to achieve this, more data is needed for genera. For example, *Pseudotsuga, Populus* and *Acacia* species are important plantation species, however, no branchiness data could be found for Acacia and it was therefore excluded (Arets et al., 2011). Moreover, the PFT composition was kept to a limited number of genera due to time constraints.

5.2. Sustainable potential

There is limited data available with clearly defined thresholds for different values important for sustainability. It is also difficult to aggregate values over such a large area as the biomes cover. This is because sustainability is very dependent on the local conditions. One soil is different from the next and has different properties that make it more or less susceptible to, for example, erosion and nutrient extraction (Vance, 2000).

For the calculations of sustainable potential only the mean values were used, this was due to time and data constraints. The assumption that 10 tonnes of residues are enough to sustain biodiversity and nutrients in the forests was based on literature. Moreover, applying it to the results from this thesis indicated that it was congruent with retaining 20-50% of the residues in the forest. However, it was also assumed that all foliage can be taken of the residues and left in the forest, which is more questionable. Nevertheless, since the foliage alone was not enough in most of the clearcut options, some branches would have to be left behind anyway.

The assumption that the amount of leaves per tree will be the same for harvest as for thinning trees is flawed since the branchiness at thinning is generally considered to be higher than for final harvest. However, there was no data available to correct this assumption and it was therefore used to provide an indication of the sustainable harvest potential.

However, more than residue retention is needed to maintain a sustainable forest. A sustainable forestry residues potential calculated per hectare will not capture all of the other aspects such as retaining live trees and protecting areas. Nevertheless, by employing different management strategies almost all of the guidelines can be adhered to, theoretically. However, in practice this will most likely not happen due to technical and economic constraints.

While this thesis only concerns environmental sustainability, social and economic sustainability are also important. Not all the residues that have been identified can be used for energy production. It is common in some areas for individuals to remove wood from the forest to serve as fuelwood (Chum et al., 2011; Duku et al., 2011; Dymond et al., 2010; Koopmans & Koppejan, 1997; Lattimore et al., 2009; Scarlat et al., 2011). In Romania, for example, firewood is harvested entirely and used for household heating (Scarlat et al., 2011). This will also reduce the amount of residues that can practically be taken out of the forest for centralised energy production.

5.3. Management

Several choices have been made in the course of this thesis that could be discussed further. First is the distinction into the two different management types: 1) natural and semi-natural forests and 2) plantations. Due to data difficulties, the choice was made to group natural and semi-natural forests together. Issues with this are that natural forests generally have no management and therefore thinning is not applied. It is possible, however, that they are clearcut to make space for plantations or because of disease or wood production.

Semi-natural forests are different in that they are planted (or regenerated naturally) and are generally managed more than natural forests. Semi-natural forests are classed with natural forests because they have a long rotation length. They are also prevalent in Europe and it is difficult to distinguish them (MCPFE, 2003; UNECE & FAO, 2011). However, using only these two categories does make it difficult to accurately explain the differences between natural and semi-natural forests. Therefore, it would be advisable to use three categories for follow up research: 1) natural forests, 2) semi-natural forests and 3) plantations.

Apart from the categories, other difficulties are involved in the choice for harvesting method. Three methods are possible: plantations, clearcut and selective logging. Selective logging was ignored in this research. Most selective logging occurs in tropical regions (Anderson et al., 2002; Arets et al., 2011). The only region that had selective cutting and also exist in the biomes from this research was Southern Africa, here the selective cut was only 5% of the total cutdown (Arets et al., 2011). While some selective cutting may be used in different regions, the majority is clearfelling (Anderson et al., 2002; Zambelli et al., 2012). However, selective cutting is sometimes used in non-tropical areas. Peckham et al. (2013) use it in their model. It is also mentioned by Schlamadinger et al. (1995) and Eriksson & Gustavsson (2008) as methods for harvest.

It is not thought to be very interesting at present to include a selective logging harvest option for the biomes researched here. There is not enough selective harvesting to ensure valuable data.

5.4. Costs

Costs play an important role in the (future) use of forestry residues for energy use. The issue is very extensive and only some main points will be outlined here. For more information on costs of forest residues and biomass see for example: Asikainen et al., 2002; Ćosić, Stanić, & Duić, 2011; Duncker et al., 2012; Eriksson and Gustavsson, 2008; Eriksson and Gustavsson, 2010; Gregg & Smith, 2010; Liu et al., 2007; Malinen et al, 2001; Mangoyana, 2011; Nilsson and Thörnqvist, 2004.

The cost of forestry residues is affected by a number of different factors including harvest costs (based on e.g. operator efficiency, type of equipment used, fuel costs and labour costs), transportation distance and costs, associated forest and equipment maintenance costs, comminuting costs and administration costs (Asikainen et al., 2002; Asikainen et al., 2008; Ćosić et al., 2011; Duncker et al., 2012; Eriksson & Gustavsson, 2008; Eriksson & Gustavsson, 2010; Gregg & Smith, 2010; Hakkila & Parikka, 2002; Liu et al., 2007; López-Rodríguez, Pérez Atanet, Cuadros Blázquez, & Ruiz Celma, 2009; Malinen et al., 2001; Mangoyana, 2011; Nilsson & Thörnqvist, 2004). However, the use of forestry residues is not only dependent on the actual costs of removing forest residues, but also on the relative costs of other potential fuel sources. These depend on factors including cost of other fuel sources, energy content of the residues, energy price, CO_2-prices, costs of recycling and subsidies (Doty, 2009; Eriksson & Gustavsson, 2008; Eriksson & Gustavsson, 2010; Malinen et al., 2001; Nilsson & Thörnqvist, 2004).

5.5. Comparison to literature

The data from this research have been retrieved from literature; however, it is interesting to note the differences between the results from this research and those found in literature. Moreover, comparing the results with literature can point to some reasons why the literature data have a high range and are variable.

5.5.1. Natural and semi-natural forest

Boreal forest and Cool-Conifer forest

According to Andersson et al. (2002), in boreal forests, 20-70 m^3/ha of thinning residues are produced per thinning. This is equivalent to 9200 kg/ha and 32200 kg/ha, multiplying this by 3 is 27600 kg/ha at the minimum end and 96600 kg/ha at the high end. The values produced in thinning as shown in Table 14 do contain both these values. The average production in this research is 28.0 m^3/ha per thinning stage. This corresponds well to the values from Hakkila (2004), where 33 m^3 is the average over all thinning stages. Helmisaari et al. (2011) produced on average 11288 kg/ha per thinning stage. The value over 3 rotations is somewhat lower than the results from this research: 33864 kg/ha vs. 38610 kg/ha. However, this difference is only 13% and well within the range. Following the same logic, Jacobson et al. (2002) thinning production is 11079 kg/ha, which is a 14% difference with the results from this research. Therefore, the data in this research regarding thinning residues are seen as a reasonable fit.

Nurmi (1999) found that a spruce stand with a stocking of 233 m^3/ha yielded 108 dry tonnes of residual material per hectare on average. This value is much higher than the residues from logging in this research. However, the stocking level is almost the same as that used in this research, so that does not explain the difference. The difference could partly be explained by the higher branchiness of spruce compared to the value used for boreal forests.

Saarinen (2006) stated that the average amount of slash in Finnish forests is between 37500 and 50000 kg/ha. This value is slightly higher than the average value that resulted from this research. The reasons for this may include that the tree species in the Finnish forests is mainly spruce, which has a higher branchiness than the value used for boreal forests.

Malinen et al. (2001) stated that of the total residues produced in boreal forests, 60% was from logging residues and 40% from thinning residues. In this research the values for harvest residues are lower than those for thinning residues, the ratio is 46:54. This shows a clear difference. However, when comparing to Hakkila (2004), the logging residues are less than those of residues (45:55 for pine and 42:58 for spruce). This again is in agreement with the data from this research. The residue production from harvest was 32200 kg/ha for pine and 59800 kg/ha for spruce in Hakkila (2004). The pine value is in agreement with the results from this thesis. The spruce data are further away, however, still within the range.

Eriksson & Hallsby (1992 in Schlamadinger et al., 1997) use a value of 40 t/ha of logging residues that can be used for bioenergy in Sweden. This value is again close to the value found in this research. Schlamadinger et al. (1997) use 30 t/ha of logging residues in their own research, which concerns temperate and boreal forests. The value they used is somewhat lower than the results here indicate but still well within range.

Temperate forests

Karaj et al. (2010) estimate a logging residues potential of 1.46 m^3/ha/yr in Albania. Albania's forests were classified as TD forests based on Appendix B. The value for logging residues potential corresponds with 794 kg/ha/yr. This value is 22% more than the value found in this research and is therefore still seen as quite a good approximation. Moreover, the value still falls well within the range.

Pérez et al. (2008) found that *Quercus* and *Fagus* produce 1.00 and 1.23 t/ha of leaf and branch residue annually. This corresponds with 730 kg/ha/yr and 828 kg/ha/yr respectively. This is higher than the values that were found in this research, which were 615 and 649 kg/ha/yr for TM and TD forests respectively. However, this is 12-17% different for *Quercus* and 28-35% difference for *Fagus*.

Hakkila & Parikka (2002) mention that 25-45% of fellings are considered residues (low-quality stems and crown mass) in developed temperate zones. Adding the residues to the production volume shows that 34 and 32% of fellings are considered residues for TM and TD forests respectively. This falls nicely within the range provided by Hakkila & Parikka (2002).

Tritton et al. (1987) performed an experiment in a temperate watershed with a thinning grade of 10% where 16 t/ha of biomass was removed, this included boles. While 16 t/ha is somewhat lower than estimated in this research, boles are excluded from the data.

Warm-Mixed forest

O'Connell (1997) found a thinning residue production in a WM forest of 64 t/ha. This is high compared to the values found in this research, however, this is because there was no log removal, which was done in adjacent forests and accounted for 40-50 t/ha of the logging residue. Thus 14-24 t/ha of logging residues were produced, which is in much better accordance with the result from this research, which is 16 t/ha.

5.5.2. Plantations

Temperate Deciduous plantations

Peréz et al. (2008) found that *Pinus radiata* produces 0.94 m^3/ha/yr (406 kg/ha/yr) of residues. This is lower than what was found for TD plantations (1367 kg/ha/yr). This may be associated with high values of production used for plantations in this research, and also higher values of branchiness for pine used in this research compared to the values found by Peréz et al. (2008).

Warm-mixed plantations

Peréz et al. (2008) also found that *Eucalyptus* produces 2.26 m^3/ha/yr (1365 kg/ha/yr) and *Pinus radiata* 0.94 m^3/ha/yr (406 kg/ha/yr) of residues. These values are significantly lower than that for WM plantations in this research. The reason for this may be that the production volume in plantations is assumed to be high in this research. Moreover, the branchiness determined from Peréz et al. (2008) is lower than that used for WM plantations.

Table 19. Final harvest potential, assuming no thinning.

Biome	**Management**	**Total final harvest potential** (kg/ha/yr)
Boreal forest	Clearcut	302
	Plantation	*n.a.*
Cool conifer forest	Clearcut	301
	Plantation	*n.a.*
Temperate mixed forest	Clearcut	334
	Plantation	*n.a.*
Temperate deciduous forest	Clearcut	356
	Plantation	691
Warm-mixed forest	Clearcut	256
	Plantation	1298

5.6. Sensitivity

This section will deal with the sensitivity of the theoretical potential based on the different parameters used. The mean value for the theoretical potential was calculated by multiplying all the mean values of the parameters (Table 13 and Table 14). The high values were calculated by using the uppermost values in the ranges for all the variables, and the low values with all the lowest values in the ranges. This created a large spread between the minimum, mean and maximum values.

