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Economics of Carbon Sinks

Case of Finland

Tuomas Lahnalampi

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Author Tuomas Lahnalampi

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Abstract

In this thesis, I analyze the economics of carbon sinks in Finland, comparing natural and technological carbon sinks. I review research, and apply theoretical models to the topic of the thesis. I conduct a comparative analysis of two options that Finland may consider in its climate policy: increasing carbon sinks in forests, versus generating technological sinks with bioenergy and carbon capture and storage (BECCS).

My research demonstrates, that the two climate mitigation methods are interconnected. I derive numerical results by applying a dynamic optimization model to the cases of BECCS and improved forest management. My numerical results show, that BECCS leads to shorter rotations and higher land values than enhancing the natural carbon sinks. In a simple cost-benefit analysis, I show that the costs of BECCS are higher than those of natural carbon sink enhancement.

Based on these exercises, I recommend a policy for Finland that enhances the natural carbon sinks before BECCS is considered. I hypothesize BECCS as a technology with potential for Finland and Finnish companies in long term. The institutional framework of the thesis demonstrates, that both options have their challenges. Necessary incentives would likely need to be established, to ensure the economic viability of either option.

Keywords Forest economics, Climate policy, BECCS, Carbon sinks, CCS

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Tiivistelmä

Tässä lopputyössä analysoin hiilinielujen taloustiedettä Suomessa, verraten luonnollisia ja teknologisia hiilinieluja. Arvioin kirjallisuutta, ja sovellan teoreettisia malleja opinnäytteen aiheeseen. Suoritan vertailevan analyysin kahdesta vaihtoehdosta, joita Suomi voi harkita ilmastopolitiikassaan: metsien hiilinielujen kasvattamista, ja teknologisten hiilinielujen (BECCS) luontia hiilidioksidin talteenoton ja varastoinnin avulla.

Tutkimukseni osoittaa, että nämä kaksi ilmastotoimea ovat yhteydessä toisiinsa. Johdan numeerisia tuloksia soveltamalla dynaamista optimointimallia BECCS:n ja parannetun metsänhoidon tapauksiin. Numeeriset tulokset osoittavat, että BECCS johtaa lyhyempiin rotaatioaikoihin sekä korkeampiin maan arvoihin kuin luonnollisia hiilinieluja vahvistettaessa. Yksinkertaisella kustannus-hyötyanalyysillä osoitan, että BECCS:n kustannukset ovat korkeampia, kuin luonnollisten hiilinielujen vahvistamisen.

Näiden harjoitelmien pohjalta suosittelen Suomelle politiikkaa, joka vahvistaa luonnollisia hiilinieluja ennen kuin BECCS:a harkitaan. Hypotetisoin BECCS:a potentiaalisena teknologiana Suomelle ja suomalaisille yrityksille pitkässä juoksussa. Opinnäytteen institutionaalinen kehys osoittaa, että molemmilla ratkaisuilla on haasteensa. Välttämättömät kannustimet tulisi todennäköisesti luoda kummankin vaihtoehdon taloudellisen elinkelpoisuuden varmistamiseksi.

Avainsanat Metsätaloustiede, Ilmastopolitiikka, BECCS, Hiilinielut, CCS

Preface

The idea for *Economics of Carbon Sinks* developed through many twists and turns. I want to thank my thesis supervisor Iivo for guiding me. Thank you also to all the professors and fellow students from whom I have learned a lot throughout my studies in Finland and Norway. Thank you to everyone I have had discussions with regarding my topic.

I am grateful for my family, my friends, and last but not least, my colleagues at Finnish Government, Equinor, and St1 Nordic, for inspiring me, and for bearing with me. While this thesis is written in English to reach a broader audience, it is written for the Finnish taxpayers, who generously fully funded my education. Kiitos.

This thesis represents the culmination of six months of intensive study and research into the topic. While I have strived to present comprehensive findings, it is important to note that my understanding of this complex field is still evolving. As such, the results and interpretations presented herein should be taken with caution. I encourage readers to consider this work as a starting point for further investigation rather than a definitive conclusion on the subject. I stand corrected for any of the mistakes made in the process.

