Impacts of stumps and roots on carbon storage and bioenergy use in a climate change context

Ylva Melin
Faculty of Forest Sciences
Department of Forest Resource Management
Umeå

Doctoral Thesis
Swedish University of Agricultural Sciences
Umeå 2014

Acta Universitatis agriculturae Sueciae

2014:79

Cover: Spruce stump, Västmanland, Sweden, August 2009
(photo: Ylva Melin)

ISSN 1652-6880
ISBN (print version) 978-91-576-8106-5
ISBN (electronic version) 978-91-576-8107-2

Print: SLU Service/Repro, Uppsala 2014

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Abstract

As a result of national and international greenhouse gas emissions reduction targets, economic incentives and political desires to be more independent regarding energy supplies, there is interest in substituting fossil fuels with renewable energy sources, such as forest fuels. Stump harvesting could be an option to further increase the bioenergy potential in forested countries; currently stump harvesting is carried out on a pilot basis in Sweden. In this thesis, the Swedish stump harvest potential is studied in a national and European climate change mitigation context.

One main objective was to develop a general system for estimating and monitoring carbon stocks and carbon stock changes in stump and root systems on a national scale. A core part of this system was a decomposition function for Norway spruce stumps and roots that was developed as part of this thesis. The decomposition rate in Norway spruce stumps and roots was estimated to be 4.6% annually. Another objective included assessment of the carbon balance trade-offs between the use of stumps for either bioenergy or carbon sequestration. This was carried out over different time scales and harvest intensities and, further, the substitution effect of using stumps for bioenergy in comparison with coal was investigated. The risks of nutrient loss linked to stump harvesting were also studied and discussed. Data from the Swedish national forest inventory and from specifically designed studies on stumps and roots were used for the analyses.

The results showed that it takes about nine years for a stump harvest scenario to become more climate-friendly than if coal were used i.e. there is a certain lag period during which the CO_2 emissions from the stump harvest scheme exceed the emissions from utilizing coal as fuel; this is due to higher calorific value in fossil fuels. However, in the long-term, the CO_2 emissions decrease if stumps and roots are used instead of coal. In the medium scenario studied, the CO_2 emissions decreased by 5.0 Tg CO_2 yr^{-1} - this corresponds to 8.6% of Sweden's current greenhouse gas emissions. It was also shown that the Swedish carbon pool in stumps and roots would start to decrease if more than approximately 107 PJ were harvested annually. Without stump harvesting, the carbon pool in stumps and roots increased over the study period (1984 – 2003) by, on average, 6.9 Tg CO_2 yr^{-1}. Also, the nutrient pools would be at risk if intensive stump harvest schemes after stem and slash harvesting were implemented. However, from a nutrient perspective, depletion of forest soils would be at least risk if a proportion of slash rather than stumps and coarse roots were left after harvesting.

Keywords: stump, root, carbon, biomass, bioenergy, climate change, substitution.

Author's address: Ylva Melin, SLU, Department of Forest Resource Management,
Skogsmarksgränd 1, 901 83 Umeå, Sweden. *E-mail:* Ylva.Melin@slu.se

Inverkan av stubbar och rötter på kollagring och bioenergi i ett klimatsammanhang

Sammanfatting (Swedish summary)

Som ett resultat av nationella och internationella mål för minskade utsläpp av växthusgaser, ekonomiska incitament och politisk vilja att bli mer självförsörjande vad gäller energi, så finns ett intresse att använda förnyelsebara energikällor istället för fossila bränslen. Stubbskörd skulle kunna vara en möjlighet att öka skogsbränslepotentialen i skogsländer; idag är Finland det land som tillämpar stubbskörd i störst utsträckning medan man i Sverige endast skördar stubbar på försöksnivå. I avhandlingen studeras möjligheterna till stubbskörd i Sverige ur ett svenskt och europeiskt klimatperspektiv.

Ett huvudsyfte var att utveckla ett system för att beräkna förändringar av kolförrådet i stubb- och rotsystem på nationell nivå. En central del av systemet är en nedbrytningsfunktion för stubbar och rötter av gran, som utvecklades inom ramen för avhandlingen; den genomsnittliga nedbrytningshastigheten beräknades till 4,6% per år. Ett annat syfte med avhandlingen var att göra avvägningar mellan användning av stubbar och rötter som bioenergi eller kolinlagring; avvägningarna gjordes över olika tidsskalor och skördenivåer. Dessutom undersöktes substitutionseffekten av att använda stubbar och rötter som bränsle istället för kol. Risken att utarma marken på näringsämnen vid stubbskörd undersöktes också. Data för analyserna hämtades från den svenska riksskogstaxeringen och från specifikt utformade stubb-rotstudier inom ramen för avhandlingen.

Resultaten visar att om lika mängd energi produceras från stubbskörd eller kolförbränning tar det ungefär nio år innan scenariot med stubbskörd blir mer klimatvänligt, d.v.s. under en inledande period överstiger CO_2-utsläppen från stubbförbränning utsläppen från användning fossilt bränsle p.g.a ett högre energivärde hos fossila bränslen. På lång sikt minskar emellertid CO_2-utsläppen om stubbar och rötter används istället för kol. För det stubbskördscenario som studerades minskade CO_2-utsläppen med 5.0 Tg per år. Detta motsvarar 8.6% av Sveriges nuvarande årliga utsläpp av växthusgaser. Vidare visades att den svenska kolpoolen i stubbar och rötter skulle börja minska om mer än ca 30 TWh skördas årligen, vilket motsvarar ca hälften av alla stubbar som uppkom per år i Sverige under studieperioden 1984 – 2003. Utan stubbskörd ökade stubb- och rotkolpoolen under studieperioden med i genomsnitt 6,9 Tg CO_2 år^{-1}. Vid studier av näringshalter i stubbar och rötter visade det sig att markens uthålliga produktionsförmåga skulle kunna äventyras om intensiv stubbskörd införs i kombination med uttag av grenar och toppar. På grund av lägre halter av näringsämnen i stubbar och rötter jämfört med grenar och toppar kan emellertid stubbskörd ha fördelar framför tillvaratagandet av grenar och toppar ur ett näringsämnesperspektiv.

Författarens adress: Ylva Melin, SLU, Institutionen för skoglig resurshushållning, Skogsmarksgränd 1, 901 83 Umeå, Sverige. *E-mail:* Ylva.Melin@slu.se

Dedication

To Elsa & Emil

Trees are made of air, primarily. When they are burned they go back to air, and in the flaming heat is released the flaming heat of the sun which was bound in to convert the air into tree, and in the ash is the small remnant of the part which did not come from air that came from the solid earth, instead. These are beautiful things, and the content of science is wonderfully full of them.

Richard P. Feynman

Contents

List of Publications **9**

Abbreviations **11**

1 Introduction **13**
1.1 Scope of this thesis 13
1.2 Climate strategies and policies 13
  1.2.1 Global level 13
  1.2.2 EU level 14
  1.2.3 Swedish level 14
1.3 Greenhouse gas emissions and reporting 15
  1.3.1 Swedish NFI and reporting 15
1.4 Decomposition models and carbon modeling 16
1.5 The role of forests in climate change mitigation 18
  1.5.1 Forest as carbon storage in the biosphere or as bioenergy 19
1.6 Bioenergy 19
  1.6.1 Global level 20
  1.6.2 EU level 20
  1.6.3 Swedish level 21
  1.6.4 Stump harvesting practices 22
1.7 Environmental effects of stump harvest 23
  1.7.1 Evaluating the risks of loss of nutrients and carbon and its influence on sustainable yield 23
  1.7.2 Other environmental aspects of stump harvest 26

2 Objectives **29**

3 Material and Methods **31**
3.1 Estimating the biomass and carbon pool of stump systems at a national scale (Paper I) 31
3.2 Decomposition of stump and root systems of Norway spruce in Sweden – A modeling approach (Paper II) 33
  3.2.1 The decomposition model 34
3.3 Assessing carbon balance trade-offs between bioenergy and using stumps for storing carbon (Paper III) 35

3.4 Nutrient concentrations in stumps and coarse roots of Norway spruce, Scots pine and silver birch in Sweden, Finland and Denmark (Paper IV) 36

4 Results 39

4.1 Estimating the biomass and carbon pool of stump systems at a national scale (Paper I) 39

4.2 Decomposition of stump and root systems of Norway spruce in Sweden – A modeling approach (Paper II) 40

4.3 Assessing carbon balance trade-offs between bioenergy and using stumps for storing carbon at varying time scales and harvest intensities (Paper III) 41

4.4 Nutrient concentrations in stumps and coarse roots of Norway spruce, Scots pine and silver birch in Sweden, Finland and Denmark (Paper IV) 45

5 Discussion 49

5.1 Future research 58

6 Conclusions 59

Acknowledgements 61

References 63

List of Publications

This thesis is based on the work contained in the following papers, referred to with Roman numerals in the text:

I Petersson, H., & Melin, Y. (2010). Estimating the biomass and carbon pool of stump systems at a national scale. *Forest Ecology and Management* 260(4), 466-471.

II Melin, Y., Petersson, H., & Nordfjell, T. (2009). Decomposition of stump and root systems of Norway spruce in Sweden – A modelling approach. *Forest Ecology and Management* 257(5), 1445-1451.

III Melin, Y., Petersson, H., & Egnell, G. (2010). Assessing carbon balance trade-offs between bioenergy and carbon sequestration of stumps at varying time scales and harvest intensities. *Forest Ecology and Management* 260(4), 536-542.

IV Hellsten, S., Helmisaari, H-S., Melin, Y., Skovsgaard, J-P., Kaakinen, S., Kukkola, M., Saarsalmi, A., Petersson, H., & Akselsson, C. (2013). Nutrient concentrations in stumps and coarse roots of Norway spruce, Scots pine and silver birch in Sweden, Finland and Denmark. *Forest Ecology and Management* 290(SI), 40-48.

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The contribution of Ylva Melin to the papers included in this thesis was as follows:

I Carried out the analysis and wrote parts of the manuscript.

II Designed the study in collaboration with supervisor; organized and participated in the field work, carried out the analysis and wrote major parts of the manuscript.

III Designed the study in collaboration with the supervisor and the co-author; planned and conducted the study; participated in developing the SQL-based code used in studies I and III; carried out the analysis and wrote major parts of the manuscript.

IV Minor contribution to the manuscript; preparation of samples for analysis.

Abbreviations

EU ETS	European Union Energy Trading System
FSC	Forest Stewardship Council
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
KP	Kyoto Protocol
LCA	Life Cycle Analysis
NFI	National Forest Inventory
NREAP	National Renewable Energy Action Plan
RE	Renewable Energy
RED	Renewable Energy Directive
SFA	Swedish Forest Agency
SOH	Stem-Only Harvesting
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WTH	Whole Tree Harvesting

1 Introduction

1.1 Scope of this thesis

This thesis describes the development of a general system for estimating and monitoring carbon stocks and carbon stock changes in stump systems at a national scale for reporting under the UNFCCC (United Nations Framework Convention on Climate Change) and the KP (Kyoto Protocol) (Paper I). In the estimates of carbon stock development over time, an empirical decomposition function for stumps and roots was needed, and so was developed as part of the thesis (Paper II). Furthermore, the general system developed was used to investigate the role of stumps as sources of bioenergy or sinks of carbon in Swedish forests in a climate change mitigation context. The carbon balance trade-offs between bioenergy and carbon sequestration were examined over varying time scales and harvest intensities, and special emphasis was given to comparisons of carbon emissions from combusting stumps from long-rotation forestry versus coal (Paper III). The positive and negative environmental effects of stump harvesting were investigated with a special focus on nutrient loss and its effects on future sustainability (Paper IV).

1.2 Climate strategies and policies

1.2.1 Global level

Currently we know that it is “extremely likely that human influence has been the dominant cause of the observed global warming since the mid-20th century” (IPCC, 2013). To keep global warming below 2°C, the world will need to reduce its emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG) by 50% before 2050 compared with 1990 levels (IPCC, 2013). Developed countries will need to reduce more – by 80 – 95% by 2050. There are multiple international responses to climate change in a climate strategy context; a major international attempt to coordinate climate change mitigation is the foundation of the UNFCCC and the adoption of its supplementary Kyoto Protocol (KP) in 1997. The KP legally binds developed Annex I parties to cap their emissions, while parties in transition, which constitute major parts of South America, Africa and Asia (including the growing economies India and China), have no binding emission targets. Currently, there are 195 parties to the convention and 192 parties to the KP, with the second period of KP 2013 – 2020 in operation. In the second period, Australia and the EU countries have binding emission reduction targets; however, important emitters such as Russia, Canada and USA have no binding targets. To achieve a significant reduction of emissions, binding targets are needed at a global level, and there are large expectations of a new international, legally-binding climate commitment, for all UNFCCC countries, scheduled to be agreed in 2015 and implemented in 2020 when the second KP period ends.