Most of the variables used had a wide spread. The reason for this was that multiple values were used to produce the mean value and these can be very variable. The spread was produced by using the highest and lowest individual value. In order to show the distribution and the effect of outliers, histograms have been produced of some of the variables. The variables that have been investigated are density (Figure F. 1.), production volume (Figure F. 2), rotation length (Figure F. 3), branchiness at harvest (Figure F. 4), branchiness at thinning (Figure F. 5) and thinning fraction (Figure F. 6).

Density is dependent on the types of trees that are present in that biome and the density of those trees. What can be seen from the histograms is that there are few outliers in the BF, CC and WM biomes (Figure F. 1.; A,B,E). For the temperate forests there is an outlier at 950-1000 kg/m^3. This value shifts the high value up by about 140 kg/m^3, in both biomes this is a difference of around 30% more.

The production volume (Figure F. 2) shows a different picture. The values for the clearcut biomes are quite well spread out. There are no significant outliers in the clearcut. However, there is more variation in the plantation biomes. For TD plantations this is the case since only a few values were used. Therefore, the impact of the highest value on the mean is large. If it would be eliminated, the mean would change from 233 m^3/ha to 180 m^3/ha, which is a 23% difference. In the WM plantations, the values are very spread out, with several high values, and several lower values, so the spread may not be exceptional.

For rotation length the data were spread out and did, most of the time, not really converge (Figure F. 3). However, there were only a few data points found, and therefore the distribution was limited. Moreover, the lack of data decreases the soundness of this variable.

Branchiness is a variable that has a lot of data points, as it requires the data points from all the individual PFTs. This means that the spread is also great (Figure F. 4). The distribution in the branchiness data does seem to converge around 0.3 kg_{crown}/kg_{stem} in the biomes. The reason why there are values around 0.6 kg_{crown}/kg_{stem} is because there were values for spruce there, and as spruce is present in BF, CC, TM and TD forests, this influences the range for all these biomes.

The branchiness for thinning was only influenced by the branchiness from pine and spruce (which has an effect on the branchiness of BF, CC, TM and TD forests). The branchiness data found were spread out, but higher than for the pine and spruce in the clearcut branchiness (Figure F. 5). There were some high values however, for spruce (Figure F. 5 A) there were multiple data points at the high end. For pine however (Figure F. 5 B), there was a single high value. This high value was unexpected because pine is usually considered to have less branches than spruce (Hakkila & Parikka, 2002). However, the effect of this single value will be limited in the calculations since it is part of a larger amount of data and is then obscured within PFTs and biomes.

Lastly the data found for the thinning fraction were limited in the clearcut biomes (Figure F. 6 A, B, C, D). Since there are only a few data points, there is not a clear distribution, although there do not seem to be any real outliers. There are more data points for the plantation biomes, but these do not seem to converge very well and have a large range (Figure F. 6 E, F). However, there do not seem to be any outliers here either.

Since there were such large data ranges, the effect of different individual variables on the final result was calculated. The variables were kept at their mean value apart from one that was to the highest and lowest value in their range. Next the new theoretical potential was calculated and the impact of that variable's range on the theoretical potential could be determined. Figure 5 and Figure 6 show the differences between theoretical potentials for the (semi-)natural biomes and plantations respectively.

There is only a limited amount of variables that have been used to determine the theoretical potential and it is therefore possible to vary all of these independently. Note that the rotation length 'high' values lead to a lower theoretical potential because the amount of residues is spread out over a longer time period. The impact of different variables is more pronounced in some biomes than in others. The boreal and cool-conifer biomes experience the greatest range from rotation length and production volume.

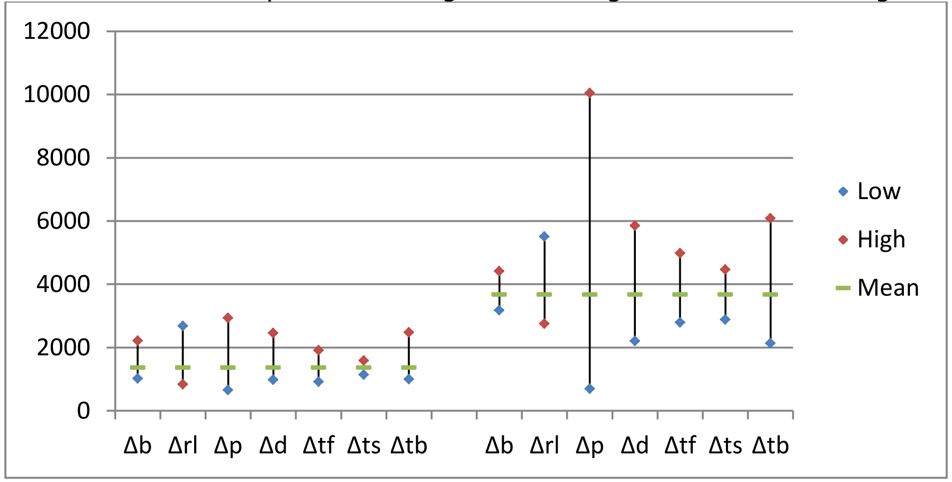

Figure 5. Sensitivity of the total theoretical potential of forestry residues for plantations determined by changing one variable. The biomes are ordered from left to right: TDP, WMP. Note that for rotation length the high value is lower than the mean.

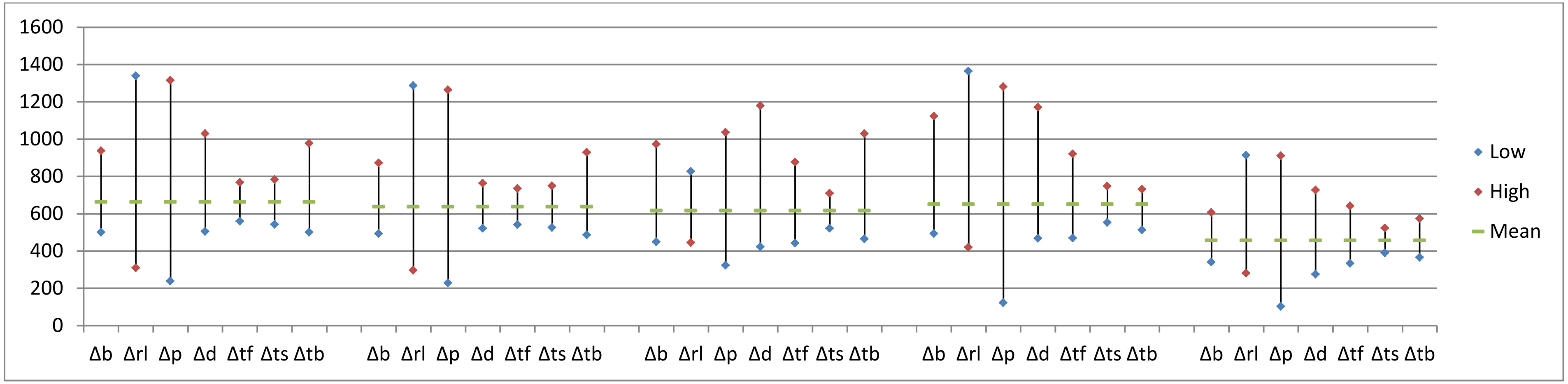

Figure 6. Sensitivity of the total theoretical potential of forestry residues for clearcut determined by changing one variable. The biomes are ordered from left to right: BF, CC, TM, TD, WM. Note that for rotation length the high value is lower than the mean.

6. Conclusions and recommendations

This section will detail the answers to the research questions as posed in section 1.3. Moreover, conclusions will be drawn and recommendations provided for future research.

6.1.1. Theoretical potential

Forestry residues are those parts of the aboveground biomass that are not sold as stemwood and can be used for energy purposes. This includes branches, leaves and the unmerchantable stem top. Sometimes the stump is included, however, there are environmental problems associated with harvesting the stumps and it is not fully classified as aboveground. The roots can also be seen as forestry residues, but are usually excluded.

The theoretical potential depends on a number of factors, mainly the amount of harvest and thinning residues produced and the rotation length of the forest. These aspects are influenced by the biome. The biomes are composed of different tree species that have varying branchiness. This influences the amount of residues that a tree can produce. Next to that are differences in the stocking density and therefore stemwood production that create variation between biomes. Connected to this is the difference in density between tree species and consequently biomes that leads to varying weights even with the same production volume. Lastly, the amount of thinning residues also plays an important role, included in this is the amount of thinning fractions.

The influence of management is the change in rotation length, in plantation forests harvest is sooner. Moreover, different species can be used in plantations than in the biomes. The choice for fast growing species is made so more money can be made by selling the wood sooner. This means that the production volume that is produced is also higher.

Overall, the theoretical potential is highest in the plantations (1367 and 3109 kg/ha/yr for TDP and WMP respectively). In clearcut management, the most northerly biomes (BF and CC) produce the most residues over their lifetime. However, they have longer rotation lengths and therefore the theoretical potential is reduced. Nevertheless, the BF, CC and TD forest produce the most residues in clearcut management (663, 638 and 649 kg/ha/yr respectively). WM clearcut produces the least residues due to low production and branchiness (456 kg/ha/yr).

6.1.2. Sustainable potential

There are clearly many environmental aspects that need to be taken into account when using forestry residues in a sustainable manner. These include aspects related to soils, hydrology, productivity and biodiversity. Within these categories are elements such as down and deadwood, residue retention and foliage harvest. The parameterisation of the factors is difficult as they depend on the local situation. However, some guidelines have been set up that include: minimum retention values of 20% of total logging residues, retaining all leaves on site, no stump and root harvest and protecting at least 10% of forest area from wood harvest.

By determining the maximum of full leave retention and 10 tonnes of residue retention, the amount of residues that should remain in the forest was calculated for the different clearcut and plantation biomes. This resulted in sustainable potentials that were highest in plantation management (937 and 1958 kg/ha/yr for TDP and WMP respectively). For clearcut, the highest sustainable potentials are in BF and TD forests (471 and 468 kg/ha/yr), and the lowest in WM forests (281 kg/ha/yr).

For the different management options, retention is over 10 tonnes in the plantations in order to adhere to the foliage guideline. It is expected that plantations produce more residues than (semi-)natural forests. Plantations have a higher production since the main goal is to produce as much wood as is possible. Moreover, because of the shorter rotation lengths, more residues can be produced over the same time period as compared to a (semi-) natural forest. This means that somewhat more than the technical limitations worth of forestry residues are left in the forest.

The minimum amount of forestry residues that should be left in the forest is between 20-50%. While the variation within this range is extremely large, most of the estimates are between 20-50%. Moreover, a 10-tonne harvest residues retention factor is employed. Foliage is between 21-37% of harvest and thinning residues. Combining all of these means that between 29-38% of the theoretical potential should be left in the forest to maintain nutrients and biodiversity.