Helsinki, 6 August 2024

Tuomas Lahnalampi

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Symbols and abbreviations

Symbols

α	the rate of decay of harvested biomass
β	the present value of CO2 emissions from harvested wood per cubic meter
c	regeneration cost of planting the forest again
p	timber price
r	interest rate
t	time in years
τ	the social valuation of carbon dioxide
θ	the quantity of CO2 per m3 of biomass
ω	the biomass expansion factor for including e.g. branches and roots

Units and quantities

1t	Ton, one metric ton
1kt	Kiloton, a thousand metric tons
1Mt	Megaton, a million metric tons
1Gt	Gigaton, a billion metric tons
1Pg	Petagram, a quadrillion grams / a trillion kilograms
kPa	kilopascal
1 EJ	one exajoule, 10^{18} joules
pa	per annum, e.g. 5Mtpa = 5 Megatons per annum

Abbreviations

CO2	Carbon dioxide
BAU	Business as Usual
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CDR	Carbon Dioxide Removal
DAC	Direct Air Capture
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
EU	the European Union
FEED	Front-End Engineering Design
IFM	Improved Forest Management
IPCC	Intergovernmental Panel of Climate Change
LULUCF	Land Use, Land Use-Change, and Forestry
MIT	Massachusetts Institute of Technology
OPEX	Operational Expenditure
P&P	Pulp and Paper

1 Introduction

Evolution of modern economies and consequently the progress of us as humankind has imposed a high cost for the future generations. Fossil energy sources needed to fuel industrialization such as coal, oil, and natural gas have increased the CO_2 concentration in the atmosphere. While CO_2 is a vital molecule for many living organisms, the current scientific consensus is that it has contributed significantly to climate change and global warming.

Capturing CO_2 from industrial processes or the atmosphere and storing it permanently underground could prove vital for climate mitigation. Carbon Capture and Storage (CCS) is broadly considered a key technology to reduce emissions from the global energy and industrial sectors to meet the goals of the Paris Agreement, to limit global warming to 1,5 to 2 degrees above the pre-industrial levels (IPCC (2014, 2019, 2022)). In Bioenergy with CCS (BECCS), carbon capture and storage is applied to combustion of biomass for energy production - enabling removal of CO_2 from the atmosphere. Generating carbon removals and enhancing carbon sinks[1] is by the likes of the European Union deemed necessary to compensate for residual emissions left in the future from, for example, agriculture.

This thesis explores the economics of natural and technological carbon sinks. Main research question is, whether investing in natural or technological sinks would be better going forward. I review literature, provide an extensive institutional background to support my case, and compare the costs and benefits of these two options. A special focus is given to Finland, a country rich in forests. The main point I make is that while the economics of the two types of sinks are different, they are linked, and cannot be treated separately.

Natural carbon sequestration done by forests is nothing new. The natural carbon sinks have likely already saved us from a much more dramatic global warming and climate change. Forests absorb around 15.6Gt/CO_2 from the atmosphere annually (Nasa, 2021). Most of this is not offset, but done 'for free' by the nature, although with a carbon price of 100€/t we could say that this is worth 1,56 trillion euros for the society. Up to half of this may be nullified by deforestation and other disturbances. Still, forests absorb around 30% of the annual CO_2 emissions and store it in living biomass and soil (Pan et al., 2011).

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[1] Terminology may cause confusion. Sink is anything that removes more CO_2 from the atmosphere than it releases. It is often used when talking about ecological carbon sinks, but in Finland the term *technological sinks* has gained popularity. It means generating permanently negative emissions with BECCS. Sequestration means long term storage of CO_2 in plants, soils, geologic formations, and the ocean.

Forest carbon stock or storage globally is approximately 861 Pg, or 861Gt (Pan et al., 2011). With carbon prices of 100€/t the global carbon storage would be valued 86 trillion euros. In comparison, world GDP is around 100 trillion (World Bank, 2022).