1.2.2 EU level

Outside the KP, the EU has committed itself to major emission reduction targets. The EU's climate and energy strategy aims at a reduction of GHG emissions by 20% compared to the 1990 level and to increase the share of renewable energy to 20% by the year 2020. In the climate and energy policy framework for 2030, the European Commission has proposed that the EU should set a target of reducing emissions by 40% below 1990 levels. For 2050, EU leaders have endorsed the objective of reducing Europe's GHG emissions by 80 – 95% compared to 1990 levels as part of an effort to convince developed countries, as a group, to reduce their emissions to a similar degree. Furthermore, the EU has adopted the Renewable Energy Directive 2009 (RED) (EC, 2009). Through the adoption of RED, each member state is obliged to have National Renewable Energy Action Plans (NREAP) that describe how the country will reach its binding 2020 targets for the proportion of their total energy consumption produced as renewable energy. Forest-based bioenergy is a source with large potential, and plays a central role in many NREAPs. Another important instrument for reducing emission and promoting bioenergy within the EU is the EU emission trading system (EU ETS) that was implemented in 2005 (Zetterberg, 2011).

1.2.3 Swedish level

Besides the international emissions reduction targets, Sweden also has emissions reduction targets at a national level. By 2020, 50% of energy should come from renewable energy sources, and the vision for 2050 is zero net emissions (SEA, 2012b). In 2013, 51% of energy came from renewable sources and, thus, this target has been reached seven years earlier than planned

(Regeringskansliet, 2013). At the beginning of the 1990s, Sweden introduced taxes on CO_2 emissions and increased energy taxes, but bioenergy is exempt from both these taxes, thus promoting the use of bioenergy in Sweden. The introduction of electricity certificates in 2003, has also favored the use of bioenergy (SEA, 2013).

1.3 Greenhouse gas emissions and reporting

Parties are obliged to report annually under the UNFCCC and the KP (IPCC, 2003). The developed countries (Annex 1) should provide national GHG inventories covering emissions and removals of direct GHGs for six sectors (Energy, Industrial processes, Solvents, Agriculture, Waste, and Land-Use, Land-Use Change and Forestry (LULUCF)), from 1990 onwards. Within the LULUCF sector, removals and emissions arising from changes in carbon pools are reported separately for each land-use category (UNFCCC: Forest land, Grassland, Cropland, Settlements, Wetlands and Other land) or for each activity (KP: e.g. Afforestation, Deforestation and Forest management). The reported carbon pools are aboveground biomass, belowground biomass, dead wood, litter, and soil organic carbon. The EU has signed the UNFCCC/KP as a Party, and thus, all member states have to support the EU with national data in addition to a separate national report directly to the UNFCCC secretariat.

The IPCC (e.g. 2003, 2006 and 2013) has reporting guidelines that state that stumps with corresponding roots should be reported and classified as either dead organic matter or dead wood – or, if living, as aboveground biomass (stump part) and belowground biomass (roots) (IPCC, 2006). However, so far, the IPCC has not produced a specific guideline for reporting stump wood.

For most Parties, LULUCF reporting is based on data from a National Forest Inventory (NFI) (Cienciala *et al.*, 2008). Estimates are sometimes based on combinations of data from field inventories and remote sensing. One way of modeling carbon in stumps and roots is to estimate the input to the carbon pool from harvest statistics. The output from the pool is then estimated based on modeled decay. If the decomposition rate is assumed to be slow, it is important to use long time series to reflex fluxes in carbon originating from stumps from historical harvests. Reported carbon stock change in stumps has also been modeled using process-based model Yasso by Finland and Norway (Anon., 2014; NEA, 2014).

1.3.1 Swedish NFI and reporting

The Swedish NFI has been monitoring permanent plots since 1983, when a systematic grid of approximately 30 000 permanents plots was implemented.

Among many variables measured on the plots, trees are callipered and positioned (Fridman *et al.*, 2014). The permanent plots are repeatedly inventoried, normally over a five year inventory cycle. Thus, from 1983 onwards, the possibilities to monitor carbon stock changes have improved due to the repeated measurements on the same plots. One advantage of the Swedish NFI-based system for carbon reporting is that the NFI covers all land-use categories and thus the carbon stock changes linked to land-use changes can be monitored. The trees are positioned and thus it is possible to match the biomass of trees and stump systems and to trace all kinds of changes back to the base year of KP (1990).

Estimates are based on sampling theory and each sample unit represents a certain area; all sample units together represent the total area of Sweden (Fridman *et al.*, 2014). On the sample units (a cluster or tract of sample plots, in total approximately 4000 tracts), the biomass of trees is estimated using allometric empirical regression models (Marklund, 1988). To be able to make estimates at a national scale for fresh stumps and roots, biomass functions have been developed and used for estimates of belowground biomass of Norway spruce and Scots pine stumps (Petersson & Ståhl, 2006); these species account for 40.9% and 39.2% of the standing volume on all land-use classes in Sweden, respectively (SLU, 2013). Species and stem diameter measured 1.3 m above the ground are the most important independent variables in the functions. Since approximately 80% of the standing volume is made up of Norway spruce and Scots pine and these species do not sprout from stumps, all stumps are considered dead and are assumed to have started decomposing in the same season as the harvest. A decomposition model for stump and roots systems only exist for Norway spruce and this model (Paper II) is applied to all species. Finally, biomass (dry weight) is converted to carbon by multiplying by 0.5 (Sandström *et al.*, 2007) and converted from carbon to carbon dioxide by multiplying by 44/12 (stoichiometric ratio C=12, O=16).

1.4 Decomposition models and carbon modeling

In order to study the development of carbon pools such as stumps and roots, there is a need to model the decomposition rate to investigate how long it takes for the carbon to decompose and either become part of the soil organic carbon pool, or leak into water or be emitted as CO_2 into the atmosphere. Most studies of the decomposition process of wood are from the perspective of dead wood aboveground, and the decomposition of aboveground wood is affected by factors such as temperature and moisture and their effects on decomposers (Mackensen & Bauhus, 1999). Other factors that affect the decay rate are related to substrate quality such as the ratio of bark to wood (Fahey *et al.*, 1988), proportion of sapwood and heartwood and tree species (Harmon *et al.*, 2000). Slope aspect (Harmon *et al.*, 1986) and log diameter (MacMillan, 1988) may also influence decay rate. However, there are also studies that have shown no relationship between decay rate and the size of coarse woody debris (Shorohova & Kapitsa, 2014).

The need for modeling decomposition of soil carbon arises from a need to understand general ecological soil processes, such as the nitrogen and carbon cycles in the ground and their importance for site productivity. The carbon and decomposition model Yasso is a dynamic process-based model applicable from stand level to national level (Liski *et al.*, 2005). The Yasso model takes into consideration some aspects affecting decomposition, e.g. type of litter, temperature and drought index (Ibid). The Q model is also a process-based model and predicts the carbon and nitrogen levels in the forest litter layer and the humus layer for a defined time period (Ågren *et al.*, 2008). These kinds of models are often complex, which means, in turn, that they are not easy to build, implement, interpret and update when needed. Thus, empirical decomposition models may sometimes be more suitable for deterministic predictive purposes.

The modeling of tree growth has a longer history than that of modeling wood decomposition. Therefore, it would be convenient to draw some parallels between the advantages and disadvantages of different categories of tree growth models with decomposition models. Kimmins (1989) proposed dividing models into two categories: knowledge-based and experience-based. Knowledge-based models (also called process-based models) have either been too simplistic, or too complex with a large requirement for calibration data that has limited their usefulness in practical applications. Therefore, these models are best used for explaining the processes behind the focus of the modeling and to explain ‘how things work’. The experience-based models (also called empirical or deterministic models), on the other hand, are often preferred when predicting future outcomes, e.g. simulation of tree growth (Vanclay & Skovsgaard, 1997). These models are often more transparent and robust. The limitations of empirical-based models are that the growth model developed from the empirical dataset is limited to the actual area where the data were sampled, and also, it is not recommended to make predictions under changing conditions. If the model is extrapolated, one must carefully evaluate whether or not the extrapolation yields relevant predictions (Kimmins et al., 2008). One way of gaining from the advantages of both process-based and empirical-based models is to set up a hybrid combination of the two categories (Gustafson, 2013; Kimmins, 1989).

The most commonly used model form used to estimate the decline of density or biomass of aboveground woody debris is the negative exponential model (Chen *et al.*, 2005; Ganjegunte *et al.*, 2004; Mackensen *et al.*, 2003b; Mackensen & Bauhus, 2003a; Naesset, 1999; Harmon *et al.*, 1987), but there are other options. The multiple-exponential model takes account of the fact that the substrate is not homogeneous, and that different components might decompose at different rates (Mackensen & Bauhus, 2003a). The lag-time model is based on the observation that decay is slow during the initial stage of decomposition until decomposers have become established within the substrate (Harmon *et al.*, 1986). The choice of independent variables in deterministic models is restricted to easily measured and robust variables. Usually when using such models, the remaining biomass is modeled by a variable correlated to the initial size of the stump system, time since death and species (Shorohova *et al.*, 2008; Yatskov *et al.*, 2003; Harmon *et al.*, 2000; Naesset, 1999; Krankina & Harmon, 1995).

Decomposition models for belowground coarse wood are sparse and only very few examples can be found (Olajuyigbe *et al.*, 2012); no models appear to be available for the entire stump-root system, i.e. including both aboveground and belowground parts. Thus, for practical applications linked to the reporting of LULUCF and CO_2 emissions there was a need to develop an empirical model of that kind. Within the framework of this thesis, an empirical model for stump and root systems has been developed using the negative exponential model (Paper II).

One thing that might be both convenient and important to remember for constructors of models: “Essentially, all models are wrong, but some are useful!” (Box & Draper, 1987).

1.5 The role of forests in climate change mitigation

In 2007, IPCC reported that land-use change, mainly deforestation, is the cause of 20% of all anthropogenic emissions, while emissions from fossil fuels, agriculture, industrial processes, use of solvents, concrete production etc. make up the other 80%. However, in the last IPCC report, land-use change and deforestation were recognized as being responsible for the emission of less than 10% of the GHGs (IPCC, 2013). This trend shows that although the use of bioenergy has increased during 2007 – 2012 (Bowyer, 2012), the emissions from land-use change have decreased. This corresponds to findings by FAO, in its global forest resources assessments (FAO, 2010), and by Pan *et al.*

(2011), who showed that at a global level forests have functioned as a large carbon sink during 1990 – 2007.

Forest and bioenergy strategies contribute to the reduction in the net flow of CO_2 emissions to the atmosphere through four mechanisms: i) storage of carbon in the biosphere; ii) storage of carbon in harvested wood products (HWP); iii) use of biofuels e.g. slash (branches and crown mass) and stumps, to replace fossil fuels and iv) use of wood products instead of products that require more fossil fuels (or concrete) for their production (Schlamadinger & Marland, 1996). In this thesis, the mechanisms (i) and (iii) are studied, with a special focus on stump and root biomass. The storage of stump carbon in the biosphere and the substitution of fossil fuels by stump and root biomass originating from long-rotation forestry are studied, and also the trade-off between the two mechanisms.

1.5.1 Forest as carbon storage in the biosphere or as bioenergy

As many countries attempt to reduce GHG emissions to mitigate climate change, there is increasing interest in the use of forest biomass for bioenergy to offset energy from fossil fuels (Ximenes *et al.*, 2012; IPCC, 2011; Berndes & Hansson, 2007; Björheden, 2006), particularly in countries with no or limited fossil fuel resources but large forest resources. It has been shown that management of forests for production has the potential to generate greater greenhouse mitigation benefits than managing for conservation alone (Ximenes *et al.*, 2012; Lippke *et al.*, 2011; Eriksson *et al.*, 2007; Schlamadinger & Marland, 1996). At the same time, there are proposals to protect forest land as carbon reservoirs, also for mitigating climate change (Pan *et al.*, 2011; Luyssaert *et al.*, 2008; Carey *et al.*, 2001; Harmon *et al.*, 1990). Other studies show that young forest grows faster and captures more carbon than old growth forest (Law *et al.*, 2013), and old growth forest may even be a net source of carbon to the atmosphere (Chen et al., 2004), strengthening the arguments for the use of forest biomass for bioenergy.

1.6 Bioenergy

Bioenergy is energy derived from biomass. Biomass may either be directly converted into energy or processed into solids, liquids or gases. Biofuels are solid, liquid or gaseous fuel produced directly or indirectly from biomass. Wood fuels are all types of biofuels originating from woody biomass. An important sub-category of wood fuels is forest fuels, which are produced directly from tree biomass by mechanical processes; the raw material has not previously had any other use (ISO, 2014).

1.6.1 Global level

GHG emissions associated with the provision of energy are a major cause of climate change (IPCC, 2011) and there are high expectations for the use of bioenergy from both climate and sustainability perspectives. Many projections at a global level imply at least a doubling of the total harvest of world plant material for bioenergy purposes. For example, the International Energy Agency has projected that the share of the bioenergy resource could supply over 20% of the world's primary energy by 2050 (IEA, 2008). The IPCC Special Report on Renewable Energy suggests that the global bioenergy potential could be as high as 500 EJ y^{-1} (IPCC, 2011), comparable to the level of current fossil fuel use. This can also be compared with the global biomass harvest for food, feed, fiber, wood products, and traditional wood use for cooking and heat, which amounts to approximately 230 EJ yr^{-1} (Krausmann et al., 2008), around half of the projected bioenergy potential. On a global basis, it is estimated that renewable energy (RE) accounted for 12.9% of the primary energy supply in 2008 and the largest RE contributor was biomass (10.2%) (IEA, 2010).