This combines nicely with technical issues. According to Ranta, the maximum technically possible extraction rate for aboveground residues is about 65% (2002, in Vis et al., 2010). Helmisaari et al., (2011) state that 60-80% of logging residues will be removed because of technological and economic reasons. Other values listed depend on the suitability of the site, e.g. "[t]he maximum extraction potential of residues from stem and branches (excluding foliage) was set at 75 % on highly suitable sites and to 50 % and 15 % on moderately and marginally suitable sites, respectively" (EEA, 2006, p. 34). In Finland two-thirds of the slash can be harvested (Saarinen, 2006). Sweden has limited harvest to 85% of logging residues, 60% of thinning residues and 95% of roundwood in Sweden, because of technical reasons (Eriksson & Gustavsson, 2010). "In some cases, it is assumed that the technical potential is the same as the ecological potential, and therefore the amount left on-site for operational reasons is sufficient for ecological reasons (e.g., Perlack et al., 2005)" (Dymond et al., 2010, p. 186). This seems to be the case in this research. If the technical potential is limited to around 65%, the 10-tonne guideline and the foliage guideline are kept in the biomes and managements.

6.1.3. Recommendations

Next to retention, more area needs to be protected from wood harvest in order to preserve biodiversity. Not all countries are currently adhering to the 10% criterion. Moreover, preservation of live and large trees, snags and naturally downed wood is important for biodiversity. Furthermore, harvest of stumps and roots is not advised, general harvest should take place during low foliage times (e.g. winter for broadleaves) and harvest should not exceed the net annual increment.

More research should be done to create a better picture of the technical and sustainable potentials for different biomes and management strategies. The amount of management options can be extended to include semi-natural forests as a separate category as this can help to show a better picture for the northerly biomes. In addition, costs and other technical limitations should be incorporated into further research, due to time restrictions this was not possible here.

All in all, the technical limitations help to maintain a sufficient amount of residues on the site, however, some additional regulations are needed to preserve biodiversity.
Nevertheless, forestry residues are seen as a viable source of green energy and should help to combat greenhouse gas emissions and supply the growing world with enough power to maintain the needs of the present generation without compromising the ability of the next generations to do the same.

Acknowledgements

I would like to thank both supervisors of this project, Birka Wicke and Vassilis Daioglou for all their help on this project. Their insights and comments have been invaluable in the formation of this thesis.

References

Acuña, E., Espinosa, M., Cancino, J., Rubliar, R., & Muñoz, F. (2010). Estimating the bioenergy potential of Pinus radiata plantations in Chile. *Ciencia e Investigación Agraria*, *37*(1), 93–102.

Alberta. (2006a). Facts on wood series: Balsam fir. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_BalsamFur.pdf

Alberta. (2006b). Facts on wood series: Balsam poplar. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_BalsamPoplar.pdf

Alberta. (2006c). Facts on wood series: Black spruce. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_BlackSpruce.pdf

Alberta. (2006d). Facts on wood series: Jack pine. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_JackPine.pdf

Alberta. (2006e). Facts on wood series: Logdepole pine. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_LodgepolePine.pdf

Alberta. (2006f). Facts on wood series: Tamarack. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_Tamarack.pdf

Alberta. (2006g). Facts on wood series: Trembling aspen. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_TremblingAspen.pdf

Alberta. (2006h). Facts on wood series: White birch. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_WhiteBirch.pdf

Alberta. (2006i). Facts on wood series: White spruce. Retrieved from http://www.albertacanada.com/files/albertacanada/AIS-BP_WhiteSpruce.pdf

Alcamo, J., Leemans, R., & Kreileman, E. (Eds.). (1998*). Global change scenarios of the 21st century. Results from the IMAGE 2.1 model*. Kidlington: Elsevier.

Andersen, R. S., Towers, W., & Smith, P. (2005). Assessing the potential for biomass energy to contribute to Scotland's renewable energy needs. *Biomass and Bioenergy, 29*(2), 73–82. doi:10.1016/j.biombioe.2005.04.004

Andersson, G., Asikainen, A., Björheden, R., Hall, P. W., Hudson, J. B., Jirjis, R., Mead, D. J., et al. (2002). Production of forest energy. In J. Richardson, R. Björheden, P. Hakkila, A. T. Lowe, & C. T. Smith (Eds.), *Bioenergy from sustainable forestry: Guiding principles and practice* (pp. 49–123). Dordrecht: Kluwer Academic Publishers.

Angelstam, P., Mikusinski, G., & Breuss, M. (2002). Biodiversity and forest habitats. In J. Richardson, R. Björheden, P. Hakkila A. T. Lowe, & C. T. Smith (Eds.), *Bioenergy from sustainable forestry: Guiding principles and practice* (pp. 216-243). Dordrecht: Kluwer Academic Publishers.

Arets, E. J. M. M., Van der Meer, P. J., Verwer, C. C., Hengeveld, G. M., Tolkamp, G. W., Nabuurs, G. J., & Van Oorschot, M. (2011*). Global wood production: Assessment of industrial round wood supply from different management systems in different global regions*. Wageningen.

Asikainen, A, Liiri, H., & Peltola, S. (2008). *Forest Energy Potential in Europe (EU27)*. Retrieved from http://www.metla.fi/julkaisut/workingpapers/2008/mwp069.htm

Augusto, L., Ranger, J., Binkley, D., & Rothe, A. (2002). Impact of several common tree species of European temperate forests on soil fertility. *Annals of Forest Science*, *59*(3), 233–253. doi:10.1051/forest:2002020

Balboa-Murias, M. Á., Rodríguez-Soalleiro, R., Merino, A., & Álvarez-González, J. G. (2006). Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. *Forest Ecology and Management*, *237*(1-3), 29–38. doi:10.1016/j.foreco.2006.09.024

Batidzirai, B., Smeets, E. M. W., & Faaij, A. P. C. (2012). Harmonising bioenergy resource potentials—Methodological lessons from review of state of the art bioenergy potential assessments. *Renewable and Sustainable Energy Reviews, 16*(9), 6598–6630. doi:10.1016/j.rser.2012.09.002

Bauen, A., Woods, J., & Hailes, R. (2004). *Biopowerswitch - A biomass blueprint to meet 15% of OECD electricity demand by 2020* (pp. 1–74). Berlin.

Bauhus, J., Van Winden, A. P., & Nicotra, A. B. (2004). Aboveground interactions and productivity in mixed-species plantations of Acacia mearnsii and Eucalyptus globulus. *Canadian Journal of Forest Research*, *34*(3), 686–694. doi:10.1139/x03-243

Bernier, P., & Paré, D. (2013). Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. *GCB Bioenergy, 5*(1), 67–72. doi:10.1111/j.1757-1707.2012.01197.x

Boreal Forest. (2012). The Canadian encyclopedia. Retrieved from http://www.thecanadianencyclopedia.com/articles/boreal-forest

Böttcher, H., Dees, M., Fritz, S. M., Goltsev, V., Gunia, K., Huck, I., Lindner, M., et al. (2010). *Illustration case for Europe* (pp. 1–168). Freiburg.

Brown, C. (2000). The global outlook for future wood supply from forest plantations. *The global outlook for future wood supply from forest plantations*. Rome.

Bunnell, F. L., & Houde, I. (2010). Down wood and biodiversity — implications to forest practices. *Environmental Reviews*, *18*(NA), 397–421. doi:10.1139/A10-019

Burger, J. A. (2002). Soil and long-term site productivity values. In J. Richardson, R. Björheden, P. Hakkila, A. T. Lowe, & C. T. Smith (Eds.), *Bioenergy from sustainable forestry: Guiding principles and practice* (pp. 165–189). Dordrecht: Kluwer Academic Publishers.

Burger, J. A. (2009). Management effects on growth, production and sustainability of managed forest ecosystems: Past trends and future directions. *Forest Ecology and Management, 258*(10), 2335–2346. doi:10.1016/j.foreco.2009.03.015

Busing, R. T., & Fujimori, T. (2005). Biomass, production and woody detritus in an old coast redwood (*Sequoia sempervirens*) forest. *Plant Ecology, 177*(2), 177–188. doi:10.1007/s11258-005-2322-8

California State University Dominguez Hills [CSUDH]. (n.d.). Physical properties of common woods. Retrieved from http://www.csudh.edu/oliver/chemdata/woods.htm

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., et al. (2011). Bioenergy. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, et al. (Eds.), IPCC special report on renewable energy sources and climate change mitigation (pp. 209–332). Cambridge UK and New York, NY, USA: Cambridge University Press.

Ciesla, W. M. (2002). *Non-wood forest products from temperate broad-leaved trees* (pp. 1–126). Rome: FAO.

Claveau, Y., Messier, C., & Comeau, P. G. (2005). Interacting influence of light and size on aboveground biomass distribution in sub-boreal conifer saplings with contrasting shade tolerance. *Tree physiology, 25*(3), 373–84.

Ćosić, B., Stanić, Z., & Duić, N. (2011). Geographic distribution of economic potential of agricultural and forest biomass residual for energy use: Case study Croatia. Energy, 36(4), 2017–2028. doi:10.1016/j.energy.2010.10.009

Dekker, M., Turnhout, E., Bauwens, B. M. S. D. L., & Mohren, G. M. J. (2007). Interpretation and implementation of Ecosystem Management in international and national forest policy. *Forest Policy and Economics*, *9*(5), 546–557. doi:10.1016/j.forpol.2006.03.003

Donoso, S. R., Peña-Rojas, K., Delgado-Flores, C., Riquelme, A., & Paratori, M. (2010). Marginal *Nothofagus macrocarpa* forest in central Chile. *Interciencia 35*(1), 65-69.

Doty, F.D. (2009). Wood energy: Predicting costs. *Science, 324*(5933), 1389. doi: 10.1126/science.324_1389b

Duku, M. H., Gu, S., & Hagan, E. B. (2011). A comprehensive review of biomass resources and biofuels potential in Ghana. *Renewable and Sustainable Energy Reviews, 15*(1), 404–415. doi:10.1016/j.rser.2010.09.033

Duncker, P. S., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., De Jong, J., Ravn, H. P., Smith, M., et al. (2012). How forest management affects ecosystem services , including timber production and economic return: Synergies and trade-offs*. Ecology and Society, 17*(4), art50. doi:10.5751/ES-05066-170450

Dymond, C. C., Titus, B. D., Stinson, G., & Kurz, W. A. (2010). Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. *Forest Ecology and Management*, *260*(2), 181–192. doi:10.1016/j.foreco.2010.04.015

Egnell, G., & Leijon, B. (1997). Effects of different levels of biomass removal in thinning on short-term production of pinus sylvestris and picea abies stands. *Scandinavian Journal of Forest Research*, *12*(1), 17–26. doi:10.1080/02827589709355379

Eriksson, E., Gillespie, A. R., Gustavsson, L., Langvall, O., Olsson, M., Sathre, R., & Stendahl, J. (2007). Integrated carbon analysis of forest management practices and wood substitution. *Canadian Journal of Forest Research*, *37*(3), 671–681. doi:10.1139/X06-257

Eriksson, L. N., & Gustavsson, L. (2008). Biofuels from stumps and small roundwood—Costs and CO2 benefits. *Biomass and Bioenergy*, *32*(10), 897–902. doi:10.1016/j.biombioe.2008.01.017

Eriksson, L., & Gustavsson, L. (2010). Costs, CO2- and primary energy balances of forest-fuel recovery systems at different forest productivity. *Biomass and Bioenergy, 34*(5), 610–619. doi:10.1016/j.biombioe.2010.01.003

Etcheverry, J., Gipe, P., Kemp, W., Samson, R., Vis, M., Eggertson, B., McMonagle, R., et al. (2004). *Smart generation: Powering Ontario with renewable energy* (pp. 1–124). Vancouver: Western Printers and Lithographers.