Finland may together with Sweden be considered the lungs of Europe. The Nordic pair accounts for circa third of the total forest area in the EU (around 50 million hectares, of which Finland accounts for 22 million). 66% of Finland's land area is forest (ranked first), and the country also has the highest area of forest per capita (Eurostat, 2020). Forests play a key role in Finland by providing a source of timber, habitats for biodiversity, and serving as a natural carbon sink. Forest growth removed 8Mt/CO_2 in 2021 (Statistics Finland).

Research has pointed out an obvious conflict between carbon sequestration in forests and use of forest biomass (Lintunen and Uusivuori, 2016). Industry view is that biomass is renewable which justifies commercial harvesting. However, while the trees grow, the forests have a carbon sink value that the timber price does not reflect. Climate activists in hand sometimes argue that we should fully conserve our forests. While *improved forest management* could indeed prove vital for climate mitigation, completely ignoring the role of harvested biomass as a feedstock for economic progress contradicts established scientific principles.

Recently, Finland's carbon sinks have been reduced due to factors such as increased industrial logging (Ministry of Agriculture and Forestry). The state of the carbon sinks of Finnish forests is of very high economic importance for the Finnish government – due to the EU's Land Use, Land Use-Change, and Forestry (LULUCF) requirements, Finland could be forced to pay other EU countries up to billions of euros (Soimakallio and Pihlainen, 2023).

BECCS could prove an effective way to reduce emissions from the Finnish forest industry, which generates a high amount of biogenic emissions. A report by Finland's Climate Change Panel (Kujanpää et al., 2023a) estimates that Finland has theoretical potential of generating up to 9,8Mt of technological sinks per year, a significant share of Finland's total emissions which were 47,6Mt in 2021. BECCS has a high policy relevance, as the current Finnish Government has mentioned in their government program, that it will provide support for technological carbon sink investments (Finnish Government, 2023).

In Nordic countries, there is geological storage capacity for up to 100Mt/CO_2 per year. With the current economic incentives, this will mostly be filled with CO_2 of fossil origin - which will help, but will not remove CO_2 from the atmosphere. Some BECCS activities are also taking place and being planned, calling for a comprehensive economic analysis.

To answer my research question, I review traditional literature on economics of forest carbon sinks and the emerging literature on (BE)CCS, and use results from economic models to analyze the case of Finland in the context of the current and possible future policies for the forest sector – namely the EU regulations and the potential incentivization of BECCS. The topics of BECCS and LULUCF are highly related, as Finland may need to balance increasing emission reductions through CCS and maintaining the carbon sink function of its forests. This tradeoff is complex, difficult to quantify, and challenging to control by policy measures. Through my paper, an understanding of this tradeoff is developed from the economics point of view. As such, this thesis will hopefully assist the various involved decision makers to *see the forest for the trees*, and support decision-making.

The aim of the thesis is not to design a generally optimal climate policy, or to compare the use of carbon sinks to any other available strategy for decarbonization, such as Carbon Capture and Utilization (CCU) or battery electric vehicles. To be able to reach fully satisfying normative conclusions answering the question – what Finland and the world should do – it would be necessary to go deeper into all the possible different decarbonization options and to find out what effects they may have economically (e.g. financial and political costs), and environmentally assessing the whole life cycle, without neglecting issues such as biodiversity loss, not in the scope of this paper. As CCU is not completely mutually exclusive with CCS, and due to its relevance for the Finnish case, a brief appendix section is devoted for it.

By concentrating on the individual case of Finland as a carbon capturer, I fill a gap in the current literature, which will hopefully be a more studied subject in the future. My work could provide ideas for analyzing both the Finnish case, and that of other countries.

The thesis is organized as follows. Section 2 gives an institutional background to the case of Finland. Section 3 reviews literature on natural carbon sinks through the lens of the traditional literature on economics of forestry. Section 4 paints the big picture of industrial (BE)CCS, and introduces its value chain in the Nordic context through an economic model to strengthen the institutional framework of the thesis. Section 5 ties everything together, studying BECCS through forest economic models, and analyzing the costs and benefits of forest carbon removal versus BECCS. Section 6 provides a discussion from a policy perspective. Section 7 concludes. Appendix sections are provided for technical details, models reviewed in section 3, robustness checks on the numerical results of section 5, and for the pathways of CCU in Finland.