1.6.2 EU level

The pressure on the bioenergy market is likely to increase due to major developments in the climate change policy field, e.g. the Europe 2020 strategy and EU's RED. Forest biomass is currently the most important source of renewable energy and accounts for around half of the EU's total renewable energy consumption (EC, 2013b). According to forecasts by UNECE/FAO (2011), the use of wood fuels is predicted to more than double in the period 2010 to 2030 in the EU. Examining the forest growing stock at the EU level confirms a growing wood fuel potential: during 1980 – 2010, the stock increased (Figure 1), and many countries more than doubled their growing stock over this period (FAO, 1980-2010). The current potential for bioenergy varies from 800 and 6000 PJ yr^{-1} (1 PJ = 0.278 TWh) in different analyses (review by Bentsen and Felby (2012)). In 2010, the gross final energy consumption reached 50176 PJ (EC, 2013a).

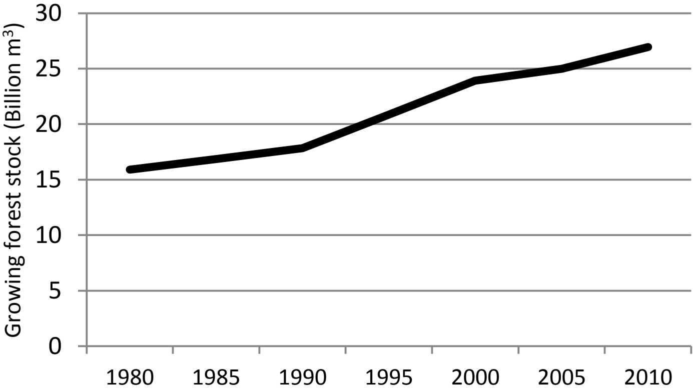

Figure 1. Total growing forest stock in Europe, excluding former Soviet Union, from 1980 to 2010. For Sweden, the growing stock increased by 43% over this period (FAO, 1980-2010).

1.6.3 Swedish level

Currently, Sweden has 28.1 million hectares (69% of the land area) of forest land and 23.1 million hectares (57% of the land area) of productive forest land. This makes Sweden, together with Finland, two of the most forested countries in EU. The Swedish forest area constitutes 18% of the total forest area in EU27 (SLU, 2013; Anon., 2011). This makes Sweden an important player with respect to wood fuel production within the EU.

The most important sources for bioenergy in Sweden are traditional biofuels such as by-products from the forest industry, e.g. the so-called black liquor and slash. However, there is potential to utilize more (SFA, 2008), and focus has been turned to new assortments such as the use of stumps for bioenergy purposes (Björheden, 2006). The use of bioenergy (including peat and waste) was 10% of total energy use or 173 PJ in 1980. In 2011, the use of bioenergy increased to 23% of total use or 475 PJ (20% from forest, 3% from peat and waste). The projected stump wood potential was 75 PJ in 2010 (SFA, 2008), which is 3.6% of the total supply to the energy system in Sweden during 2011 (2077 PJ) (SEA, 2013). In Sweden, the biofuel potential, primarily based on biomass, is expected to increase by 122 PJ over the period 2007 – 2030 (SEA, 2012a).

There is also forest fuel potential from young dense “clearing stands”, and it is an open question whether or not future first thinning stands will be harvested for pulp production (as at present) or bioenergy (Nordfjell, 2008). Thus, there is a need to further analyze the potential for increased use of bioenergy and also the consequences of such an increase.

1.6.4 Stump harvesting practices

Historically, stumps have been harvested for tar production since the 1600s in Sweden and Finland. Especially during the 1800s, tar exports from Sweden and Finland were considerable (SFA, 2009). In the 1970s and 1980s, Sweden and Finland experimented in using stumps to obtain fiber for the pulp and paper industry. This practice stopped due to problems with excessive mineral concentrations in the substrate. Stump harvesting was revived in 2001 for the generation of power in paper mills in Finland (Kalliola, 2004).

In British Columbia, Canada, stump harvesting has traditionally been carried out for root rot control with stump systems often being left exposed on-site or moved to the road side and only occasionally burned (Berch *et al.*, 2012). Currently, there is an increased demand for forest biomass to use for energy. Those stumps already extracted to inhibit root rot might be an important feed stock for use as fiber for pulp and paper, and energy (Ibid).

The United Kingdom has been investigating stump harvesting as an opportunity to reduce GHG emissions by using stumps as fuel in order to fulfill the requirements specified in the RED (Walmsley *et al.*, 2011) and, at the same time, reduce root rot (Persson, 2013).

In the northwestern United States, removal of infected stumps has been carried out for many years to eliminate root rot in Douglas fir and other conifer species forest. In so doing, the disease has been reduced in succeeding stands (Zabowski *et al.*, 2008).

In Finland, the government gives subsidies for stump harvesting (Walmsley & Godbold, 2010), which may be the main reason for the expansion of this field. In the early 2000s, Finland started stump harvesting on a large scale (5000 m^3 stump forest chips consumed by heating and power plants); by 2010, 1 million m^3 stump forest chips were consumed in heating and power plants (Metla, 2013).

In Sweden, stump harvesting has not yet evolved from the pilot level. In 2009, the SFA concluded that stump harvesting will likely not exceed 10 000 – 20 000 ha (5 – 10%) of the annual regeneration area (SFA, 2009). However, since then, stump harvesting has not expanded this much. Various aspects have affected the somewhat weak development of stump harvesting in Sweden. The Swedish Forest Stewardship Council (FSC) has a major influence on the future of stump harvesting, since almost all of it is carried out by FSC certified companies. From 2011 to 2013, the stump harvested area in Sweden decreased from approximately 1700 ha to 800 ha in FSC certified forest, although up to 2500 ha yr^{-1} was allowed on such land. There are several reasons for this decline. FSC Sweden is cautious about approving the applications from FSC companies for stump harvesting (Kårén, 2014) and this reduces the companies’ interest in stump harvesting since they simply do not know if it will be allowed. Also, during warm winters (such as in 2013/2014), the demand for forest fuel decreases, and as stumps are more expensive to harvest than other forest fuels (stems and slash), stumps will be the first resource not to be harvested. In 2014, heavy storms, snow and bark beetle pests in middle Norrland (central Sweden) caused lower quality wood to be produced which the pulp and timber industries were not interested in. Thus, the supply of relatively cheap aboveground wood increased and made harvesting stumps for forest fuel less attractive. The decreased demand for paper, especially newspaper, also has an impact on the wood market. First, pulpwood has been used as forest fuel, thus reducing the pressure on the forest sector to harvest more woody biomass. Second, an indirect effect has been the reduction in electricity demand from the pulp and paper industries, reducing the demand for forest fuel even more. The increased supply of recycled wood may also have affected the market (Hofsten, 2014). Generally, the stump resource has low value and a high cost of harvesting, making stumps less competitive than e.g. slash. Due to all these reasons, the future of stump harvesting in Sweden is, at the time of writing, uncertain.

1.7 Environmental effects of stump harvest

There are many environmental concerns to take into consideration before stump harvesting. In the following section, the focus is on how to maintain a sustainable wood yield whilst retaining the carbon capture capacity in the production forest by preserving soil carbon, carbon stock and nutrient concentrations in the ground. Some possible negative impacts for biodiversity, methyl mercury flow, soil compaction and erosion, are also briefly discussed, along with possible positive impacts on the survival of plants and regeneration.

1.7.1 Evaluating the risks of loss of nutrients and carbon and its influence on sustainable yield

Nitrogen: In the boreal forest, N is typically the growth-limiting nutrient (Hyvönen *et al.*, 2007; Bonan & Shugart, 1989; Mälkönen, 1976), and thus also determines carbon sequestration abilities. External inputs of N arise from deposition and, to some extent, biological N fixation; fertilization is quite uncommon. In Sweden, the deposition of N varies, with more in the south than in the north (Pihl Karlsson *et al.*, 2013). The availability of N for tree growth is also determined by the amount of N released and immobilized in decomposition of soil organic matter. The CN ratio of the decomposing litter or residue largely determines whether N is mineralized and becomes available for uptake by vegetation (low CN ratio) or is immobilized by decomposers (high CN ratio) (Brady & Weil, 2008). Not only does the CN ratio have a large effect on the decomposition of soil organic matter and mineralization of N but so does the lignin (L) content or the LN ratio of litter (Prescott *et al.,* 2000).

It is often the case that, before stump harvesting, the harvesting of slash takes place (SFA, 2009). From a N perspective, there is a higher risk of loss of N after harvesting of slash since, for pine and spruce stumps, the N concentration (0.6 – 1.1 mg g^{-1}) is very low compared to foliage (9 – 11 mg g^{-1}) or branches (3 – 4 mg g^{-1}) (Persson, 2013; Palviainen *et al.,* 2004). However, stump harvesting after whole tree harvest (WTH) did not affect the total amount of nitrogen in the soil organic layer (Karlsson & Tamminen, 2013) and, in the mineral soil layer, the amount of nitrogen increased after stump harvesting compared to stem-only harvesting (SOH) (Kataja-aho *et al.*, 2012). These studies indicate that there is no severe risk of N loss from additional stump harvesting after harvesting slash. However, if the soil is low in N, it might be relevant to add N using fertilizers after harvesting of forest residues (SFA, 2002).

Phosphorus and base cations: The supply of plant-available mineral nutrients, primarily Ca, K and Mg, is ultimately related to the weathering of soil minerals (Palviainen & Finer, 2012; Likens & Bormann, 1995), especially in areas with low atmospheric deposition such as the Nordic countries (Ruoho-Airola *et al.*, 2003). Ca and Mg are both relatively abundant in forest soil, both in minerals and in water soluble cation form, with only a small fraction of the base cations bound into the vegetation (Likens & Bormann, 1995). K is not incorporated into any structures within the soil complex but remains, instead, in ionic form in the plant material, thus making it a more mobile nutrient than Ca and Mg (Brady & Weil, 2008). P and K are rapidly released from the decomposing logging residues after clear-cutting (Fahey *et al.*, 1991), whereas Ca is released relatively slowly (Olsson *et al.*, 1996), especially from woody litter meaning that branches could serve as a long-term source of Ca to vegetation (Fahey *et al.*, 1991). Few studies have investigated how the nutrient and base cation concentrations in the soil respond to stump harvesting. However, there are studies examining the effects of SOH and WTH. Several studies have shown that WTH has negative effects on soil base cation pools and P (Brandtberg & Olsson, 2012; Saarsalmi *et al.*, 2010; Wall, 2008; Thiffault *et al.*, 2006; Rosenberg & Jacobson, 2004), but there are also findings showing that after WTH, some base cation pools have increased at some sites (Karlsson & Tamminen, 2013; Saarsalmi *et al.*, 2010; Thiffault *et al.*, 2006). When harvesting forest residues rich in nutrients, there is also a potential risk of acidification of the soil. When removing base cations (Ca, Mg and K), the buffering capacity of the soil is reduced and acidification may occur (Olsson *et al.*, 1996). However, Karlsson and Tamminen (2013) showed that the pH did not change significantly in the soil organic layer after stump harvesting, which indicated that the buffer capacity of the base cations was not largely affected. However, another study by Iwald *et al.* (2013) indicated that stump harvesting was responsible for 13 – 24% of total excess base cation extraction, depending on harvesting intensity and tree species. Harvesting of logging residues made up as much as 27 – 45% of the total net base cation extraction, which can be explained by the higher content of base cations in needles and branches than in stumps. Thus, from a strict base cation perspective, stumps are better for use as bioenergy than logging residues (Iwald *et al.*, 2013; Persson, 2013). It should be remembered that the nutrient concentration varies within the stump and root system harvested. Studies have shown that nutrient levels in coarse roots are higher than in stems and lower than in foliage. However, small roots have high nutrient concentrations (Helmisaari *et al.*, 2009; Ingerslev, 1999; Thelin *et al.*, 1998; Rosengren-Brinck & Nihlgard, 1995), and should be avoided at stump harvesting.

Carbon: By harvesting stumps, there is a potential risk of decreased soil C and carbon in the ecosystem. There are many causes of such potential reductions in carbon. One reason is the immediate reduction of carbon at harvest time, and the loss of input from decomposing stumps. Another is soil disturbance and mixing which increase aeration and expose new surfaces which, in turn, lead to increased CO_2 emissions. Furthermore, the non-tree vegetation input to the soil organic matter may also be affected by stump harvesting and thus affects the soil C over a rotation period (Eliasson *et al.*, 2013; Persson, 2013). At the same time, the CN ratio will be changed and this might influence decomposers of soil organic matter.