European Environment Agency (EEA). (2006). *How much bioenergy can Europe produce without harming the environment?* (pp. 1–72). Copenhagen.

Farrell, E. P., Führer, E., Ryan, D., Andersson, F., Hüttl, R., & Piussi, P. (2000). European forest ecosystems: Building the future on the legacy of the past. *Forest Ecology and Management*, *132*, 5–20. doi:S0378-1127(00)00375-3

Flaspohler, D.J., Webster, C.R. & Froese, R.E. (2011). Bioenergy, biomass and biodiversity. In B.D. Solomon & V.A. Luzadis (Eds.), *Renewable energy from forest resources in the United States* (pp. 133-162) London: Routledge.

Food and Agriculture Organization of the United Nations [FAO]. (2004). *Unified bioenergy terminology* (pp. 1–50).

Food and Agriculture Organization of the United Nations [FAO]. (2010). *Global forest resources assessment 2010. Main report* (pp. 1–378). Rome.

Forest Stewardship Council [FSC]. (1996). *FSC International standard. FSC principles and criteria for forest stewardship* (pp. 1–12). Bonn.

Forest Stewardship Council [FSC]. (2012). *FSC® International standard. FSC principles and criteria for forest stewardship* (pp. 1–37).

Ganjegunte, G. K., Condron, L. M., Clinton, P. W., Davis, M. R., & Mahieu, N. (2004). Decomposition and nutrient release from radiata pine (Pinus radiata) coarse woody debris. *Forest Ecology and Management*, *187*(2-3), 197–211. doi:10.1016/S0378-1127(03)00332-3

Goldemberg, J., & Teixeira Coelho, S. (2004). Renewable energy—traditional biomass vs. modern biomass. *Energy Policy, 32*(6), 711–714. doi:10.1016/S0301-4215(02)00340-3

Graham, R. T., Harvey, A. E., Jurgensen, M. F., Jain, T. B., Tonn, J. R., & Page-Dumroese, D. S. (1994). *Managing coarse woody debris in forests of the Rocky Mountains* (pp. 1–16). Ogden, UT.

Grebner, D.L, Perez-Verdin, G., Sun, C., Munn, I.A., Schultz, E.B., & Matney, T.G. (2011). Woody biomass feedstock availability, production costs and impolications for bioenergy conversion in Mississippi. In B.D. Solomon & V.A. Luzadis (Eds.), *Renewable energy from forest resources in the United States* (pp. 261-280) London: Routledge

Gregg, J. S., & Smith, S. J. (2010). Global and regional potential for bioenergy from agricultural and forestry residue biomass. *Mitigation and Adaptation Strategies for Global Change, 15*(3), 241–262. doi:10.1007/s11027-010-9215-4

Grigal, D. F. (2000). Effects of extensive forest management on soil productivity. *Forest Ecology and Management*, *138*(1-3), 167–185. doi:10.1016/S0378-1127(00)00395-9

Hakkila, P. (2002). Operations with reduced environmental impact. In J. Richardson, R. Björheden, P. Hakkila, A. T. Lowe, & C. T. Smith (Eds.), *Bioenergy from* *sustainable forestry: Guiding principles and practice* (pp. 244–261). Dordrecht: Kluwer Academic Publishers.

Hakkila, P. (2003). *Developing technology for large- scale production of forest chips (Interim report)* (pp. 1–58). Helsinki.

Hakkila, P. (2004). *Developing technology for large-scale production of forest chips (Final report)* (pp. 1–102). Helsinki.

Hakkila, P., & Parikka, M. (2002). Fuel resources from the forest. In J. Richardson, R. Björheden, P. Hakkila, A. T. Lowe, & C. T. Smith (Eds.), *Bioenergy from sustainable forestry: Guiding principles and practice* (pp. 19–48). Dordrecht: Kluwer Academic Publishers.

Hall, D.O., Rosillo-Calle, F., Williams, R.H., & Woods, J. (1993). Biomass for energy: Supply prospects. In T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williams & L. Burnham (Eds.). *Renewable energy. Sources for fuels and electricity*. London: Earthscan Publications Ltd.

Harrington, T. B., Slesak, R. A., & Schoenholtz, S. H. (2013). Variation in logging debris cover influences competitor abundance, resource availability, and early growth of planted Douglas-fir. *Forest Ecology and Management, 296*, 41–52. doi:10.1016/j.foreco.2013.01.033

Helmisaari, H.-S., Hanssen, K. H., Jacobson, S., Kukkola, M., Luiro, J., Saarsalmi, A., Tamminen, P., et al. (2011). Logging residue removal after thinning in Nordic boreal forests: Long-term impact on tree growth. *Forest Ecology and Management*, *261*(11), 1919–1927. doi:10.1016/j.foreco.2011.02.015

Holtsmark, B. (2011). Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change, 112*(2), 415–428. doi:10.1007/s10584-011-0222-6

Jacobson, S., Kukkola, M., Mälkönen, E., & Tveite, B. (2000). Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. *Forest Ecology and Management, 129*(1-3), 41–51. doi:10.1016/S0378-1127(99)00159-0

Juodvalkis, A., Kairiukstis, L., & Vasiliauskas, R. (2005). Effects of thinning on growth of six tree species in north-temperate forests of Lithuania. *European Journal of Forest Research*, *124*(3), 187–192. doi:10.1007/s10342-005-0070-x

Karaj, S., Rehl, T., Leis, H., & Müller, J. (2010). Analysis of biomass residues potential for electrical energy generation in Albania. *Renewable and Sustainable Energy Reviews*, *14*(1), 493–499. doi:10.1016/j.rser.2009.07.026

Kellomäki, S. (2012). *Management of the boreal forests for biomass – potentials and use*. Presentation of the Thematic Day of ENERWOODS- project, Joensuu, Finland.

Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K. T., & Strandman, H. (2008). Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *363*(1501), 2341–51. doi:10.1098/rstb.2007.2204

Kelty, M. J. (2006). The role of species mixtures in plantation forestry. *Forest Ecology and Management*, *233*(2-3), 195–204. doi:10.1016/j.foreco.2006.05.011

Koopmans, A., & Koppejan, J. (1997). Agricultural and forest residues - Generation, utilization and availability. Regional Consultation on Modern Applications of Biomass Energy (pp. 1–23). Kuala Lumpur.

Lal, P., Alavalapati, J. R. R., Marinescu, M., Matta, J. R., Dwivedi, P., & Susaeta, A. (2011). Developing sustainability indicators for woody biomass harvesting in the United States. *Journal of Sustainable Forestry*, *30*(8), 736–755. doi:10.1080/10549811.2011.571581

Lamers, P., Thiffault, E., Paré, D., & Junginger, H. M. (in press). Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. *Biomass and Bioenergy*.

Lamiales. (2013). In *Encyclopædia Britannica*. Retrieved from http://www.britannica.com/EBchecked/topic/328712/Lamiales/276508/Lamiaceae

Lamson, N. I. (1987). *Appalachian hardwood stands* (pp. 1–7). Broomall, PA.

Lattimore, B., Smith, C. T., Titus, B. D., Stupak, I., & Egnell, G. (2009). Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices*.* *Biomass and Bioenergy, 33*(10), 1321–1342. doi:10.1016/j.biombioe.2009.06.005

Leemans, R., & Van der Born, G. J. (1994). Determining the potential distribution of vegetation crops and agricultural productivity. *Water, Air, and Soil Pollution, 76*, 133–161.

Lesch, W., & Scott, D. F. (1997). The response in water yield to the thinning of Pinus radiata, Pinus patula and Eucalyptus grandis plantations. *Forest Ecology and Management*, *99*(3), 295–307. doi:10.1016/S0378-1127(97)00045-5

Liu, C., Ruel, J.-C., & Zhang, S. Y. (2007). Immediate impacts of partial cutting strategies on stand characteristics and value. *Forest Ecology and Management, 250*(3), 148–155. doi:10.1016/j.foreco.2007.05.010

López-Rodríguez, F., Pérez Atanet, C., Cuadros Blázquez, F., & Ruiz Celma, A. (2009). Spatial assessment of the bioenergy potential of forest residues in the western province of Spain, Caceres. Biomass and Bioenergy, 33(10), 1358–1366. doi:10.1016/j.biombioe.2009.05.026

Mabee, W. E., Fraser, E. D. G., McFarlane, P. N., & Saddler, J. N. (2006). Canadian biomass reserves for biorefining. *Applied biochemistry and biotechnology*, *129-132*, 22–40. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/16915629

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., et al. (2007). The human footprint in the carbon cycle of temperate and boreal forests. *Nature*, *447*(7146), 848–50. doi:10.1038/nature05847

Mahendrappa, M. K., Pitt, C. M., Kingston, D. G. O., & Morehouse, T. (2006). Environmental impacts of harvesting white spruce on Prince Edward Island. *Biomass and Bioenergy*, *30*(4), 363–369. doi:10.1016/j.biombioe.2005.07.016

mahogany. (2013). In *Encyclopædia Britannica*. Retrieved from http://www.britannica.com/EBchecked/topic/358323/mahogany

Malinen, J., Pesonen, M., Maatta, T., & Kajanus, M. (2001). Potential harvest for wood fuels (energy wood) from logging residues and first thinnings in Southern Finland. *Biomass and Bioenergy, 20*, 189–196.

Mangoyana, R. B. (2011). Bioenergy from forest thinning: Carbon emissions, energy balances and cost analyses. *Renewable Energy*, *36*(9), 2368–2373. doi:10.1016/j.renene.2011.01.026

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. L. (2011). Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology, 45*(2), 789–95. doi:10.1021/es1024004

MNP. (2006). *Integrated modelling of global environmental change. An overview of IMAGE 2.4.* A.F. Bouwman, T. Kram & K. Klein Goldewijk (Eds.). Bilthoven: Netherlands Environmental Assessment Agency (MNP).

Nave, L. E., Vance, E. D., Swanston, C. W., & Curtis, P. S. (2010). Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management*, *259*(5), 857–866. doi:10.1016/j.foreco.2009.12.009

Nilsson, B., & Thörnqvist, T. (2004). *Clean hydrogen-rich synthesis gas. Logistics, availability and cost for stump harvesting in Sweden*. Kalmar.

Nunery, J. S., & Keeton, W. S. (2010). Forest carbon storage in the northeastern United States: Net effects of harvesting frequency, post-harvest retention, and wood products. *Forest Ecology and Management*, *259*(8), 1363–1375. doi:10.1016/j.foreco.2009.12.029

Nurmi, J. (1999). The storage of logging residue for fuel. *Biomass and Bioenergy, 17*(1), 41–47. doi:10.1016/S0961-9534(99)00023-9

O'Connell, A. M. (1997). Decomposition of slash residues in thinned regrowth in Western eucalypt forest Australia. Journal of Applied Ecology, 34(1), 111–122.

Olson, S.M. (2003). The wood properties of New Zealand silver beech (Nothofagus menziesii), a lesser-known hardwood species. *Forest Products Journal, 53*(5), 80-86.