2 Finnish forest in the European periphery

This section provides institutional background to the case of Finland. The impact of the country's forest industry for its economy and emissions is detailed, and the relevant regulatory framework is summarized.

2.1 Forest industry has a large impact on Finland's economy and CO_2 emissions

Finnish Government has an ambitious goal of becoming carbon neutral in 2035. Understanding the sources of emissions in the country and their proportions, as well as the part that the forest plays, is paramount for devising effective abatement policies. Finland's forest industry contributes significantly to Finland's total emissions. What makes the analysis complicated, is that the industry indirectly also affects the wider forest sector and land emissions.

Finland has, akin to Sweden, established a strong forest industry. While the importance of the forest industry has during the recent decades been reduced, it still today plays an important role in Finland's economy, paying 3,5 billion in taxes annually, and giving work and livelihood to around 100,000 people (Metsäteollisuus ry). Key players of the industry today are big pulp and paper producers, such as UPM, Stora Enso, and Metsä Group.

Forest ownership in Finland is diverse, comprising private, state, and community-owned forests, each with its own management objectives and practices According to UPM Forest (2020), 60% of forest is owned by private landowners, and of the wood that Finnish forest industry uses 80% come from domestic private forests. The most common forest owner used to be a farmer living on the land they own, but that is no longer the case, as agriculture as a source of livelihood has lost importance. 'Remote forest owners' with other main sources of income are on the rise.

Finnish Land-Use, Land-Use-Change, and Forestry (LULUCF) sector has traditionally been a net carbon sink, but it has in the recent years become a net emitter (Kujanpää et al., 2023b). In 2021, the forest land and harvested wood products net carbon sink was negative 8,7Mt/CO_2. This was not enough to compensate for the emissions from the LULUCF sector, which were 3,5Mt/CO_2 (Statistics Finland). Factors such as degradation of peatlands, slow forest growth, and excessive cone production have contributed to the decline in the carbon sink. However, increased logging for industrial use has been identified as the primary reason for the reduction in the carbon sink (Soimakallio and Pihlainen, 2023).

Finland's total emissions (without LULUCF) were 47,6Mt in 2021 (Statistics Finland). Total emissions of the Finnish forest industry were 20,9Mt/CO_2 in 2021[2] (Kujanpää et al., 2023a). Forest industry emissions hence take a large share (43%) of the national emissions. In comparison, the transport sector emits around 10Mt/CO_2 (Statistics Finland).

The forest industry has been able to switch almost entirely from fossil fuels to fuels that they produce themselves from wood and pulp production residues, such as black liquor. Of the sector's total emissions 19,6Mt (93%) are biogenic, absorbed from the atmosphere by the forest while it grows. Due to the switch of fuels, more wood fuels are used in Finland than oil or coal. In total, around 31% of Finland's total energy consumption is from bioenergy, forming 77% of the total renewable energy consumption in Finland (Bioenergia ry, 2022). Black liquor and other residual solutions used in the forest industry constitute the largest portion of bioenergy consumption. In addition, heat and power plants emit 15,1Mt/CO_2 of which 8Mt (53%) is biogenic (Kujanpää et al., 2023a). Most of this is harvest residues and parts of trees which are not suitable for commercial use of the forest industry.

Commercial forestry has been practiced for over 150 years, yet Finland has been able to avoid deforestation. Carbon sinks and biodiversity have been of secondary importance, but on the global rankings Finnish forests perform well. Crowther et al. (2015) maps tree densities in the world's forests, and finds that Finland's forests are the densest in the world. Whether this kind of forestry where major part of the forest is managed almost as a tree plantation is truly sustainable, remains open to debate. Forest industry point of view often is, that what they do is the definition of sustainability. Biomass renews itself, whereas fossil fuels do not - fair point, to say the least.