Some studies of the effect on carbon stock after stump harvesting have been carried out. Predictions of carbon storage in growing stock over two simulated rotation periods showed no negative effect after stump harvesting (Alam *et al.*, 2013). Levels of soil carbon were unaffected by stump harvesting in the study by Karlsson & Tamminen (2013). However, Strömgren *et al.* (2013) found that stump harvesting resulted in a lower C stock in the soil organic layer, compared with conventional stem harvesting, 25 years after the harvest (no effect on the mineral soil layer was found). However, studies over an entire rotation period would be needed to determine whether or not this would be maintained as the remaining stumps and logging residues continued to decompose and the regenerated stand developed (Ibid). Another study showed that CO_2 flux or soil decomposition processes two years after soil disturbance as a result of stump harvesting or harrowing (conventional scarification method) was equal or 10% higher, respectively, compared to patch scarification (Strömgren & Mjöfors, 2012). However, from a short-term perspective, the effect of stump harvesting on CO_2 flux or soil decomposition processes were small or absent compared to site preparation such as mounding (Strömgren *et al.*, 2012). Neither of the studies found clear evidence of a major effect from stump harvesting on soil C or ecosystem carbon stock.

Conventional soil preparation using mounding often results in a disturbance of 20 – 30% of the soil surface, whereas the corresponding figure for stump harvested areas is 40 – 90%. Naturally-regenerated seedlings have a 50% higher probability of surviving in a stump harvested area than after conventional soil preparation (Kardell, 1992). Also, the long-term effect (33 years) was an improved survival of planted trees and an increase in natural regeneration after stump harvesting, compared to conventional stem harvest with removal of logging residues (Karlsson & Tamminen, 2013). Few studies have been carried out into stump harvesting and soil compaction. One study argued that if stump harvesting is carried out carefully, it only disrupts the soil surface soil layers (Walmsley & Godbold, 2010; Hope, 2007).

Another factor that influences forest growth and future sustainable yields in productive forests is root rot. Fungal pathogens residing in roots and stumps can remain viable for decades after final felling and put stands at an increasing risk of infection in subsequent rotations. Stump removal is one strategy that can be used to reduce the impact of root rot fungi in regenerating stands (Cleary *et al.*, 2013; Persson, 2013; Vasaitis *et al.*, 2008; Stenlid, 1987).

1.7.2 Other environmental aspects of stump harvest

Coarse woody debris is an important substrate for many species such as mosses, lichens and insects (Stokland *et al.*, 2012). For instance, stump extraction has been shown to reduce the number of species of saproxylic beetles (Victorsson & Jonsell, 2013). Persson *et al.* (2013) identified six species of macro arthropods, highly dependent on the bark and wood of spruce and pine stumps, whose populations would therefore probably be reduced by stump harvesting. Furthermore, stumps are an essential habitat for certain lichens and bryophytes (Caruso, 2008; Rudolphi, 2007). One could also argue that, due to the extended forest management in forested countries such as Sweden, there is unlikely to be a lack of stumps. In 2011/12, 91.3 million m^3sk were harvested in Sweden by thinning (364 000 ha), cleaning (262 000 ha) and final felling (186 000 ha) (SLU, 2013), which, in turn, resulted in a large number of stumps.

Forest operations may increase the total mercury (THg) and methylmercury (MeHg) run-off in catchment streams and biota (Eklöf *et al.*, 2014), however little is known about the relative contribution of different forest practices (Ibid). A study by Eklöf *et al.* (2013) showed no difference in mercury concentrations between run-off water from stump harvested areas and areas treated with ordinary site preparation compared to reference areas. The study indicated that the mercury concentrations were more dependent on organic carbon, hydrology, temperature and initial logging rather than on the soil disturbance caused by either stump harvesting or site preparation (Eklöf *et al.*, 2013; Persson, 2013).

2 Objectives

The overall objective of this thesis was to examine the potential for Swedish stump harvesting in a Swedish and European climate change mitigation context. Furthermore, this work aimed to develop a general system for estimating and monitoring carbon stocks and carbon stock changes in stump systems at a national scale. This system is used for evaluating the role of stumps as sources of bioenergy or sinks of carbon in Swedish forests in a climate change mitigation context. The carbon balance trade-offs between bioenergy and carbon sequestration over varying time scales and harvest intensities is analyzed, with special emphasis on comparing benefits from the long-term substitution of coal for energy with the combustion of stumps. The positive and negative environmental effects of stump harvesting are also investigated with a special focus on nutrient loss and its effects on future sustainable yield and carbon capture capacity.

The specific objectives of papers I – IV were:

Paper I: To develop a general system for estimating and monitoring carbon and carbon stock changes in stump systems at a national scale.

Paper II: To develop an empirical decomposition model for Norway spruce stumps and roots.

Paper III: To assess the carbon balance trade-off over time between the use of stumps for bioenergy at different harvest intensities, and the use of stumps for storing carbon. The substitution effects of using stumps rather than coal as an energy source were also investigated.

Paper IV: To evaluate the concentration of nutrients in stumps and coarse roots of Norway spruce, Scots pine and Silver birch in Sweden, Finland and Denmark, and to assess how nutrient concentrations vary with site characteristics, stand age and root size.

3 Material and Methods

3.1 Estimating the biomass and carbon pool of stump systems at a national scale (Paper I)

Paper I describes a study of the influence of storing carbon in stumps and roots from a carbon budget perspective, and to what extent different assumptions in the modeling, such as length of historical harvesting records used, may affect the results. A sensitivity analysis of how the assumed decomposition rate of stumps and roots may affect the results was also carried out. The paper develops and evaluates a system for estimating and monitoring the carbon in stumps and roots at national scale.

The biomass originating from the stump and root systems of dead or harvested trees before the start of inventorying permanent NFI plots (in 1983) also constitutes part of the current carbon pool and was predicted separately using two different data sources. The first source of data was the temporary plots of the NFI (sample plots inventoried only once, in our case utilizing plots from 1956 onwards). The second source was round-wood production statistics published by the SFA (from 1853 onwards, but with higher accuracy from 1944 onwards). For the first data source (temporary plots), no data at the level of individual trees were available (as for permanent plots). Instead, stem volume was converted to biomass of stump systems. Estimates were based on aboveground stem volumes (Näslund, 1947) of harvested trees, and trees that had died due to natural causes. We used NFI data in terms of five-year averages from 1956 onwards; to obtain the biomass of stump-root systems a conversion factor was applied to the aboveground volume estimates. The conversion factor was derived by applying the models by Marklund (1988) and Näslund (1947) on data from the Swedish NFI during the period 1998/2002. The result was that 1 m^3 stem-wood corresponded to 166 kg stump and root system biomass. These historical stump-carbon estimates were then combined with data from the permanent plots (established 1983 – 1987) to account for the decomposition of stumps from 1956 to 1983.

For the second data source, the same conversion factor was used, with estimates of stem-volume carbon based on gross total cuttings, considering also natural mortality, using data from the SFA (2009). For both data sources, decomposition of stump and root systems was modeled by a function developed in paper II. Estimates of biomass (dry weight) were converted to C by the factor 0.5 and further to CO_2-equivalents by the stoichiometric ratio 44/12.

For prediction of carbon in stump systems produced from 1983 and onward about 30 000 permanent sample plots from the Swedish NFI were used. The sample plots have been inventoried every 5 – 10 years, and consistently every 5 years since 2003. Within each sample plot, among several parameters, stem diameter, species and spatial positions have been recorded. Stem diameters larger than 99 mm (measured 1.3 m above ground) were considered in the study. The stem diameters of harvested trees were estimated by extrapolating from their last known diameter recorded in a previous inventory, to the time of harvest, using data of incremental growth from permanent NFI sample plots. The biomass of the stump system at death or harvest was thereafter estimated from allometric biomass functions, using stem diameter and species as independent variables. In the calculations of biomass of a stump system, all roots >2 mm were included and the stump was assumed to be 1% of the tree height (Petersson & Ståhl, 2006). After trees were harvested, or had died naturally, the decay of the remaining biomass was modeled for all species with the decomposition function developed in paper II.

To improve the estimates of core forest parameters, such as above- and belowground biomass, the Swedish NFI has divided the country into 31 strata. Within each stratum, the area has been divided into 16 national land-use categories, with the carbon stock and carbon stock change estimated for each relevant category. The Swedish 16 national land-use categories have been transformed into the six broad land-use categories of IPCC (2003).

Statistical estimators corresponding to the NFI design (Fridman *et al.*, 2014) were used to quantify the carbon stock and the change in carbon stock within each stratum and land-use category. The area-based sample design of the Swedish NFI is constructed as stratified systematic clusters. Area-based sampling implies that the biomass, in our case on a single sample unit (a cluster, or Tract, of sample plots), represents a certain area, and all sample units taken together give the biomass of the total land area of Sweden. Thus, by using area sampling and data from permanent sample plots, it was possible to estimate both the total carbon pool of stump systems in Sweden, and changes in it.

3.2 Decomposition of stump and root systems of Norway spruce in Sweden – A modeling approach (Paper II)

Data set: To improve the predictions of stump decomposition in the system for estimating and monitoring carbon stocks and carbon stock changes, derived in papers I and III, the work of paper II aimed to develop a decomposition model for Norway spruce stumps and roots in Sweden. To do this, a sample of Norway spruce stumps and roots from southern (Asa) and northern Sweden (Vindeln), was analyzed. 71 stumps with roots, fresh and decomposed, were collected from 18 stands: nine in Asa and nine in Vindeln. At both locations, the stands were subjectively selected on the basis of the following criteria: the soil class had to be sandy to gravel moraine; before cutting, Norway spruce had to be the dominant species, and the variation in time since cutting had to be 1 – 39 years. We assumed that our selected stumps constituted a random sample of all the original stumps, and also that all stumps up to 39 years old were still present. Our assessment was that it was possible to determine the original diameter of all stumps. To complement the dataset, 28 fresh stumps with roots used previously in a study by Petersson and Ståhl (2006) were added. These stumps were sampled at the same locations, with the exception of 6 stumps sampled in central Sweden (Jädraås). Thus, in total 99 stump systems were used in the study.

Field work: Within each stand, two single starting points were selected subjectively by the field team. From these points, a search direction was randomly selected; moving in this direction, the first Norway spruce stump found that had a perpendicular stump diameter of 20 – 50 cm, was sampled. Within each stand, up to eight samples were collected with the restriction that sampled stumps should be at least 20 m apart.

In the field, the decomposition class of the stump was determined using the decay class system developed within the Swedish NFI. Subsequently, one quarter of the stump cross-sectional area was randomly selected. This part of the stump was excavated together with one of the roots originating from this part of the stump; this root was also randomly selected and traced until its diameter was approximately 1 cm. All roots originating from the sampled stump section were revealed and the diameter of the base of each root was measured. The roots were assumed to have the same decomposition class as the stump. A chain saw or hand saw was used to remove the root from the stump and hand tools were used during the excavation of roots.

In the laboratory, the samples were dried at 85°C until they had constant dry weight for at least 48 hours. To calculate the total biomass of the stump and root systems, the dry weight and cross-sectional area of the sampled stump sector were measured, and the dry weight of each non-sampled stump sector was assumed to be proportional to its measured cross-sectional area. To estimate the dry weight of the remaining roots, which were not sampled and for which only diameters were measured, simple regression functions were developed, one for each decomposition class. The diameter over bark where the root was attached to the stump was used as an independent variable in the functions. As for the non-sampled stump sectors, the roots not sampled were assumed proportional to the cross-sectional area of the stump they originated from.

3.2.1 The decomposition model

The remaining dry weight, (DWt, [g]), was modeled by the negative exponential model using stump diameter and the number of years since cutting as independent variables (Eq. 1):

$$DW_t = \beta_0 \times dia^{\beta 1} \times e^{\beta 2t} \times \varepsilon, \qquad (1)$$

where dia is the stump diameter [cm], t is the number of years since cutting, and β_0, β_1 and β_2 are parameters; ε is a random error assumed to be log-normally distributed. For linearization, the model was transformed using natural logarithms:

$$\ln DW_t = \ln\beta_0 + \beta_1 \ln dia + \beta_2 t + \ln \varepsilon \qquad (2)$$

This model (Eq. 2) was used in the regression analysis, using ordinary least squares regression. The statistical analyses were conducted using the Statistical Analysis Software (SAS Institute Inc. 2004).

However, diameter measurements for individual stumps are not always available; in this case it might be convenient to develop a stump size independent decomposition model. Thus, we selected a model form where the decay rate is independent of stump diameter, i.e. if $t=0$ is inserted in Eq. 1, ignoring ε, it is seen that the model will provide the dry weight (DW_0) for a newly cut stump as $\beta_0\, dia^{\beta 1}$. Thus, by dividing DW_t by DW_0 a simple relative model (Eq. 3) is obtained.

$$DW_t / DW_0 = e^{\beta_2 t} \qquad (3)$$

The validity of assuming that the decay rate is independent of diameter is assessed in Figure 6, where the residuals of the linearized model (Eq.2) are plotted versus diameter and other potential explanatory variables. No clear trends were found. Neither diameter, nor time since cutting or decomposition class showed any distinct trends when plotted against the residuals. No outliers had substantial effects on the result. The residuals suggested that there was high within-location variability.

While the model in Eq.1 requires knowledge about diameter, the relative model (Eq. 3) can be applied on, for example, both the level of individual trees and stands. It also allows for the application of any kind of models (e.g. Petersson and Ståhl, 2006) for estimating the biomass of the stump and root system at $t=0$. This is important, since the limited material available for the study in paper II might provide less accurate estimates of the dry weight of the stump-root system compared to using other models.