Oosterbaan, A., Hochbichler, E., Nicolescu, V.-N., & Spiecker, H. (2009). Silvicultural principles , goals and measures in growing valuable broadleaved tree species. *Die Bodenkultur, 60*(3).

Ouro, G., Pérez-Batallón, P., & Merino, A. (2001). Effects of sylvicultural practices on nutrient status in a Pinus radiata plantation : Nutrient export by tree removal and nutrient dynamics in decomposing logging residues, *58*, 411–422.

Paré, D., Bernier, P., Thiffault, E., & Titus, B. D. (2011). The potential of forest biomass as an energy source for Canada. *The Forestry Cronicle*, *87*(1), 71–76.

Peckham, S. D., Gower, S. T., Perry, C. H., Wilson, B. T., & Stueve, K. M. (2013). Modeling harvest and biomass removal effects on the forest carbon balance of the Midwest, USA. *Environmental Science & Policy*, *25*, 22–35. doi:10.1016/j.envsci.2012.09.006

Pérez, S., Renedo, C. J., Ortiz, a, & Mañana, M. (2008). Energy potential of waste from 10 forest species in the North of Spain (Cantabria). *Bioresource technology, 99*(14), 6339–45. doi:10.1016/j.biortech.2007.12.014

Perlack, R., Wright, L., Turhollow, A., Graham, R., Stokes, B., & Erback, D. (2005). *Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply* (pp. 1–60). Oak Ridge, TN.

Planbureau voor de Leefomgeving (PBL). (2001). IMAGE 2.2. Computer program. Available at http://www.pbl.nl/en/publications/2001/Main_disc__The_IMAGE_2_2

Polagye, B., Hodgson, K., & Malte, P. (2007). An economic analysis of bio-energy options using thinnings from overstocked forests. *Biomass and Bioenergy, 31*(2-3), 105–125. doi:10.1016/j.biombioe.2006.02.005

Poudel, B. C., Sathre, R., Bergh, J., Gustavsson, L., Lundström, A., & Hyvönen, R. (2012). Potential effects of intensive forestry on biomass production and total carbon balance in north-central Sweden. *Environmental Science & Policy, 15*(1), 106–124. doi:10.1016/j.envsci.2011.09.005

Prentice, I. C., Cramer, W., Harrison, S. P., Leemans, R., Monserud, R. A., & Solomon, A. M. (1992). A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography, 19*(2), 117–134.

Prévosto, B., & Ripert, C. (2008). Regeneration of Pinus halepensis stands after partial cutting in southern France: Impacts of different ground vegetation, soil and logging slash treatments. *Forest Ecology and Management, 256*(12), 2058–2064. doi:10.1016/j.foreco.2008.07.027

Raile, G. K. (1982). *Estimating stump volume* (pp. 1–4). St. Paul, MN.

Raison, R. J. (2002). Environmental sustainability. In J. Richardson, R. Björheden, P. Hakkila, A. T. Lowe, & C. T. Smith (Eds.), *Bioenergy from sustainable forestry: Guiding principles and practice* (pp. 159–164). Dordrecht: Kluwer Academic Publishers.

Richardson, J. (2002). Framework for conventional forestry systems for sustainable production of bioenergy. In J. Richardson, R. Björheden, P. Hakkila, A. T. Lowe, & C. T. Smith (Eds.), Bioenergy *from sustainable forestry: Guiding principles and practice* (pp. 321–330). Dordrecht: Kluwer Academic Publishers.

Roos, A. (2002). Policy and institutional factors affecting forest energy. In J. Richardson, R. Björheden, P. Hakkila, A. T. Lowe, & C. T. Smith (Eds.), *Bioenergy from sustainable forestry: Guiding principles and practice* (pp. 299–320). Dordrecht: Kluwer Academic Publishers.

Saarinen, V.-M. (2006). The effects of slash and stump removal on productivity and quality of forest regeneration operations—preliminary results. Biomass and Bioenergy, 30(4), 349–356. doi:10.1016/j.biombioe.2005.07.014

Scarlat, N., Blujdea, V., & Dallemand, J.-F. (2011). Assessment of the availability of agricultural and forest residues for bioenergy production in Romania. *Biomass and Bioenergy, 35*(5), 1995–2005. doi:10.1016/j.biombioe.2011.01.057

Schlamadinger, B., Spitzer, J., Kohlmaier, G. H., & Lüdeke, M. (1995). Carbon balance of bioenergy. *Biomass and Bioenergy, 8*(4), 221–234.

Second Ministerial Conference on the Protection of Forests in Europe [MCPFE]. (1993). *RESOLUTION H1 General guidelines for the sustainable management of forests in Europe* (pp. 1–5). Helsinki.

Simetric. (2011). *Weight of various types of wood*. Retrieved from http://www.simetric.co.uk/si_wood.htm

Siry, J. P., Cubbage, F. W., & Ahmed, M. R. (2005). Sustainable forest management: global trends and opportunities. *Forest Policy and Economics, 7*(4), 551–561. doi:10.1016/j.forpol.2003.09.003

Smeets, E. M. W., & Faaij, A. P. C. (2006). Bioenergy potentials from forestry in 2050. An assessment of the drivers that determine the potentials. *Climatic Change, 81*(3-4), 353–390. doi:10.1007/s10584-006-9163-x

Soulé, M. E., & Sanjayan, M. A. (1998). ECOLOGY: Conservation Targets: Do They Help? *Science (New York, N.Y.), 279*(5359), 2060–2061. doi:10.1126/science.279.5359.2060

Standish, J. T., Manning, G. H., & Demaerschalk, J. P. (1985). *Development of biomass equations for British Columbia tree species* (pp. 1–49).

Stupak, I., Asikainen, A., Jonsell, M., Karltun, E., Lunnan, A., Mizaraite, D., Pasanen, K., et al. (2007). Sustainable utilisation of forest biomass for energy—Possibilities and problems: Policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. *Biomass and Bioenergy, 31*(10), 666–684. doi:10.1016/j.biombioe.2007.06.012

Summer green forests. (2012). *The free dictionary.* Retrieved from http://encyclopedia2.thefreedictionary.com/Summer+Green+Forests

teak. (2013). In *Encyclopædia Britannica*. Retrieved from http://www.britannica.com/EBchecked/topic/585216/teak

Thomas, S. C., Halpern, C. B., Falk, D. A., Liguori, D. A., & Austin, K. A. (1999). Plant diversity in managed forests: Understory responses to thinning and fertilization. *Ecological Applications*, *9*(3), 864–879.

Titus, B. D., Maynard, D. G., Dymond, C. C., Stinson, G., & Kurz, W. A. (2009). Wood energy: Protect local ecosystems. *Science*, *324*(5933), 1389–90. doi:10.1126/science.324_1389c

Tritton, L. M., Martin, C. W., Hornbeck, J. W., & Pierce, R. S. (1987). Biomass and nutrient removals from commercial thinning and whole-tree clearcutting of central hardwoods. *Environmental Management*, *11*(5), 659–666. doi:10.1007/BF01880165

Tsujino, R., & Yumoto, T. (2007). Spatial distribution patterns of trees at different life stages in a warm temperate forest. *Journal of Plant Research, 120*(6), 687-695.

Ulvcrona, K. a., Claesson, S., Sahlen, K., & Lundmark, T. (2007). The effects of timing of pre-commercial thinning and stand density on stem form and branch characteristics of Pinus sylvestris. *Forestry, 80*(3), 323–335. doi:10.1093/forestry/cpm011

United Nations Economic Commission for Europe [UNECE], & Food and Agriculture Organization of the United Nations [FAO]. (2011). *State of Europe's forests 2011*.

Van Minnen, J. G., Strengers, B., & Eickhout, B. (2006). Simulating carbon exchange between the terrestrial biosphere and the atmosphere. In A. F. Bouwman, T. Kram, & K. K. Goldewijk (Eds.), *Integrated modelling of global environmental change. An overview of IMAGE 2.4* (pp. 113–130). Bilthoven: MNP.

Vance, E. D. (2000). Agricultural site productivity: principles derived from long-term experiments and their implications for intensively managed forests. *Forest Ecology and Management*, *138*(1-3), 369–396. doi:10.1016/S0378-1127(00)00425-4

Vis, M. W., Van der Berg, B. T. G., Anttila, M. ., Böttcher, H., Dees, M., Domac, J., Eleftheriadis, I., et al. (2010). *Volume I Best Practices and Methods Handbook* (Vol. I, pp. 1–220). Freiburg.

Wetzel, S., Duchesne, L., & LaPorte, M. (2006). *Bioproducts from Canadian forests: New partnerships in the bioeconomy*. Dordrecht: Springer.

Wikström, F. (2007). The potential of energy utilization from logging residues with regard to the availability of ashes. *Biomass and Bioenergy*, *31*(1), 40–45. doi:10.1016/j.biombioe.2006.05.002

Wilkerson, E.G., & Perlack, R.D. (2011). Resource assessment, economics and technology for collecting and harvesting. In B.D. Solomon & V.A. Luzadis (Eds.), *Renewable energy from forest resources in the United States* (pp. 69-91) London: Routledge.

Wiser, S. K., Allen, R. B., Benecke, U., Baker, G., & Peltzer, D. (2005). Tree growth and mortality after small-group harvesting in New Zealand old-growth Nothofagus forests. *Canadian Journal of Forest Research*, *35*(10), 2323–2331. doi:10.1139/x05-158

Woods, J. (2007). Appendix 2.1 Residue calculations. In F. Rosillo-Calle (Ed.), *The biomass assessment handbook: Bioenergy for a sustainable environment* (pp. 57-60).

World Agroforestry Centre. (2013). AgroForestTree database. Retrieved from http://www.worldagroforestry.org/treedb2/

World Commission on Environment and Development [WCED]. (1987). *Our common future.* G. Brundtland (Ed.). Oxford: Oxford University Press.

Xu, W., Li, Y., & Carraway, B. (2008). Estimation of woody biomass availability for energy in Texas.

Young, H. E., Strand, L., & Altenberger, R. (1964). Preliminary fresh and dry weight tables for seven tree species in Maine. *Technical Bulletin, 12*, 1–78.

Zambelli, P., Lora, C., Spinelli, R., Tattoni, C., Vitti, A., Zatelli, P., & Ciolli, M. (2012). A GIS decision support system for regional forest management to assess biomass availability for renewable energy production. *Environmental Modelling & Software, 38*, 203–213. doi:10.1016/j.envsoft.2012.05.016

Zanchi, G., Pena, N., & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, *4*(6), 761–772. doi:10.1111/j.1757-1707.2011.01149.x

Zanchi, G., Pena, N., & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. GCB Bioenergy, 4(6), 761–772. doi:10.1111/j.1757-1707.2011.01149.x

Zhou, X., & Hemstrom, M. A. (2009*). Estimating aboveground tree biomass on forest land in the Pacific Northwest : A comparison of approaches* (pp. 1–25). Portland, OR.

Appendix A Tree density

Table A. 1. Mean air dried tree density of different plant genera, if available, range between brackets.