However, biomass renews itself slowly. Harvesting affects negatively the forest carbon sink, an important climate mitigation tool. The carbon sink is also economically relevant, as Finland is required to increase it according to the EU LULUCF requirements. If unsuccessful,

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[2] Data in Kujanpää et al. (2023a) includes industrial plants in the emissions registry with emissions >100ktpa. As the data is from 2021, also data from Statistics Finland is taken from 2021. Data differs by some extent perhaps due to the inclusion of small industry in the latter source. This is hardly dangerous, as the data is illustrated to describe the proportions.

Finland may need to pay billions of euros for other EU countries. Regulatory framework concerning Finnish forests and CO_2 emissions is next given.

2.2 Regulatory framework

The Forest Act of Finland sets minimum requirements for forest regeneration and biodiversity preservation. (Ministry of Agriculture and Forestry). Ever since the 1800s, the Finnish law has required the forests to be planted back after harvests. Forests are managed according to a sustainable forestry management model, according to which more wood should be grown than cut (Proby, n.d.). Wood production is maximized by optimizing harvesting and conducting silvicultural practices like thinning. Most commonly the thinning is done from below to make way for the bigger trees to grow.

Finnish forests have been taxed through land area (wealth tax) or wood sales (income tax). In 1993, the government shifted to a tax based solely on realized wood sales, fully implemented by 2006 (Leppänen and Hänninen, 2015). Private forest owners are subsidized for forest and nature management. The new subsidy scheme Metka taken in use in 2024 does not directly subsidize forest growth or carbon sequestration (Metsäkeskus). However, forest owners in Southern Finland are compensated for participating in the voluntary forest protection scheme Metso, with compensation based on wood volume, type, price, and protection period length (Metso).

The forest industry has due to the big economic impact a strong lobby, and say on the policymaking. The industry has a strong effect on the economy and employment of rural areas. Government balances between maximizing the total welfare and distributing it equally. Maintaining a forest industry may be seen as a tool for balancing between these objectives. Also, votes from rural areas are important for the politicians. Parties with high popularity in the countryside such as the Centre party and recently also the Finns party are frequently part of the coalition in power.

A member state of the European Union, Finland operates within the European regulatory framework. The European Union has a target to become carbon neutral by 2050, 15 years later than Finland. This section provides a brief overview of key EU emission abatement regulations: the emissions trading system (ETS), effort-sharing regulation (ESR), and Land Use, Land-Use Change, and Forestry (LULUCF) regulations. Although not directly linked, particularly ETS and LULUCF are important for the case of the technological sinks, introduced and analyzed later in this thesis. Conversely, the ESR and LULUCF frameworks are linked and offer some flexibility for the member countries. For a more complete regulatory analysis, see for example Hocksell (2023) and Wallén (2024).

EU ETS is the cornerstone for emissions abatement in the region. ETS is the world's biggest carbon market, requiring the actors involved to buy permits for the emissions that they generate. It is a 'cap and trade' system, meaning that the pollution permits are tradeable, bankable, and have a cap which is annually reduced to incentivize further emissions reductions. ETS covers CO_2 emissions from electricity and heat production, energy-intensive industry, aviation and maritime. Pulp & paper producers are included in the ETS, but it is not necessary to pay for biogenic CO2 emissions. EU has improved the system by mechanisms like carbon border adjustment mechanism, aiming to reduce carbon leakage. (EU Commission)

ESR covers emissions from those sectors not covered by the ETS, such as road transport, heating of buildings, agriculture, small industry, and waste management. Of these, waste management will be included in the ETS in 2026. Also, a second ETS will be opened in 2027, covering fuel combustion in the ESR sectors. EU members have a binding target to reduce ESR sector emissions 40% by 2030. For this target, there is flexibility with the LULUCF requirements explained in detail below.