3.3 Assessing carbon balance trade-offs between bioenergy and using stumps for storing carbon (Paper III)

The description of data and sampling design used in the Swedish NFI were the same for paper I and paper III, with the exception that SFA data were not used in paper III. Also, the estimation algorithm was similar with the exception that stump harvesting was only taken into consideration in the estimations in paper III. While paper I develops and evaluates a system for estimating and monitoring the carbon in stumps and roots at national scale, paper III applies this in practice after adding a tool handling stump harvesting. In this section, only methods and materials not used in paper I are described.

The biomass of the harvested part of the stump and root system in paper III was calculated using biomass functions derived by Marklund (1988), which were developed to predict the biomass extracted using stump harvesting technology. To extract the stump systems, a winch was used to pull down each tree onto a fell bench. The remaining biomass after stump harvesting was estimated to be the biomass estimated according to Petersson and Ståhl (2006) minus the biomass estimated according to Marklund (1988). Furthermore, the decomposition of the remaining stump and root biomass after death or harvesting of trees was modeled using the function developed in paper II.

Recommendations for stump harvesting in Sweden issued by SFA (2009) were used as the basis in the harvesting scenario analyses, and the environmental, technical and economical restrictions defined were based on these recommendations. The scenarios were called ‘High intensity’, ‘Medium intensity’, ‘Low intensity’, and ‘Max scenario’. The restrictions could be implemented in our study since various site, stand and tree variables are collected for NFI plots, thus making it possible to simulate different restrictions on extracting stumps, such as distance to water and moisture class of land. The minimum distance to water required for stump harvesting was 25m, and the soil moisture class required for harvest was mesic-moist, mesic and dry for the medium and low intensity scenarios. For the high intensity scenario, stump harvesting was also carried out on moist soils. The required standing volume before cutting was lower for the high intensity scenario than for the medium and low intensity scenario. In the high intensity scenario, stumps from all three species investigated (pine, spruce and birch) were harvested. In the medium intensity scenario pine and spruce stumps were harvested and in the low intensity scenarios only spruce stumps were harvested. A maximized scenario, to estimate the theoretical maximum of all stump and root biomass available for harvesting (including final felling, thinning and natural mortality), was also examined. It was assumed that stump harvesting would only be undertaken after final felling, whereas the remaining carbon in stump and root biomass included all stumps i.e. those originating from clear-felling, thinning and natural mortality. Biomass harvest potentials and retained carbon during 1984 – 2003 in Sweden were estimated for the scenarios. For a detailed description of the restrictions taken, see Table 1, Paper III. In addition, a ‘No harvest’ scenario was used to examine the full potential of stump and root carbon sequestration.

3.4 Nutrient concentrations in stumps and coarse roots of Norway spruce, Scots pine and silver birch in Sweden, Finland and Denmark (Paper IV)

The study based its analysis on nutrient concentrations in stumps and root samples from the species Norway spruce, Scots pine and birch. The sample sites were all unfertilized and located in Sweden, Finland and Denmark.

Sampling design: In Sweden, the samples were collected from 24 subjectively chosen stands at three different locations in southern (7 stands), central (8 stands) and northern (9 stands) Sweden. Within each stand, up to four samples trees were selected. Where available, the sampled trees represented the size classes: dbh 0 – 10 cm, 10 – 20 cm, 20 – 30 cm and >30 cm. Each tree was felled using the methodology introduced by Marklund (1988). For each sample tree, up to three broken roots of different sizes (small, medium and large) were subjectively selected and excavated (Petersson & Ståhl, 2006). Roots were cut into fractions, >5mm diameter and <5mm diameter, and the content of carbon, nutrients (N, P and K) and base cations

(Ca, Mg and Na) was analyzed for each fraction. In total, 253 stump and root samples (109 spruce, 107 pine and 37 birch) were used for analyzing the nutrient concentration in the study.

In Finland, at two of three sample sites, five sample trees were selected from each site, and the stump and root systems were excavated with the methodology described in Flower-Ellis (1996) and Iivonen *et al.* (2006). So, within a circle of 75 or 125 cm, coarse roots were excavated down to a depth of 30 cm. Then, the stump and roots were lifted and washed carefully, and a sample 2 cm disc was extracted from each root. One randomly selected root for each sample tree was dug out manually. In the third sample site, five sample trees were selected and felled with an excavator so that roots smaller than 5 cm in diameter were cut off. However, some smaller roots were also present in the sampling process. Sample discs were taken from both stumps and roots. For all three sites, 15 stumps in total were selected.

In Denmark, two stands from the study by Skovsgaard *et al.* (2011) were selected to represent Danish forests. Stump and root samples from ten randomly selected sample trees within each stand were used for this study; in total, 20 sample trees were selected. The extraction was carried out using a combination of machinery and manual labor. All roots with a diameter larger than 2 mm were included. Then, ten samples were taken from each stump and three roots were randomly selected. Root samples were taken 50 cm, 10 cm and 150 cm away from the stump center.

Preparation, nutrient analysis and statistical analysis: The stump and root samples were dried in the oven at 85°C until they achieved constant weight. A pie slice from the root or stump disc was cut, ground and mixed in order to produce the right proportion of wood and bark. Nutrient concentrations from 104 stumps, in total 443 stump and root samples, were analyzed for N, P, K, Ca, Mg and Na. IPC (Inductively Coupled Plasma) analysis was used to analyze the concentration of macronutrients (P, K, Ca, Mg and Na).

A database with nutrient concentrations of stumps and roots from three subsets (Sweden, Finland and Denmark) was developed and assessed in the statistical analysis to evaluate how nutrient concentrations vary with tree species, root fraction, sample type and tree age. Statistical tests were carried out using ANOVA procedures (analysis of variance) (Statgraphics, 1991). The Swedish subset was the largest with 253 samples and also the only subset to include three species: spruce, pine and birch. To facilitate the ANOVA analysis of how nutrient concentrations vary with tree age at harvest, the samples were allocated to one of the following age classes: <20 years, 20 – 29 years, 30 – 39 years, 40 – 49 years, 50 – 59 years, 60 – 79 years, 80 – 99 years and 100 – 120 years. For the Swedish sub-sample, ANOVA was used to assess how nutrient concentrations varied with root fraction and age. The Finnish subset was used to assess nutrient concentrations in wood and bark separately, and for this subset, ANOVA was used to assess how nutrient concentrations varied with root fraction, for wood and bark separately. To assess how nutrient concentration varied with root diameter, linear regression analysis was used with the Danish subset.

Outside the framework of the analysis carried out in paper IV, data from that paper were analyzed to determine the amount of nutrients and base cations harvested per hectare. This was done in order to evaluate whether forest soils in long-rotation forestry are depleted after stump harvesting. To achieve this, the nutrient concentrations in the stump and coarse root parts were weighted in proportion to size (Norway spruce: stump part 32%, coarse root part 68%); Scots pine: stump part 53%, coarse root part 47%), as defined by Hakkila, 2004. The analyzed samples were taken from wood and bark, in southern (Asa), central (Jädraås) and northern (Svartberget) Sweden (kg ha^{-1}). The productivity of the stump harvest was assumed to be 20 – 29 ton dry weight biomass ha^{-1} (Kellomäki *et al.*, 2013; Kärhä, 2012; Athanassiadis *et al.*, 2011). In the analysis, roots >5mm were included in the coarse root category as defined by Hakkila (2004). Studies of nutrient loss in connection with stem and slash harvesting (Egnell, 2009; Björkroth & Rosén, 1977) were used for comparison purposes.

4 Results

4.1 Estimating the biomass and carbon pool of stump systems at a national scale (Paper I)

A system for estimating and monitoring carbon stock changes in stump systems, mainly at a national scale, was developed. The main components required for this system are the levels of stump system carbon stocks obtained from repeated field sampling or a time series of harvest data combined with conversion factors, usually relating stem volume to stump biomass at death. In addition, a decomposition model is needed. The model was used for estimating carbon and carbon stock changes in stumps and roots in Sweden.

The results indicate a gradually increasing carbon pool in stumps and roots (Table 1), on average 6.9 Tg CO_2 yr^{-1} over the period 1984 – 2003, with this trend explained by increasing harvests. As expected for Sweden, nearly all the carbon in stumps is found on forest land.

Table 1. *Predicted biomass and CO_2-equivalents of stump systems in Sweden, based on data from approximately 30 000 sample plots*

Year	Biomass (dry weight)		CO_2- equivalents	
	[Tg] Stock	[$Tg \cdot yr^{-1}$] Change in Stock	[Tg CO_2] Stock	[Tg $CO_2 \cdot yr^{-1}$] Change in Stock
1990	224	4.11	410	7.53
1991	227	3.45	416	6.33
1992	229	2.36	421	4.32
1993	233	3.21	426	5.89
1994	237	4.70	435	8.62
1995	241	3.51	442	6.44
1996	244	2.94	447	5.39
1997	248	4.08	454	7.47
1998	251	2.74	459	5.03
1999	255	4.51	468	8.26
2000	259	3.52	474	6.45
2001	261	2.53	479	4.63
2002	265	3.46	485	6.34
2003	270	5.15	495	9.44

4.2 Decomposition of stump and root systems of Norway spruce in Sweden – A modeling approach (Paper II)

Primarily to improve the system for estimating stump carbon stocks in Paper I (but also for general use), an empirical decomposition model for Norway spruce was developed using the negative exponential model for estimation of the biomass remaining in stump and root systems. The model was derived from two chronosequences - one from southern Sweden and one from northern Sweden - using stump diameter at harvest and the number of years since cutting as independent variables, and dry weight as a dependent variable in the regression model.

The relative decomposition of Norway spruce stumps in Sweden was modeled to be 4.6% per year (the model parameter $\beta 2$). The decomposition model was applied to all species in Paper I and Paper III. This extrapolation was motivated by the fact that, before the present study, no model existed for predicting the decomposition of stump systems in Sweden.

The model parameter estimates and other corresponding statistics – following ordinary least squares regression using Eq. 2 – are reported in Table 2.

Table 2. *Parameter estimates and test quantities for the stump and root system decomposition function (Norway spruce). RMSE=Root mean square error and R^2= coefficient of determination*

Parameter	Parameter estimate	t-value
$\ln\beta_0$	2.7443	6.17
β_1	2.3064	16.60
β_2	-0.0460	-8.89
RMSE=0.6389	R^2=0.7542	

4.3 Assessing carbon balance trade-offs between bioenergy and using stumps for storing carbon at varying time scales and harvest intensities (Paper III)

Given environmental, technical and, to some extent, economic restrictions, we predicted the annual bioenergy potential in stumps and roots in Sweden to be 1.5, 2.7 and 4.1 Tg DW (~ 29, 51 and 79 PJ) in three scenarios with different harvest intensities. In 2011, the bioenergy sector contributed 475 PJ to the total energy supply which corresponds to 23% of the total energy supply in Sweden (SEA, 2013). Norway spruce was the dominant species utilized, followed by Scots pine, birch and "other deciduous" trees. As a reference, the biomass of all stumps from harvest and natural mortality was estimated to be 12.2 Tg DW (Max scenario) (Figure 2).

Before harvesting stumps, the land owners need permission, granted by the SFA which has issued recommendations for stump harvesting. These recommendations take into account environmental factors and we wanted to analyze how these restrictions actually reduced the stump harvesting potential. One such restriction was harvest intensity, since too intensive stump harvesting was assumed to impact negatively on e.g. forest regrowth. In addition, we investigated some economic restrictions (no stump harvesting after thinning, minimum number of stumps per hectare and Norway spruce being the dominant tree species). It was shown that economic restrictions had most effect on the bioenergy potential, and also the environmental restriction "harvest intensity" (SFA recommend 15 – 25% of stump volume to be left). Environmental restrictions such as "distance to water", "soil moisture class" and "high proportion of deciduous trees" had less impact (Figure 5 in paper III).

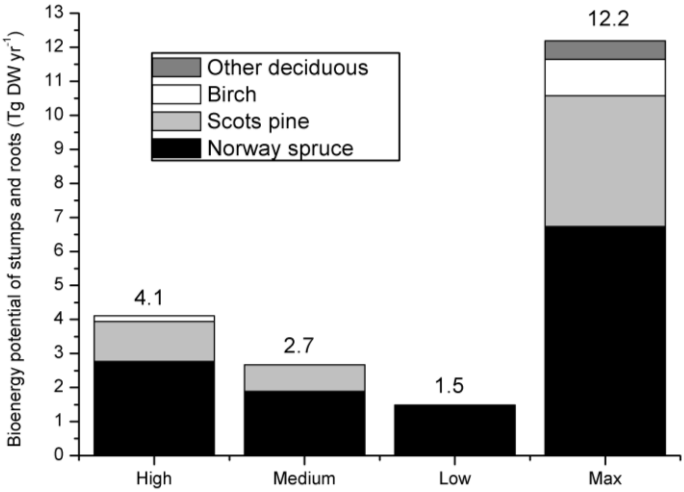

Figure 2. Harvest potential of the three stump harvest scenarios (High, Medium, Low) and the theoretical maximum biomass available in stumps and roots. Average over the period 1984 – 2003 (Tg DW yr^{-1}).