Genera	**Name**	**Density** (kg/m^3)	**Source**
Abies	Fir	393 (350-415)	Alberta, 2006a; California State University Dominguez Hills [CSUDH], n.d.
Betula	Birch	621 (552-714)	Alberta, 2006h; CSUDH, n.d.
Eucalyptus	Eucalyptus	606 (599-615)	Olson, 2003
Fagus	Beech	672 (655-689)	CSUDH, n.d.; Olson, 2003;
Larix	Larch	550 (506-587)	Alberta, 2006f; CSUDH, n.d.
Nothofagus	Southern beech	661 (545-833)	Olson, 2003
Picea	Spruce	415 (390-440)	Alberta, 2006c; 2006i
Pinus	Pine	431 (420-444)	Alberta, 2006c; 2006d; 2006e
Populus	Poplar	444 (408-510)	Alberta, 2006b; 2006g
Pseudotsuga	Douglas fir	482 (446-512)	Alberta, 2006c; CSUDH, n.d.
Quercus	Oak	731 (640-977)	Alberta, 2006b; CSUDH, n.d.
Salix	Willow	414 (408-420)	CSUDH, n.d.; Simetric, 2011
Sequoia	Redwood	480 (450-510)	Simetric, 2011
Thuja	Cedar	346 (315-380)	Simetric, 2011; CSUDH, n.d.
Tsuga	Hemlock	448 (431-480)	CSUDH, n.d.

Table A. 2. Mean air dried tree density of biomes, including ranges.

Biome	**Mean density** (kg/m^3)
Boreal forest	460 (350-714)
Cool conifer forest	429 (350-512)
Temperate mixed forest	510 (350-977)
Temperate deciduous forest	542 (390-977)
Warm-mixed forest	523 (315-833)

Appendix B Biome distribution

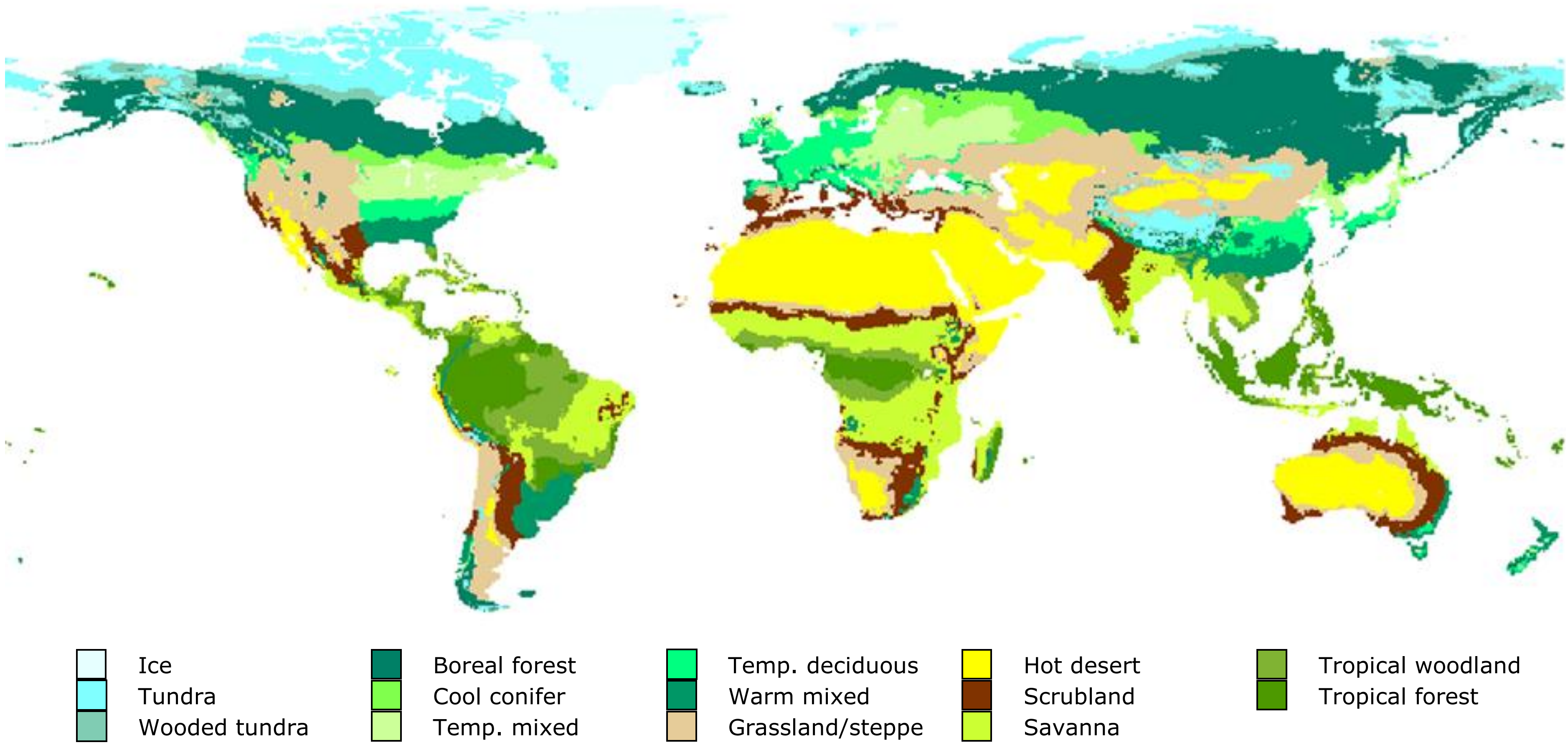

Figure B. 1. Biome distribution in IMAGE 2.2 model (PBL, 2001).

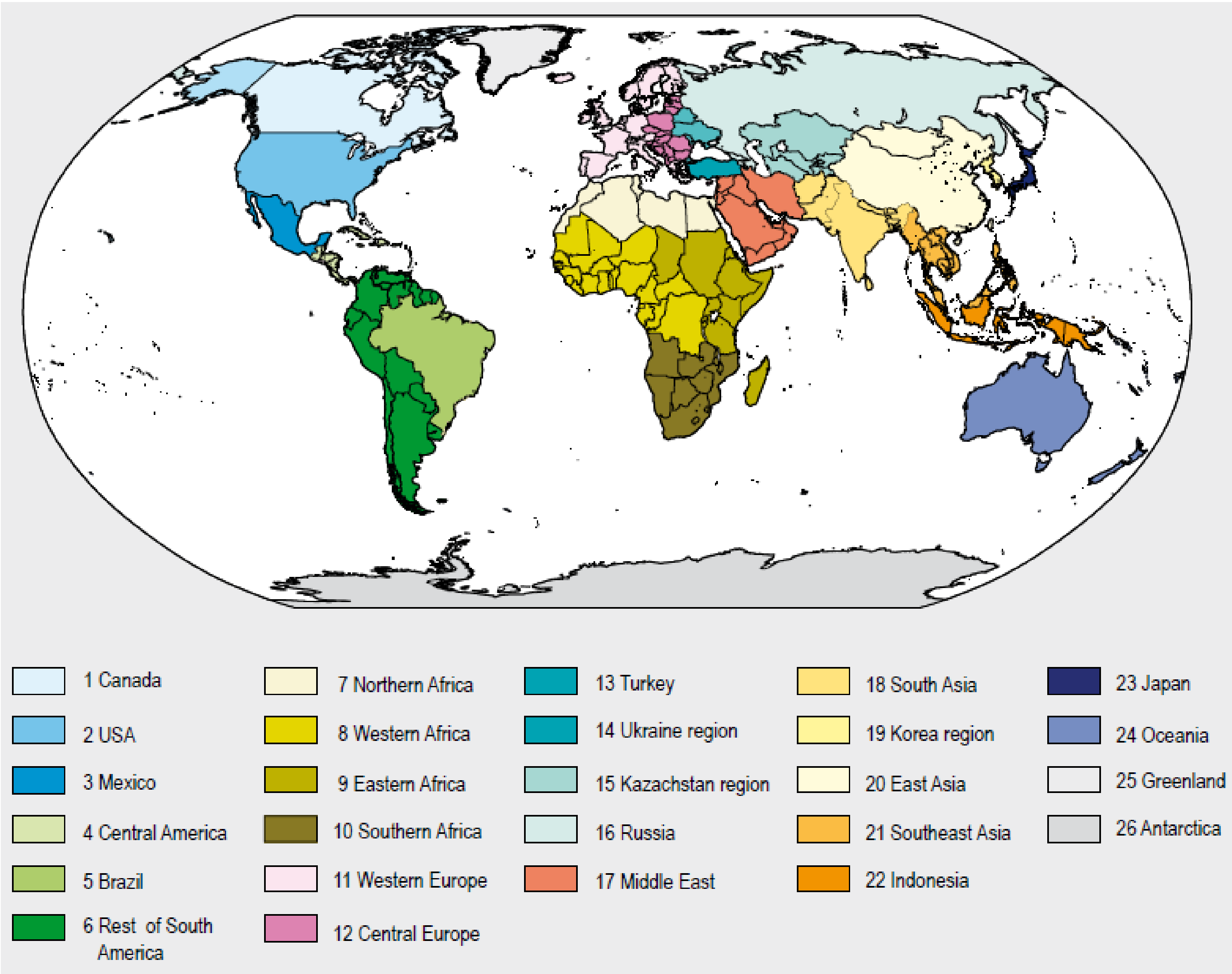

Figure B. 2. IMAGE regional breakdown (MNP, 2006).

Appendix C Production volume

Table C. 1. Production volume for productive plantations and clearcut for different world regions.

Region	**Productive plantations** (volume cutdown m^3/ha)	**Clearcut;** (volume cutdown m^3/ha)	**Source**
Canada		238	1
USA	306	357	1
Rest South America	409	231	1
Southern Africa	216		1
OECD Europe	173	422	1
Eastern Europe		281	1
Turkey	173	227	1
Ukraine		202	1
Russia		155	1
Korea	113	111	1
East Asia	133	111	1
Japan		154	1
Oceania	501	40	1
Temperate Europe		227	2
Finland		220-330	3
Boreal forest		120	4
Sweden		80-85	5
Canada		160	6

1 Arets et al., 2011; 2 UNECE & FAO, 2011; 3 Hakkila, 2004; 4 Kellomäki, 2012; 5 Mangoyana, 2011; Liu et al., 2007.

Appendix D Tree components

Table D. 1. Mean percentages of tree components in different genera. Stemmass (wood and bark) crown, and foliage as percentage of crown.

Genera	**Wood + bark** (%)	**Crown** (%)	**Foliage** (% of crown)	**Source**
Abies	53.6	46.4	45.2	1
Betula	71.4	28.6	20.9	1
Eucalyptus	80.9	19.1	42.9	2
Fagus	76.3	23.7	8.2	3
Larix	85.5	14.5	16.8	1
Nothofagus	78.4	21.6	15.1	4
Picea	58.2	41.8	39.3	1
Pinus	72.5	27.5	31.1	1
Populus	68.7	31.3	16.9	1
Pseudotsuga	74.5	25.5	31.3	1
Quercus	81.5	18.5	10.8	3
Salix	77.8	22.2	9.7	3
Sequoia	88.0	12.0	*unknown*	5
Thuja	65.3	34.7	36.6	1
Tsuga	79.3	20.7	34.9	1

1 Standish et al., 1985; 2 Pérez et al., 2009; 3 World Agroforestry, 2013;4 Donoso et al., 2010; 5 Busing & Fujimori, 2005.