LULUCF regulation defines rules for how emissions and sinks from the LULUCF sector are considered in the EU's climate targets from 2021 to 2030. This period is divided into two five-year periods. No emissions are allowed from the LULUCF sector during this time. Accounting is done at state level. In Finland, the National Resources Institute Finland (hereinafter, Luke) is responsible for the calculations.

Finland, like other EU countries, sets a reference level for the two periods on individual criteria set for them in the regulation. Forest reference level calculation must be based on the realized forest use for 2000-2009 period. If the net sink is higher than the reference level, Finland may benefit from a net removal up to 2.5MtCO_2 per year. Credits generated from this may be used to meet the targets of the effort-sharing sector up to 4.5Mt/CO_2 in the whole period. If the sink is below required, Finland will need to compensate by reducing emissions in the effort-sharing sector or by acquiring LULUCF credits from some other EU member state (Ministry of Agriculture and Forestry). Finland has been allowed a flexibility of 10Mt/CO_2 for the whole period as a highly afforested country.

A report by Soimakallio and Pihlainen (2023) calculates scenarios for the greenhouse gas accounts for the 2021-2025 period, and finds that in most cases the Finnish LULUCF sector becomes a net emitter, and that Finland will not meet the requirements set by the regulation. The outcome depends on the eventual reference level, realized growth of forest and amount of total reduction in wood due to logging, residual collection, and natural decay. Including the extra flexibility, Finnish LULUCF sector's deficit is estimated to be 0-37Mt/CO_2 per year.

What this means for the public finances of Finland is still very uncertain. Current reference level may still change due to technical adjustments to ensure methodological consistency in reporting. If the annual deficit is 37Mt/CO_2, and if the carbon credits are based on the price of ETS – assuming a price of 100€/t, Finland could be required to pay other EU countries up to 37 billion euros for the whole decade [3]. Neglecting the state of the carbon sink in the current policy could prove very costly.

Whether the other EU countries have been able to generate this much carbon sinks and hence credits for Finland to buy, is another question (still not known how the payments would in practice happen). Hyyrynen, Ollikainen, and Seppälä (2023) create forecasts for EU member countries, and find that in total the whole EU national sinks will be behind targets. Finland particularly will need to buy sink units, but only a handful of countries will according to the forecasts be in the position to offer them for sale.

The LULUCF requirements set a constraint for use of biomass for the Finnish government, but means for Finland to control the use of forests and landowner's and companies decisions are limited and unpopular. Rapid actions to increase the carbon sink of forests are difficult. Drastically reducing the effort-sector emissions to compensate for LULUCF emissions will be difficult. The current government has on the contrary low ambitions in the transport sector.

As is evident from the institutional background, understanding the economic dynamics of forestry is crucial for sound decision making. As is shown in later sections, the technological carbon capture, proposed as a key tool for meeting the country's net zero targets, is strongly linked to the forest industry and hence, the natural carbon sinks. Billions of taxpayer money are at play, as the Finnish government faces a complex tradeoff between utilizing wood biomass for economic progress, and increasing the carbon sinks. In the next sections, an overview of both natural and technological sinks is given.

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[3] This is the absolute worst case scenario. LULUCF carbon sink credit price may be lower than 100€.

3 Natural carbon sink in forests

Economics of forests is a complex subject of study. To not jump to rash conclusions, this section rigorously reviews relevant research, giving ingredients for an analysis of Finland's climate and forest policy. This section utilizes to a large extent the explanations of Amacher, Ollikainen, applying the contents to the topic of the thesis. First, traditional forest rotation modeling is presented as a key theoretical framework of the thesis. After that, results of the models are compared to results from literature going deeper into the forest.

3.1 Traditional rotation forestry

Models reviewed are the evergreen rotation model by Faustmann (1849), and an extension to it including carbon sinks (Korhonen and Tahvonen, 2023). While these models are oversimplified, they are powerful in explaining the forests' economic dynamics. First, some necessary background to understand the models is given.