The results indicate that, for the medium scenario, if coal is substituted with stumps and roots for energy, it would take nine years before the emissions from stump combustion have accounted for less net CO_2 production than coal. This is because the CO_2 emitted per unit of energy is larger for burning wood (112 000 kg CO_2 TJ^{-1}) than for coal (96 920 kg CO_2 TJ^{-1}) (IPCC, 2006) and because stumps and roots will decay, although at a relatively slow rate, if left in the forest. However, in this specific scenario, after nine years, the accumulated emissions from the combustion of coal and the decomposing stumps will be larger than the accumulated CO_2 emissions from stump and root combustion and will favor the use of stumps as bioenergy (Figure 3a+b). Using stumps and roots instead of coal would result in a long-term reduction of CO_2 emissions by 2.8, 5.0, and 7.7 Tg CO_2 yr^{-1}, respectively, for the three scenarios.

The realizable potential of stump harvesting in Sweden was estimated to be 12 – 34% of the total amount of stump and root systems.

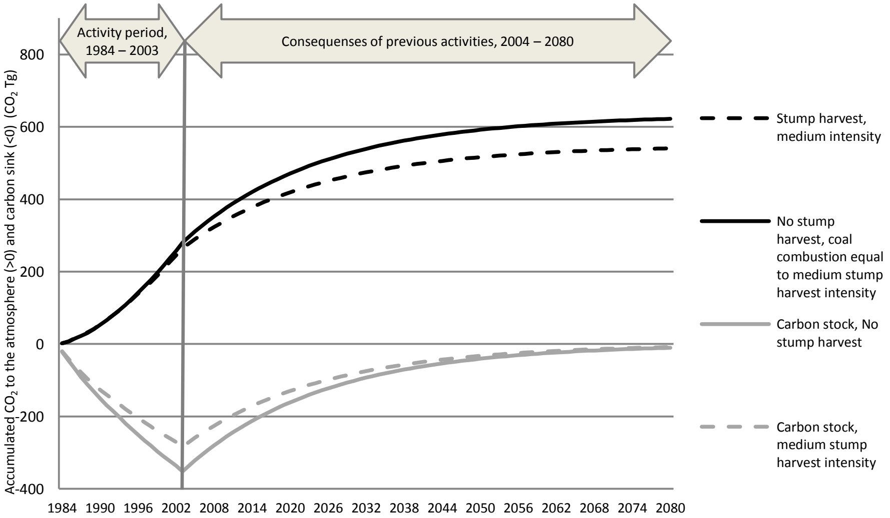

Figure 3a. Energy utilization activity over 20 years (1984 – 2003) and consequences of the energy utilization activities over the decomposition period of stumps in the boreal forest (2004 – 2080). *Black curves:* Accumulated CO_2 emitted into the atmosphere if stump harvesting scenario medium is put into action (decay from stumps not harvested and combustion of stumps in the energy industry) and if coal is burnt instead of stumps (coal combustion in the energy industry equal to medium stump harvest scenario and decay from all stumps). *Grey curves:* Accumulated carbon stock with stump harvesting (stumps left in the ground after harvest in scenario medium, minus decay) and without stump harvesting (all stumps left and accumulated in the ground minus decay) during the activity period, plus decomposition of stumps and roots in the period 2004 – 2080.

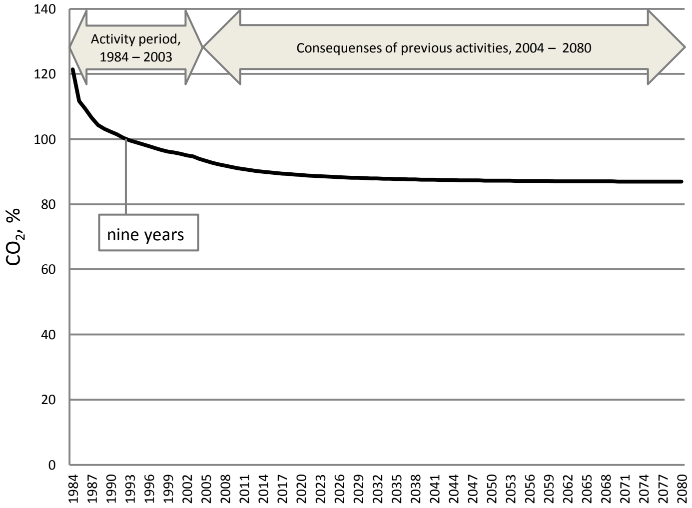

Figure 3b. Based on 3a, relative net accumulation (net emission) of CO_2 into the atmosphere (bioenergy emissions from the medium harvest scenario, divided by emissions from coal combustion, equal to combustion from the medium stump harvesting intensity). The figure shows a larger net emission from using bioenergy over the first nine years. Thereafter, using bioenergy is associated with a lower net emission than when using coal.

When estimating the remaining carbon pool in the ground over the period 1984 – 2003, the retained stump and root carbon pool increased for the harvest scenarios high, medium and low. However, in the theoretical scenario (Max scenario) including all stumps, and those not likely to be harvested, the carbon pool decreased (Figure 4). The Swedish carbon pool in stumps and roots would start to decrease if more than approximately 107 PJ (43% of the total physical amount of stump system biomass) were harvested annually. Without stump harvesting, the carbon pool in stumps and roots was a carbon sink in the study period (1984 – 2003) and accumulated 6.9 Tg CO_2 yr^{-1}.

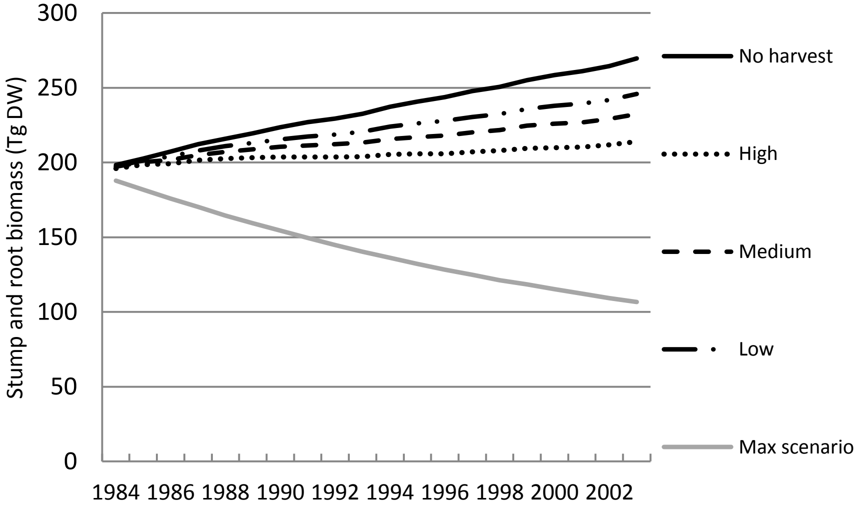

Figure 4. Stump and root biomass retained in the ground on the basis of scenarios High, Medium, Low, the Max scenario and if there was no harvesting (accumulation of stumps during 1984 – 2003 plus retained biomass after decomposition of stumps harvested 1956 – 1983).

4.4 Nutrient concentrations in stumps and coarse roots of Norway spruce, Scots pine and silver birch in Sweden, Finland and Denmark (Paper IV)

In Swedish stumps, the nutrient concentrations were generally higher in birch stumps for all nutrients except for Ca, where the nutrient concentration in the spruce stand was at a similar level as the birch stand. For all nutrients (except Ca), the nutrient concentrations were at similar levels in the spruce and pine stands. The N concentrations in the stumps in the southern part of Sweden and Finland were higher than at the sites located further north. The P concentrations in the stumps were rather similar in Sweden and Finland, although somewhat higher in the sites located in the north of Sweden and Finland compared with the southern sites. Danish stumps had the highest Na concentration.

The statistical analysis of the Swedish stumps showed that the nutrient concentration increased with decreasing root diameter for spruce, pine and birch, with the exception of Na concentration in birch. For the Finnish spruce stumps, the concentrations of N, P, K, Ca and Mg increased with decreasing wood root fraction but, for the bark fraction, this was only the case for N. Linear regression analysis of the Danish subset indicated that nutrient concentrations from one of the sample sites decreased significantly with increasing root diameter for all nutrients except Na. When the mean root radius was plotted against nutrient concentration (N, P, K, Mg, Ca and Na) the results indicated that, for spruce at these sites and with these tree ages, there can be a threshold value at root radius <30 – 40 mm below which concentrations of N, Mg, Ca and P can become quite high.

The statistical assessment of the Swedish stumps showed a correlation between N, P, K and Ca concentrations and stand age for spruce, where concentrations decreased with age up to 65 years. Older samples did not show this correlation.

In addition to the analyses carried out in the paper IV, the loss of nutrients and cations by Norway spruce and Scots pine stump harvest per hectare was estimated for conventional stump harvesting (Table 3).

Table 3. *Estimated loss of nutrients and base cations in connection with Norway spruce and Scots pine stump and roots harvest when 20 – 29 ton dry weight ha^{-1} (Kellomäki et al., 2013; Kärhä, 2012; Athanassiadis et al., 2011), was harvested. Nutrient and base cation concentrations in the stump part and in the coarse root part were weighted in proportion to size as defined by Hakkila, 2004. The concentrations analyzed were based on samples from southern (Asa), central (Jädraås) and northern (Svartberget) Sweden (kg ha^{-1}). The samples included bark.*

Spruce	N	P	K	Ca	Mg
Asa	25 – 37	2.4 – 3.5	17 – 24	28 – 40	4.6 – 6.7
Jädraås	19 – 28	2.2 – 3.2	18 – 26	28 – 40	3.5 – 5.1
Svartberget	24 – 35	3.0 – 4.4	19 – 27	32 – 46	3.4 – 4.9
Pine					
Asa	18 – 26	1.4 – 2.0	11 – 16	10 – 14	3.5 – 5.1
Jädraås	18 – 27	2.0 – 2.9	16 – 23	13 – 19	3.5 – 5.1
Svartberget	16 – 23	2.5 – 3.6	16 – 24	13 – 19	3.6 – 5.2

In current stump harvest schemes, slash is always harvested before stumps. The proportion of lost nutrients and base cations (N, P, K, Ca and Mg) of the whole tree (including stumps and roots) arising from slash and stem harvesting is 47 – 65% and 27 – 43% respectively, and the nutrient loss of stump harvesting amounts to 7 – 14% (Egnell, 2009; Björkroth & Rosén, 1977) paper IV) (Table 4).

Table 4. *Estimated loss of nutrients and base cations (kg ha^{-1}) connected with Norway spruce stump harvesting (20 – 29 ton dry weight ha^{-1} (Kellomäki* et al., *2013; Kärhä, 2012; Athanassiadis* et al., *2011)) compared to slash and stem harvesting. Data on stem and slash harvesting in northern Sweden come from a stand with growing stock 290 m^3 ha^{-1} in Västerbotten, Sweden; data on stem and slash harvesting in southern Sweden come from a stand with growing stock 325 m^3 ha^{-1} in Halland, Sweden (Egnell, 2009; Björkroth & Rosén, 1977).*

North	N	P	K	Ca	Mg
Stem	107	12	54	202	18
Slash	165	20	84	242	20
Stump	24 – 35	3.0 – 4.4	19 – 27	32 – 46	3.4 – 4.9
South					
Stem	120	10	54	98	21
Slash	280	24	68	133	28
Stump	25 – 37	2.4 – 3.5	17 – 24	28 – 40	4.6 – 6.7

5 Discussion

There are great expectations about the world's capacity to produce sufficient biomass for bioenergy as a substitute for fossil fuels. Between 2000 and 2008, the use of fossil fuel at a global level increased by approximately 9000 PJ annually (IEA, 2013), and the need to replace fossil fuels with more sustainable alternatives such as bioenergy is enormous. Examining the use of bioenergy at an EU level, it has increased significantly over the last few years and contributed 4115 PJ to the gross final energy consumption of 50 175 PJ in the EU in 2010 (EC, 2013a). This contribution of bioenergy to the total renewable energy system was 66%, corresponding to 8% of the gross final energy consumption within the EU27. With an additional 28.5 – 79.0 PJ from Swedish stumps (depending on harvest intensity), the share of renewables in the EU27 would increase by 0.06 – 0.16% (EC, 2013a; Melin *et al.*, 2010).

Sweden has been experiencing tremendous change in the energy production sector and, currently, 23% (475 PJ) of Sweden's total energy supply comes from bioenergy (SEA, 2013). In 2012, Sweden reached the national 2020 goal set by the EU to have at least 49% of renewable energy in end use, a figure that reached 50.9% in 2014. If Sweden used the stump harvesting scenarios proposed in paper III (28 – 79 PJ yr^{-1}), and substituted this wood for fossil fuels, the share of renewable energies in end use would increase from 51 to 53 – 57%. The realizable potential of stump harvesting in Sweden is estimated to be 12 – 34% of the total potential of stump and roots systems. However, currently, stump harvesting is very limited in Sweden for several reasons. The market situation, with higher harvesting costs for stump biomass than slash and round wood, make slash and round wood more competitive, and a higher demand for biomass is needed before stumps become profitable. The exception is Finland were subsidies for stump harvesting makes this assortment profitable. If the demand for bioenergy continues to increase at a European level, Sweden could be a possible exporter of biomass to the EU and, with a higher demand, stumps might become part of a new assortment. The market situation of other fuels such as coal and oil will also affect the use of forest fuels: high prices of coal and fossil fuels might possibly advantage the forest fuel market. Future trends in the bioenergy sector, e.g. the second generation of biofuels, where forest biomass is used in biorefineries (Söderholm & Lundmark, 2009), may also change the market and make biomass sources, such as stumps, profitable.