Appendix E Protected forests

Table E. 1. Country data on protected forests and amount of forest with different regeneration (FAO, 2010).

	Primary forest		Other naturally regenerated forest			Planted Forest			Total forest area	Forest within protected areas	
Country/area	1 000 ha	% of forest area	1 000 ha	% of forest area	% of which intro-duced species	1 000 ha	% of forest area	% of which introduced species	1 000 ha	1 000 ha	% of forest area
Republic of Moldova	0	0	384	99	-	2	1	-	386	64	16.6
Turkey	973	9	6943	61	-	3418	30	2	11334	269	2.4
Azerbaijan	400	43	516	55	-	20	2	-	936	-	0.0
Georgia	500	18	2059	75	0	184	7	0	2743	551	20.1
Brazil	476573	92	35532	7	-	7418	1	96	519523	89541	17.2
Colombia	8543	14	51551	85	-	405	1	-	60499	-	0.0
Ecuador	4805	49	4893	50	-	167	2	100	9865	-	0.0
India	15701	23	42522	62	-	10211	15	13	68434	19774	28.9
Kyrgyzstan	269	28	628	66	-	57	6	-	954	80	8.4
Peru	60178	89	6821	10	-	993	1	-	67992	-	0.0
Tajikistan	297	72	12	3	-	101	25	4	410	44	10.7
Sweden	2609	9	21981	78	0	3613	13	18	28203	1435	5.1
Finland	0	0	16252	73	0	5904	27	n.s.	22156	1925	8.7
Russian Federation	256482	32	535618	66	0	16991	2	0	809091	17572	2.2
Iceland	0	0	3	10	0	27	90	78	30	n.s.	0.0
Norway	223	2	8367	83	0	1475	15	18	10065	167	1.7
Canada	165448	53	135723	44	-	8963	3	-	310134	24859	8.0
Mongolia	5152	47	5601	51	-	145	1	-	10898	5152	47.3
Switzerland	40	3	1028	83	n.s.	172	14	2	1240	90	7.3
Chile	4439	27	9408	58	-	2384	15	100	16231	3992	24.6
Estonia	964	43	1085	49	0	168	8	1	2217	213	9.6
United Kingdom	0	0	662	23	0	2219	77	64	2881	145	5.0
Japan	4747	19	9906	40	-	10326	41	-	24979	13149	52.6
Germany	0	0	5793	52	-	5283	48	8	11076	2754	24.9
Hungary	0	0	417	21	48	1612	79	41	2029	424	20.9
Republic of Korea	2957	48	1443	23	-	1823	29	67	6223	-	0.0
China	11632	6	118071	57	5	77157	37	28	206860	24671	11.9
Czech Republic	9	n.s.	13	n.s.	-	2635	99	-	2657	740	27.9
France	30	n.s.	14291	90	4	1633	10	36	15954	313	2.0
Ireland	0	0	82	11	18	657	89	76	739	58	7.8
Italy	93	1	8435	92	3	621	7	15	9149	3265	35.7
Poland	54	1	394	4	-	8889	95	n.s.	9337	187	2.0
Spain	0	0	15493	85	3	2680	15	37	18173	2499	13.8
Albania	85	11	598	77	0	94	12	8	777	162	20.8
Belgium	0	0	282	42	8	396	58	75	678	209	30.8
Croatia	7	n.s.	1843	96	3	70	4	39	1920	54	2.8

Denmark	25	5	112	21	31	407	75	47	544	40	7.4
Luxembourg	0	0	59	68	-	28	33	-	87	-	0.0
Netherlands	0	0	0	0	-	365	100	25	365	83	22.7
Slovenia	109	9	1112	89	0	32	3	-	1253	241	19.2
FYR Macedonia	0	0	893	89	-	105	11	-	998	-	0.0
Romania	300	5	4827	73	-	1446	22	-	6573	1746	26.6
Ukraine	59	1	4800	49	-	4846	50	-	9705	-	0.0
Slovakia	24	1	950	49	3	959	50	2	1933	1104	57.1
USA	75277	25	203382	67	n.s.	25363	8	2	304022	30225	9.9
Bulgaria	338	9	2774	71	6	815	21	5	3927	313	8.0
Lithuania	26	1	1613	75	0	521	24	1	2160	433	20.0
Serbia	1	n.s.	2532	93	-	180	7	-	2713	452	16.7
Armenia	13	5	228	87	-	21	8	-	262	-	0.0
Belarus	400	5	6373	74	0	1857	22	n.s.	8630	1208	14.0
DPR Korea	780	14	4104	72	-	781	14	-	5665	780	13.8
Latvia	15	n.s.	2711	81	0	628	19	n.s.	3354	610	18.2
Bosnia and Herzegovina	2	n.s.	1184	54	-	999	46	-	2185	-	0.0
Australia	5039	3	142359	95	0	1903	1	53	149301	26621	17.8
New Zealand	2144	26	4313	52	-	1812	22	100	8269	3607	43.6
Mexico	34310	53	27289	42	-	3203	5	-	64802	8488	13.1
Madagascar	3036	24	9102	73	-	415	3	100	12553	4752	37.9
Angola	0	0	58352	100	-	128	n.s.	-	58480	1862	3.2
Argentina	1738	6	26268	89	0	1394	5	98	29400	1160	3.9
Bhutan	413	13	2833	87	-	3	n.s.	-	3249	883	27.2
Ethiopia	0	0	11785	96	-	511	4	-	12296	-	0.0
Kenya	654	19	2616	75	-	197	6	100	3467	-	0.0
Lesotho	0	0	34	76	-	10	24	100	44	1	2.3
Myanmar	3192	10	27593	87	-	988	3	-	31773	2081	6.5
Nepal	526	14	3067	84	13	43	1	23	3636	526	14.5
Portugal	24	1	2583	75	6	849	25	99	3456	700	20.3
South Africa	947	10	6531	71	0	1763	19	100	9241	947	10.2
Swaziland	0	0	423	75	-	140	25	-	563	-	0.0
Uruguay	306	18	460	26	-	978	56	100	1744	-	0.0
Zimbabwe	801	5	14715	94	0	108	1	100	15624	801	5.1

Notes: Countries with names in light red, have limited amounts of the biomes that are of interest in this research.

Values in light red in the last column are those that have less than 10% of forest area protected.

Values in yellow in the last column are those that have less than 12% but more than 10% of forest area protected.

Appendix F Sensitivity

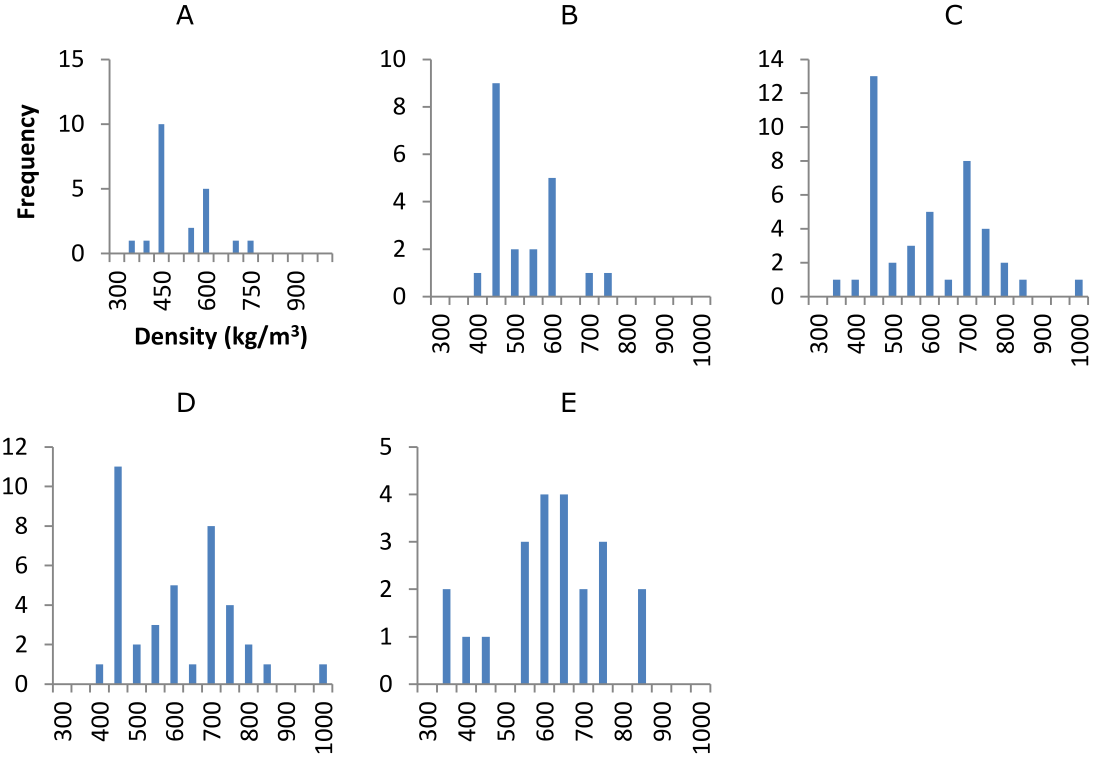

Figure F. 1. Histograms of the distribution of the values used to calculate density, axis labels for all graphs same as for A. A for BF, B for CC, C for TM, D for TD forest and E for WM.

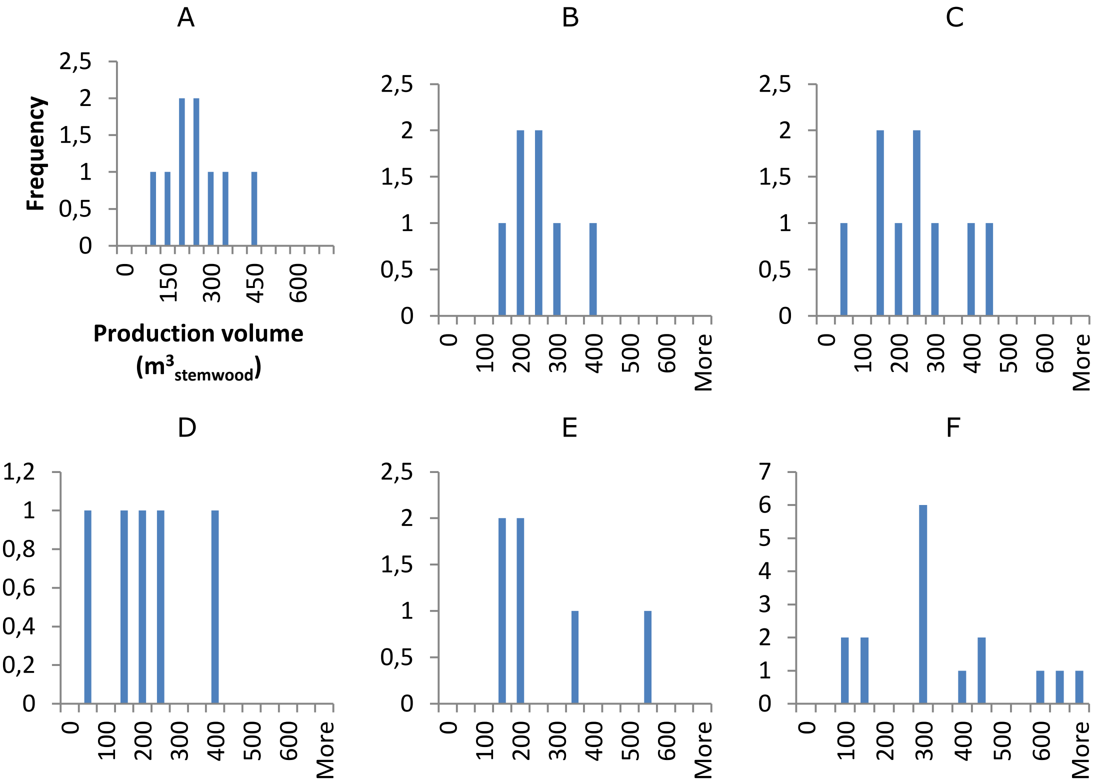

Figure F. 2. Histograms of the distribution of the values used to calculate production volume, axis labels for all graphs same as for A. A for BF and CC, B for TM, C for TD, D for WM, E for TD plantations and F for WM plantations.