Even-aged forest management or rotation forestry has historically been typical in commercialized boreal forests such as that of Finland. In it, the trees in a 'stand' of forest are assumed to be identical. Harvesting is done through clear-cutting a stand at once. A rotation starts as the forest is planted, and ends at harvest. Another option to manage forest is uneven-aged forest management, where the forest is managed through continuous cover forestry. In rotation forestry, tree stands are artificially regenerated (planted) after harvest, whereas continuous cover forestry relies on natural regeneration. Border between these two ways of forestry can sometimes be unclear. One way to distinguish the two is to ask whether clear-cuts take place. If yes, we talk about even-aged management, or rotation forestry.

The growth of trees typically follows a sigmoid type of path, first increasing a lot and then decreasing when maturity is reached. Stand growth can be measured by statically calibrating (estimating empirically) or basing on process (biology based causal processes). We herein denote forest growth in m^3 in time as $f(t)$. Silvicultural practices such as thinning are an important tool to improve forest growth but do not affect the sigmoid path. Thinning can be executed from above by cutting older trees to make way for the growth of the younger ones, or from below, where the younger trees are cut to make way for the older ones. As said in the previous section, thinning from below has in Finland been the common practice. In this subsection, thinning is still abstracted from.

Preferences of landowners are key for economic modelling. In a traditional forest rotation model, we step in the shoes of a landowner, and maximize the net present value the forest land over an infinite cycle of rotations. A rotation begins when forest is artificially planted, and ends at harvest. First one to knowingly having formalized this kind of a rotation model was Faustmann in 1849. The five *heroic* assumptions required for the model as identified by Samuelson (1976) are: (1) Timber prices and regeneration costs are constant and known. (2) Future interest rates are constant and known. (3) The growth function of stands is known. (4) Forestland markets are perfect. (5) Financial capital markets are perfect.

Faustmann (1849) is deemed to be the first infinite horizon model in economics, and it is still considered fundamentally correct today. It goes a bit like this: In the beginning there are bare land, tree seeds and a landowner. Prices p for eventual timber harvesting are assumed net of logging costs. Assume fixed planting technology with cost c, and no other variable production inputs. Landowner's decision variable is the rotation age (harvesting time) T. Variable r stands for the interest rate.

Landowner's net present value from harvesting in the first rotation at T is $pf(T)\,e^{-rT} - c$, where e^{-rT} is the discount factor, a continuous time approximation for $1/(1{+}r)^T$. After harvesting, a new rotation is started, and the process is continued forever. Faustmann formula:

$$V = \left(1 - e^{-rT}\right)^{-1} \left[pf(T)\,e^{-rT} - c\right] \tag{1}$$

The formula is an infinite sum of discounted rotations. As we factor out the landowner's profits for each period, the discount factors converge to the term inside the first brackets by definition of geometric series. The model is all about timing. The optimal point in time to cut down the forest is reached by differentiating with respect to the rotation age T. According to Faustmann, the landowner should *clear-cut* an even-aged stand at an age at which the marginal return from delaying harvest is equal to the opportunity cost of delaying harvest. If land value is negative, leaving forest unmanaged or without replanting after first harvest is optimal. As noted by Samuelson (1976), you could mine your forest land and sell it onwards without replanting. Infinity is however somewhat reasonable assumption, as forest owners generally tend to leave the forests as bequests for the next generations.

The strong assumptions of certainty, known forest growth, and perfect markets perhaps make the model unrealistic, but it has until today not been proved to be fundamentally incorrect. Faustmann provides a basic building block for more detailed policy-oriented analyses.

3.2 Towards improved forest management

While Faustmann laid the groundwork for the economics of forestry, it disregards the forest's function as a carbon sink. Forests may prove to be a tool to help us reduce the atmospheric CO_2-concentrations closer to the levels of year 1849. This requires switching to improved forest management activities, increasing carbon stocks[4] in the forests in comparison to business as usual forestry. Economists have in the past 30 years worked to extend Faustmann's model to show that the carbon sinks matter also from an economics point of view. The results put the carbon neutrality of biomass under scrutiny.