From an environmental perspective, one could question the convenience for countries like Sweden, with an already high energy supply from renewable energy sources (51%), of extracting energy from stumps where there may be negative environmental consequences. However, Sweden could become a pioneer country by showing how the substitution of fossil fuels with renewable energy could be achieved, and stump harvesting could – if carried out in a sustainable way – be one such example to other countries that use fewer renewable sources in their energy mix.

Another aspect of this thesis examined how countries can improve their carbon reporting system for stumps and roots under the UNFCCC and the supplementary Kyoto Protocol. The NFIs from most countries cover only forest land and cannot be used to monitor carbon in stump systems in other land-use classes. However, as shown in paper I, in forested countries such as Sweden, the great majority of carbon in stump systems is present on land that was, and still is, forest land and most stumps will therefore be monitored. However, if stumps are common on non-forest land not covered by the NFI, stumps may indirectly be estimated using conversion factors from harvested volume stem wood from consumption/productions statistics. The carbon stock changes in stumps may then be subjectively divided between land-use categories. It should be noted that there is a severe risk of introducing systematic errors when converting e.g. production statistics to belowground biomass (Satoo & Madgwick, 1982). To use the system developed at a national level, the main components required for this system are the levels of stump system carbon stocks obtained from repeated field sampling or a time series of harvest data combined with conversion factors, usually relating stem volume to stump biomass at death (Lehtonen *et al.*, 2004). In addition a decomposition model is needed. The model developed in paper II is, to our knowledge, the first to model the relative decomposition rates for combined stump and root systems of Norway spruce and is, currently, one of the functions used in the carbon balance estimates in the Swedish carbon reporting to UNFCCC and its supplementary Kyoto protocol. In comparison with other decomposition models from the literature, the annual relative Norway spruce decomposition rate recorded was mainly for logs, but also for snags and stumps (aboveground), and was in the range 3.2 – 5.2%. The value of 4.6% was in the upper quartile (Figure 5).

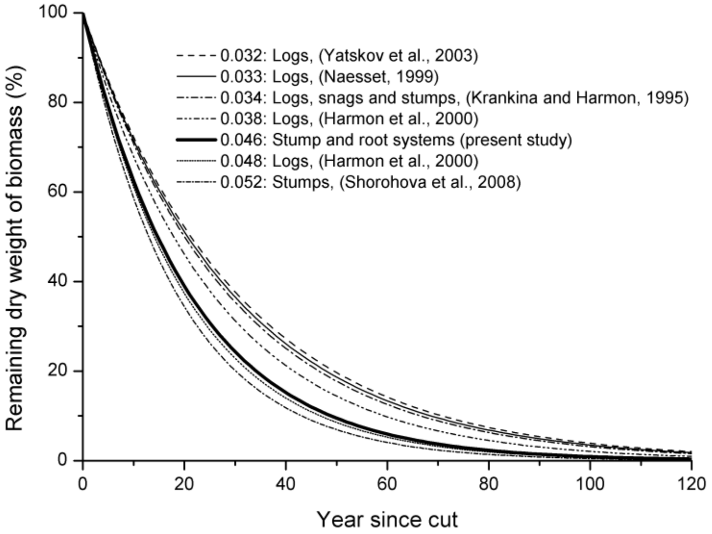

Figure 5. Comparison of decomposition models of Norway spruce logs, stumps and roots.

The advantage of the relative approach is that it is simple to apply without unduly compromising accuracy. However, there are some discrepancies with the decomposition model. The chronosequences used in paper II covered the first 39 years of decomposition, which means that from 40 years on, the model is only an extrapolation. However, according to the function developed, only about 15% of the initial biomass remains after 39 years, so the potential for incorrect asymptotic extrapolation has a limited influence on the results. To investigate whether the relative decomposition model was independent of the variables stump size, year since cutting, decomposition class according to Swedish NFI and location, residuals were plotted for these variables (Figure 6).

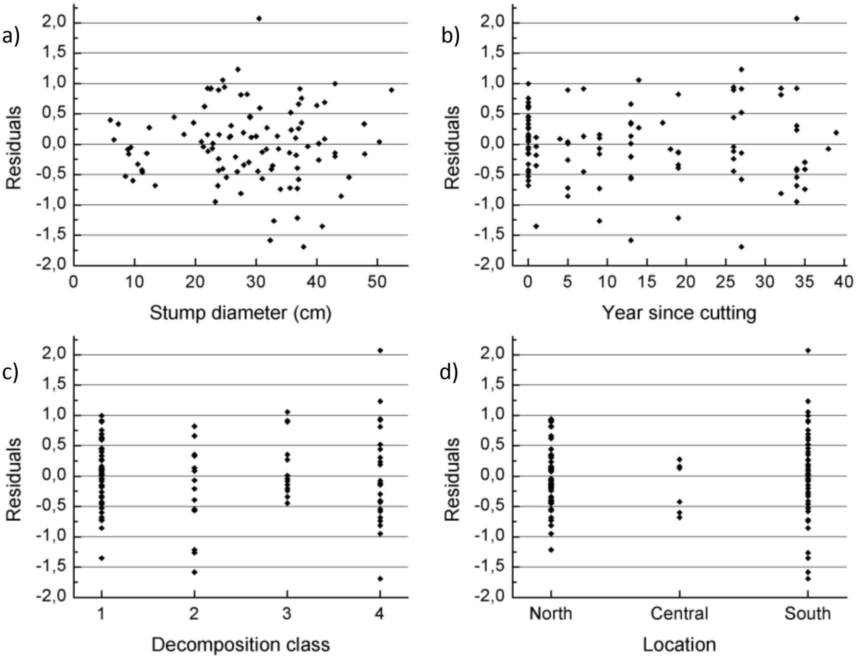

Figure 6. Standardised residuals from equation 2 plotted against: a) stump diameter; b) year since cutting; c) decomposition class; and d) location.

Within the range of stump sizes studied, the relative decomposition rate was essentially independent of stump size. Previous studies have presented different results. Naesset (1999) and MacMillan (1988) showed that Norway spruce logs with a greater diameter had a significantly higher decay rate than logs with smaller diameters. However, Brown *et al.* (1996) measured a faster decay rate for small logs than for large logs. For roots, a study by Olajuyigbe *et al.* (2011) showed no correlation between diameter and decay rate. The residuals plotted against year since cutting did not indicate the need for including a lag phase in the model. Similarly, the residuals for the decomposition class did not indicate the need for separate functions for modeling heartwood and sapwood for Norway spruce. Only two locations were sampled for decayed stumps. However, within these locations, several conditions and types of stands and sites were present. The residual studies relating to location indicate greater within-location variation than that between the two locations (Figure 6). Although there are many variables that affect decomposition, it was possible to predict the remaining biomass quite accurately using just the independent variables stump diameter and time in the regression analysis.

Using one decomposition model for Norway spruce for all dominant tree species is also a crude simplification. There is a possibility that we underestimated the potential carbon pool in stump and root systems due to a decomposition rate that was too low, or if the decomposition was higher, the stump quantity would be less than in our estimates. To evaluate the influence of decomposition rate on the estimated carbon pool, three different decay rates were tested: 3%, 4.6% and 6%. The results indicate that the trend in changing stump system biomass is slightly dependent on the decay rate chosen, and that the level of the trend is indeed dependent on the decay rate (Figure 7).

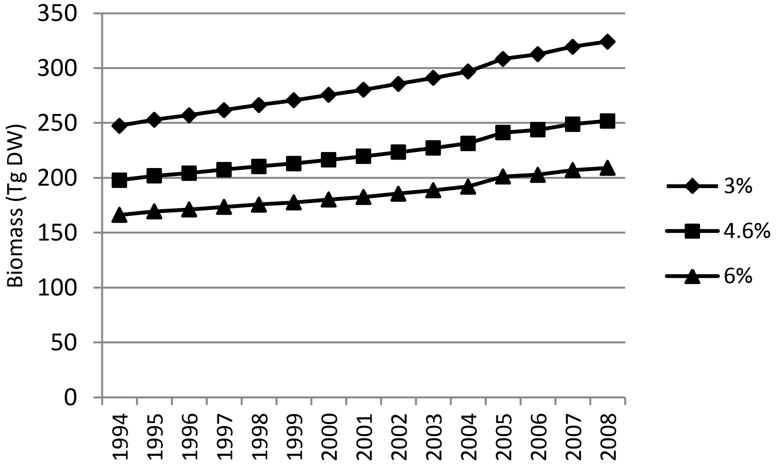

Figure 7. Predicted annual biomass of stump systems in Sweden using different decomposition rates. Underlying data are from 1956 to 2008.

The strength of using historical data based on measurements of individual trees in permanent sample plots was that we achieved high accuracy in ranking the estimates of bioenergy potential and carbon sequestration in stumps for each scenario. A projection would probably introduce uncertainty but is useful for forecasting future potentials. A fundamental assumption of using historical data is that the choice of each selected stand for harvesting was assumed independent by the additional income from the harvested stumps. With the current low price for stump wood and relatively high extraction and harvesting costs, this might be considered as a reasonable assumption.

When applying the system and model developed in papers I and II, it is important to use long time series to correctly model “historical stumps”. If not, and assuming a constant input of new stumps, the carbon pool of stumps will gradually increase until it reaches a steady state. Such an increase is artificial and neglects the decomposition of “historical stumps”. To avoid this problem, a long time series should be used, particularly if the decomposition rate is assumed to be slow.

In Sweden, the harvest levels have increased and the average net sink of stump systems was estimated to be 6.9 Tg CO_2 yr^{-1} over the period 1984 – 2003. This figure can be compared with the reported net removal of about 35 Tg CO_2 equiv. yr^{-1} (stumps included) for the entire Land-Use, Land-Use Change, and Forestry sector (SEPA, 2014). This means that, from a climate perspective, this relatively large carbon sink in stumps and roots is important. However, the Swedish stump sink potential is not credited within the current KP accounting framework. This is because under the KP, the LULUCF sector is accounted for differently from other sectors. Carbon stock changes, under the most important activity Forest management, are heavily discounted by a country-specific cap. This cap limits the value of increasing carbon pools at the expense of reducing emissions, which means that the accounting makes no consideration to whether carbon stored above the cap is used for forest fuel or carbon storage. This favors the use of biomass as a substitute for fossil fuels compared to storage of carbon in forests or in harvested wood products (Ellison *et al.*, 2013), since no credits are given above the cap. In addition, after harvest, forest fuels are considered to be a decrease in 'living biomass' in the LULUCF sector, and are assumed to end up in the atmosphere directly. To avoid double accounting, the emissions from combustion of forest fuels are therefore counted as zero, which favors the use of bioenergy before storing carbon even further.

The basis for promoting renewables, including bioenergy, rests on the assumption that the GHG emissions associated with their use are low, and significantly lower than from fossil fuels (Bowyer, 2012), so that the long-term net emissions are reduced. Bioenergy will always result in lower net emissions over a longer period, since some fossil fuels have been permanently offset by using the biomass that was going to decompose anyway. Therefore, in the long run, fossil fuels will have a stronger negative climate impact compared to forest fuel (Repo *et al.*, 2011; Zetterberg, 2011; Lindholm *et al.*, 2010; Melin *et al.*, 2010).

Another general important aspect to consider in any such discussion as to whether to choose bioenergy or fossil fuels, is that the carbon cycle absorbs carbon into the biosphere continuously, and thus into possible forest fuel sources, in contrast to the fossil carbon that is absorbed only to a negligible extent. Therefore, from a policy point of view, it is important to consider biomass for bioenergy as the most sustainable alternative.

Regarding GHG emissions, using stumps and roots instead of coal would result in a long-term reduction of CO_2 emissions by 2.8, 5.0, and 7.7 Tg CO_2 yr^{-}

^{1}, respectively, for the three scenarios. Comparing these figures to the current total CO_2 emissions in Sweden (excl. the LULUCF sector) of 58 Tg CO_2-equivalents (SEPA, 2013), use of stumps and roots has a potential to reduce the CO_2 emissions (long-term) by 4.8%, 8.6%, and 13.2%, respectively, of Sweden's current emissions.

The above figures concern the long-term effects of using stumps and roots instead of fossil fuels. With a long-term perspective (about 100 years) almost all the stump-root biomass that is not burned for energy will instead return to the atmosphere as CO_2 through decomposition. This means that when coal is combusted, the decomposing stumps still emit their carbon content into the atmosphere as CO_2.