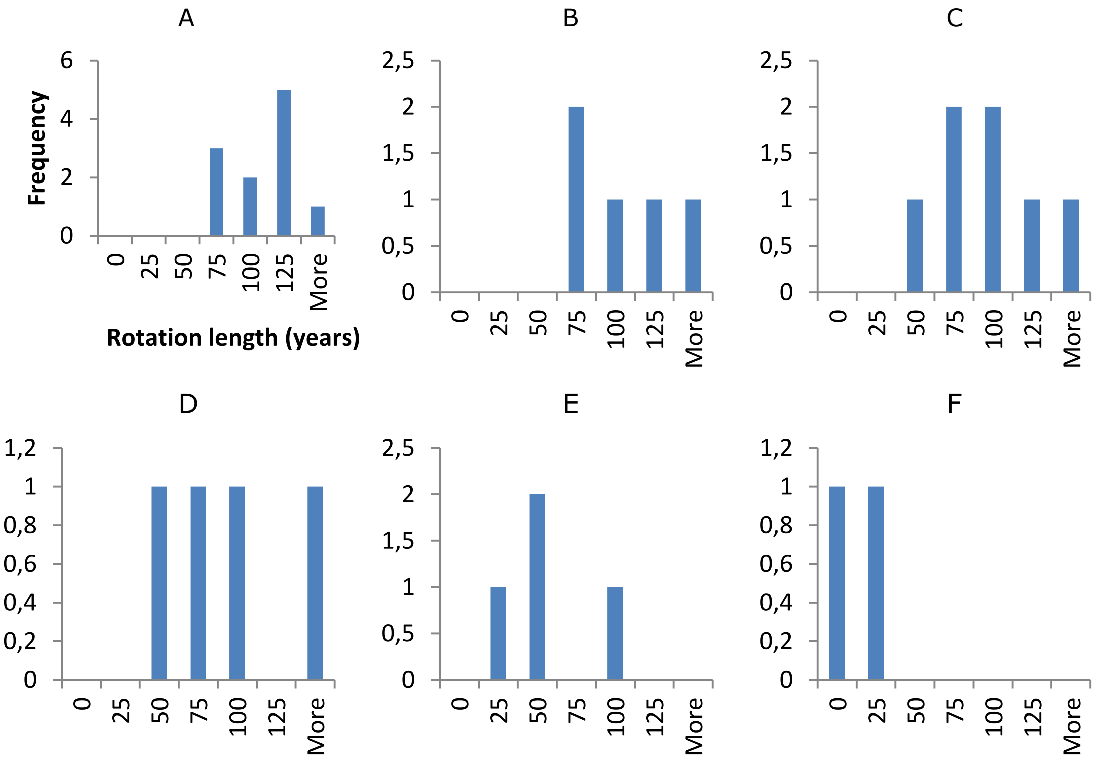

Figure F. 3. Histograms of the distribution of the values used to calculate production volume, axis labels for all graphs same as for A. A for BF and CC, B for TM, C for TD, D for WM, E for TD plantations and F for WM plantations.

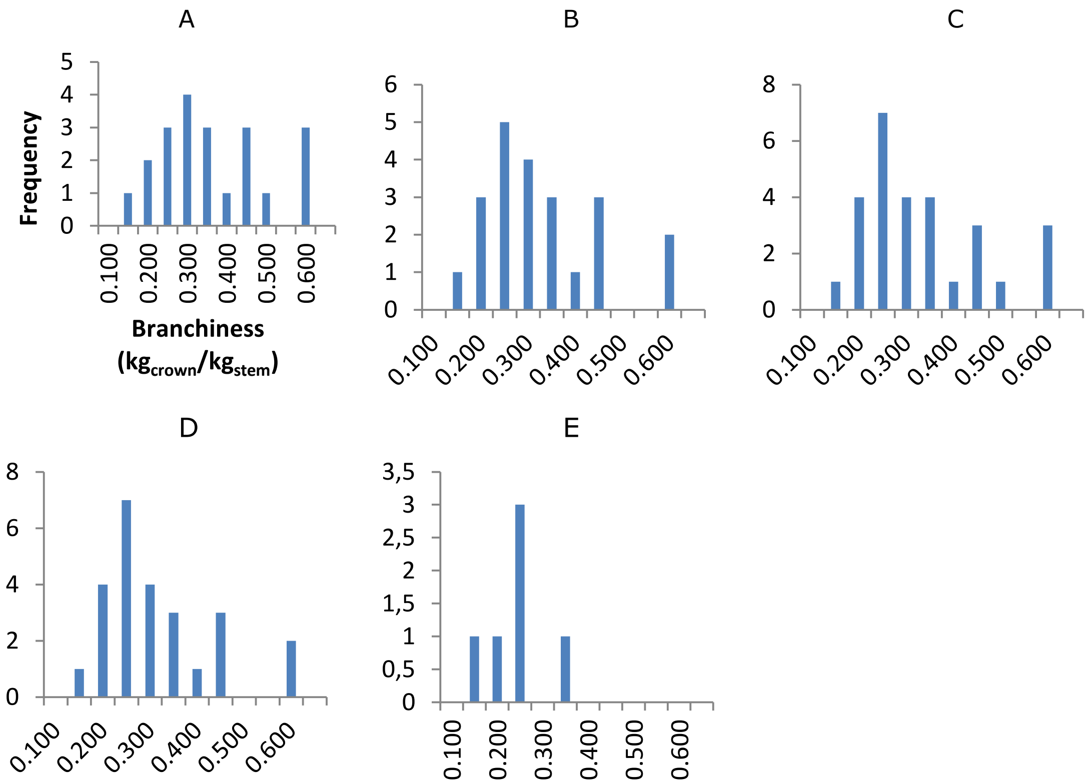

Figure F. 4. Histograms of the distribution of the values used to calculate branchiness, axis labels for all graphs same as for A. A for BF and CC, B for TM, C for TD, D for WM, E for TD plantations and F for WM plantations.

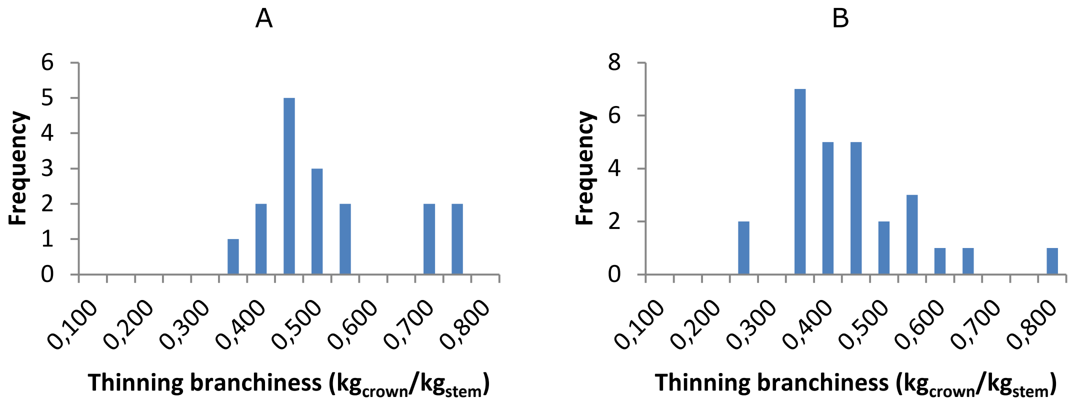

Figure F. 5. Histograms of the distribution of the values used to calculate spruce (A) and pine (B) branchiness at thinning.

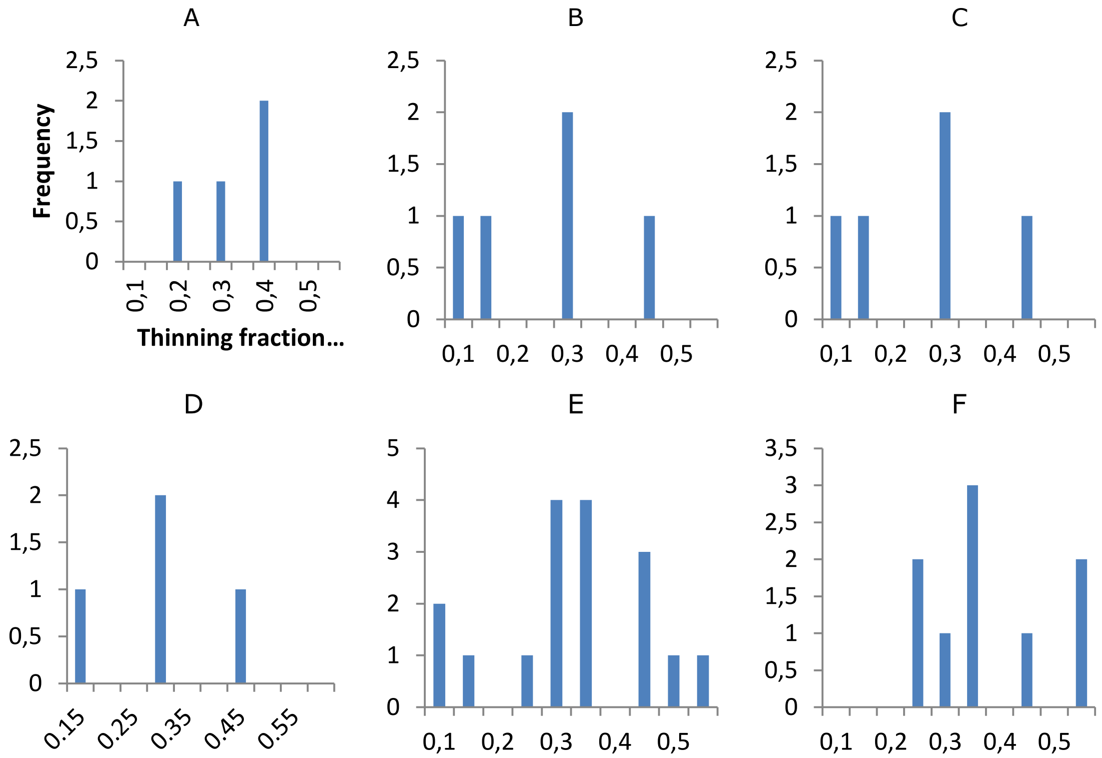

Figure F. 6. Histograms of the distribution of the values used to calculate thinning fraction, axis labels for all graphs same as for A. A for BF and CC, B for TM, C for TD, D for WM, E for TD plantations and F for WM plantations.