However, in the short-term the emissions from stump combustion will be larger compared to using coal as an energy source because of greater emissions from burning wood (112 000 kg CO_2 TJ^{-1}) compared to coal (96 920 kg CO_2 TJ^{-1}) (IPCC, 2006) per produced energy unit (Figure 3a). The break-even point in the medium scenario was nine years after the initiation of stump harvesting; use of a larger portion of biofuels and/or a lower decomposition rate would delay the break-even point, and vice-versa. However, Figure 3a should be seen as an analysis with narrow system boundaries that points to the principal difference between combustion of bioenergy (stumps) and fossil fuel (coal). The system boundaries were limited to the combustion of coal combined with decomposition of stumps and roots and using stumps for bioenergy (thus substituting fossil coal). Other stages of the carbon cycle, such as absorption to oceans and sedimentation on oceans floors were not considered. For an entire picture of the net accumulation of CO_2 in the combustion examples, a complete LCA would have been required to take account of all emissions emitted over the life cycle of both the bio-based and the fossil fuels (Eriksson *et al.*, 2007). However, the results from LCAs vary considerably due to the use of different approaches (Helin *et al.*, 2013; Cherubini & Strømman, 2011) and, thus, the LCA concept seldom yields the 'entire picture' of all emissions emitted over the life cycle of the fuel (Cherubini & Strømman, 2011; Cherubini *et al.*, 2009).

The analysis in paper I and III assumes that all decomposed biomass is emitted into the atmosphere. This is likely a simplification, since using process-based decomposition models indicates long retention times for some fractions of soil carbon (Manzoni *et al.*, 2009; Wutzler & Reichstein, 2007).

Stump and root harvesting could contribute to future CO_2 emission reduction targets and have positive effects from a climate change mitigation perspective. However, not only climate concerns should be considered, but also other environmental concerns should be taken into account along with an examination of cost efficiency. Therefore, some important concerns were taken into account when defining the harvest intensities scenarios in paper III. In the three harvest scenarios, stump harvesting at the time of thinning was not allowed, because its cost efficiency was too low, and also because of the risks of damaging the remaining stand. Stumps less than 10 cm in stem diameter (before cutting) were also excluded as they were not considered economically feasible to extract with current harvesting technology, and a threshold level of standing stock before cutting was specified for the same reason. In the scenarios, 20 – 40% of the stump biomass was retained in order to sustain biodiversity (Brin *et al.*, 2009; Caruso *et al.*, 2008; Jonsson *et al.*, 2005), and minimize loss of nutrients and base cations from the soil. For biodiversity and economic reasons, only the most common tree species – Norway spruce, Scots pine and birch species – were allowed to be harvested in the scenarios. Buffer zones along streams, lakes, coasts and ditches were specified and taken into account due to the increased risk of erosion and leakage of heavy metals, nutrients and humus in these zones (SFA, 2009; Page-Dumroese *et al.*, 1998). Paper III does not include all potentially appropriate restrictions. For example, the distances to roads and power plants, which affects cost efficiency, were not included (SLU, 2009).

After considering environmental and economic efficiency concerns, we suggest that the potential bioenergy yielded from high intensity harvesting of stumps would be 79.0 PJ, 51.3 PJ for medium intensity harvesting and 28.5 PJ for low intensity harvesting, i.e. about 34%, 22% and 12%, respectively, of the total amount of stump and root systems (Max scenario). However, in a scenario analysis carried out by SKA-08, the potential was estimated to be 75.6 – 122.4 PJ (2010 – 2019) (SFA, 2008). However, paper III showed that if more than approximately 107 PJ had been harvested from 1984 to 2003, the overall stump carbon stock would start to decrease. It should be noted that this study explicitly examined the carbon pool in stumps and roots and took no account of other effects on carbon storage in soil organic matter or the total carbon in the ecosystem after stump harvesting, e.g. the effect of increased aeration and the effects on plant growth.

From a sustainable nutrient perspective, it is important to consider the nutrient loss of the forest soil if stump harvesting is carried out. It has been shown that increased biomass harvest of stumps and slash depletes the pool of base cations significantly, particularly in spruce forest (IVL, 2010). Furthermore, it has been shown to be better to extract stumps and coarse roots than slash, with associated needles, due to the higher concentrations of nutrients in the latter (Persson, 2013; Palviainen *et al.*, 2004). However, extraction of small roots should be avoided due to their higher nutrient concentrations. In paper IV, it was shown that nutrient concentrations increased significantly with decreasing root diameter. Also, coarse roots have higher concentrations compared to the stump part. To avoid harvesting of roots, special techniques where the roots are left in the ground may be applied (Nordfjell *et al.*, 2011). Furthermore, it may be unsuitable to remove stumps from certain tree species (birch), and also to remove stumps at thinning of young stands, since the results indicated higher nutrient concentrations in stumps from younger trees. The location may also be interesting to consider, as nutrient levels in stumps, as well as the nutrient status of the soil, varies within the country (Hellsten *et al.*, 2013). In boreal coniferous forests, inputs of N by deposition would be able to replace the export of N caused by conventional SOH in final cutting (Merilä *et al.*, 2014), but the sustainability of the site productivity will be challenged when more intense WTH regimes including stump and coarse roots are utilized, as the loss of N may result in the degradation of long-term site productivity (Merilä *et al.*, 2014; Helmisaari *et al.*, 2011; Jacobson *et al.*, 2000). Decomposing roots can form an important source of nutrients and thereby make a direct contribution to the growth of new trees in regenerations (Weatherall *et al.*, 2006). Stump harvesting of Norway spruce approximately corresponds to a loss of 24 – 37 kg ha^{-1} N (Table 3) from a clear- cut area. This would correspond to <10% of the total N loss during a whole tree harvest (including stump and coarse roots). N in stem would be approximately 30% of the N in the whole tree with most of the N (>50%) being in the slash part (Table 4). The proportion of all lost nutrients and base cations (N, P, K, Ca and Mg) arising from slash and stem harvesting is 47 – 65% and 27 – 43% respectively, and the nutrient loss of stump harvesting amounts to 7 – 14% (Egnell, 2009; Björkroth & Rosén, 1977) paper IV) (Table 4). From a nutrient perspective, the risk of depletion would be lower if a proportion of slash was left after harvesting than if stump and coarse roots were harvested. However, in current stump harvesting schemes, slash is always harvested before stumps, and this might create a complication.

The deposition of N in Sweden alters over time and along a north-south gradient, with higher deposition in the south than in the north. Many environmental aspects such as biodiversity, acidification, leakage and eutrophication etc. are negatively affected by high N deposition. Sweden has reported <5 kg N ha^{-1} yr^{-1} as a critical threshold for a negative impact on ground vegetation in coniferous forests (Moldan, 2011). In northern Sweden, the deposition of N is relatively low (< 3 kg N ha^{-1} yr^{-1}), and if stump harvesting is preceded by slash and stem harvesting, N deposition will not likely compensate for all N harvested in stems, slash and stumps over a rotation period of 100 years. For southern Sweden, the annual deposition is approximately 2 – 10 kg N ha^{-1} yr^{-1}. If the deposition is in the upper part of that range (5 – 10 kg N ha^{-1} yr^{-1}), deposition of N will likely compensate for both stump and slash harvesting over the rotation period (80 years) (Pihl Karlsson *et al.*, 2013). However, with deposition at the lower end of that range (which is also desired for the other environmental aspects mentioned), stem, slash and stump harvesting will likely not be totally compensated for by N deposition.

From a biomass harvest perspective, the deposition can be seen as compensation for the harvested N, but it is important also to consider the other environmental issues. Fertilizing the forest is one way to compensate for lost N but has also negative side effects on e.g. ground vegetation (Moldan, 2011).

5.1 Future research

Monitoring, controlling and measuring biomass for sustainable bioenergy production and carbon storage is an area that needs further research. Accurate figures are needed for decision makers to plan the future use of biomass in order to achieve low net emissions into the atmosphere. This decision making is complicated by the trade-offs between different uses of wood, i.e. reduced emissions may be obtained both by using wood-fuels in order to substitute fossil fuels and by storing carbon in harvested wood products.

To improve estimates in the reporting to KP, a first step is to develop stump decay models for major species. In Sweden, this refers to Scots pine and birch species. The current model for Norway spruce is quite crude and might also be improved.

Another step would be to carry out scenario analyses of the future of stump harvesting in Sweden using the Heureka forest decision support system (Wikström *et al.*, 2011). This system can predict carbon development in stumps and roots as well as bioenergy potential of stump harvesting at a national level based on National Forest Inventory data. The study could also show how the carbon balances are affected by the different silvicultural systems in use, and also how the use of different decomposition models would affect the carbon balance. Other questions to be answered include how different price levels affect the output volume of stump harvesting and thus a forest owner’s response to market opportunities. The scenario analyses should also include other forest fuels such as slash.

6 Conclusions

Without stump harvesting, the carbon pool in stumps and roots is currently increasing. Based on NFI data for the period 1984 – 2003 the average increase corresponded to 6.9 Tg CO_2 yr^{-1}. To facilitate the estimation of carbon pool changes in stump-root systems a decomposition model for Norway spruce stumps and roots was developed. The average annual decomposition rate was found to be 4.6%.

If Sweden would apply any of the stump harvesting scenarios ‘low’, ‘medium’ or ‘high’, as proposed in paper III (28, 51 and 79 PJ yr^{-1}), and substituted fossil fuels by biofuels from stumps and roots, the share of renewable energy sources would increase from 51% to 53 – 57%. Regarding GHG emissions, using stumps and roots instead of coal would result in a long-term reduction of CO_2 emissions by 2.8, 5.0, and 7.7 Tg CO_2 yr^{-1}, respectively, for the three scenarios. Comparing these figures to the current total CO_2 emissions in Sweden (excl. the LULUCF sector) of 58 Tg CO_2-equivalents (SEPA, 2013), use of stumps and roots has a potential to reduce the CO_2 emissions (long-term) by 4.8%, 8.6%, and 13.2%, respectively, of Sweden’s current emissions. The realizable potential of stump harvesting in Sweden was estimated to be 12 – 34% of the total amount of stump and root systems.

The above figures concern the long-term effects of using stumps and roots instead of fossil fuels. With a long time perspective (about 100 years) almost all the stump-root biomass that is not burned for energy will instead return to the atmosphere as CO_2 through decomposition. However, in the short-term the emissions from stump combustion will be larger compared to using coal as an energy source because of greater emissions from burning wood compared to coal per produced energy unit. The break-even point in the medium scenario was nine years after the initiation of stump harvesting; use of a larger portion of biofuels would delay the break-even time point.

The Swedish carbon pool in stumps and roots would start to decrease if more than 107 PJ (43% of the total amount of stumps) were harvested annually over the study period 1984 – 2003.

The nutrient loss as a result of stump harvesting accounts for only 7 – 14% of the total loss from harvesting all parts of a tree, i.e. stem, slash and stump. Therefore, from a nutrient perspective, it would be more efficient to leave slash instead of stumps and roots in order to minimize loss of nutrients and base cations.

Acknowledgements

First and foremost, I want to send my most sincere thanks to my main supervisor Hans Petersson, for helping and supporting all parts of the work in this thesis. You have always found time for questions and discussions, and always shared your positive spirit which, many times, has inspired me and helped me to stride forwards in times of difficulty. Thank you Hans!

I also want to thank my deputy supervisor Tomas Nordfjell. You were the one that talked me onto the scientific path some years ago now and I appreciate the guiding hand you have given me with tips and tricks in the life as a scientist – especially the reminders to keep things simple was truly appreciated!

Warmest thanks go to Gustaf Egnell, thank you for the productive collaboration we have had with our paper, and also for invaluable help with the summary part of this thesis.

I feel deep appreciation towards Sofie Hellsten, IVL, for doing the excellent work with our paper and for letting me publish this paper in my thesis.

My thanks also go to Frida Björkelid, and to all the field workers who undertook the heavy task of digging stumps and roots. There is a reason why there is a lack of empirical data on decomposed roots ;-), digging roots is simply the best sleeping pill ever!

Also, the warmest thanks to Sören Holm for contributing with your unquestionable knowledge about statistics – you are outstanding!

I also want to sincerely thank Karl-Erik Grundberg for the programming work in papers I and III, and David Alger for being so supportive in this work. Thank you both for your endless (and necessary!) patience with us throughout the entire process.

Many thanks also to Henrik von Hofsten, Skogforsk, Jenny Stendahl, Skogsstyrelsen and Ola Kårén, SCA for you valuable update on the “stumpfront” – thank you.

Special thanks to Cornelia Roberge, thank you for being such a good friend and happy person to hang around with – life is much easier with you in the same ‘bunker’ ;-).

Part of this thesis was financed by the Swedish Energy Agency. Additional funding from the Department of Forest Resource and Management, SLU, Umeå, made this project possible. I feel great gratitude towards the Department for letting me do this research and, again, towards Hans Petersson for solving the financial issues. To all present and former colleagues at the Department of Forest Resource Management: thank you for providing such a nice and friendly working atmosphere! Thanks to you all, I always have a good feeling going to work in the mornings.

I also want to sincerely thank my parents who have always been so supportive and curious about my subject, a subject that must sound somewhat peculiar to “normal” ears. Without your support, especially during the latter part of this project, this thesis would probably have taken much longer to complete.

Finally, thanks to Göran for being there, listening and discussing. Phrases such as “You can do it if you want to” and “If you write it right at first, it goes faster” (!) have spread light on this long journey.

Elsa and Emil – my gratitude towards you is beyond words, thank you for bringing so much joy, love and another dimension to my life. ♡

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