van Kooten, Binkley, and Delcourt (1995) optimizes wood production and carbon sequestration of forest. Authors examine the use of carbon subsidies and taxes to affect the landowners' forest management by building a theoretical model and solving it numerically. Inclusion of the valuation of the forest's carbon sink to the landowner's problem is found to prolong the optimal rotation age compared to Faustmann with increasing carbon prices.

van Kooten et al. discusses the potential of using forests for climate change mitigation. In today's policy, biogenic CO_2 is considered carbon neutral. However, the ultimate disposition of the biomass and the release of carbon to the atmosphere remains a problem and makes forests as we today use them only a temporary method of carbon storage. van Kooten et al. proposes that biogenic CO_2 should be taxed as any CO_2 - but that the temporary storage in forests should be compensated for, as it increases welfare. Duration of biogenic CO_2 storage depends on biomass utilization method, which should be considered in the analysis. If left standing, the forest will ultimately decay and release carbon slowly into the atmosphere. Some of the deadwood will remain in the soil, but not forever.

Discussion paper by Korhonen and Tahvonen (2023) applies *a theoretically coherent and analytically solvable* stand-level model to optimize wood production and carbon sinks. Korhonen and Tahvonen expand the Faustmann model and take the work started by the likes of van Kooten et al. forward in order to find the correct equation which would give us the exact answer to the question - how should we use our forests. Even if a simple rotation model would not give us a sufficient basis for decision making, Korhonen and Tahvonen is an intuitive

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[4] Important to note is the difference between stocks and flows. Trees absorb CO_2, and use it in photosynthesis to produce oxygen, storing the carbon. Stock is the amount of carbon in storage in a reservoir, whether biomass or atmosphere. Flows describe the movement of carbon between reservoirs through processes like combustion, reacting with oxygen and other molecules.

model for understanding the basic message: Both wood production value and carbon sink value should be considered when making decisions about the forest. If we value carbon sink, rotations are generally longer than in Faustmann. This means that more carbon is stored in the forests than in the business as usual case. The same result that van Kooten et al. finds numerically for the effect of carbon valuation on optimal rotation is proved analytically in Korhonen and Tahvonen. In addition, carbon sink value is shown to impact the value of a forest stand, challenging the classic forest economic results.

The model in a way formalizes the complexities involved in today's forestry. In the model, forest soil and harvesting residues are abstracted from. Soil, residues, albedo, and other factors are important, and may change the results. After building an understanding of this simple model, results from more nuanced interdisciplinary models are reviewed.

Let W be the landowner's maximization problem, a sum of the values $V_w + V_c$ of wood production value and net carbon sinks. Let τ equal social valuation of CO_2, θ the quantity of CO_2 per m^3 of biomass, β the present value of CO_2 emissions from harvested wood per m^3 (equal to $\alpha/(\alpha+r)$, where α is the rate of decay of harvested biomass), and ω the biomass expansion factor for including e.g. branches and roots. Problem is written as:

$$W(t) = V_w\,(t) + V_c\,(t) = \frac{pf\,(T)\,e^{-rT} - c}{1 - e^{-rT}} + \frac{\tau\theta\omega[\int_0^T f'\,(s)\,e^{-rs}ds - \beta f\,(t)\,e^{-rT}]}{1 - e^{-rT}} \tag{2}$$

Wood production value (V_w) is the equation (1), the good old Faustmann rotation function. In carbon sink value (V_c), the numerator's first term represents the present value of gross sink, and the second term the present value of emissions. First order optimality condition for the function above is (see the exact derivations in Appendix 1):

$$W'\,(t^*) = V_w\,(t^*) + V_c'\,(t^*) = 0 \tag{3}$$

Which can be written as:

$$[p + \tau\alpha\omega(1-\beta)]f'(t) - r(p - \tau\alpha\omega\beta)f(t) - rJ(t) = 0 \tag{4}$$

In line with van Kooten et al. (1995), an optimal policy could be implemented by imposing a subsidy for forest growth of $\tau\alpha\omega$ and a tax on harvesting (emissions) of $\tau\alpha\omega\beta$. We are still in the Faustmann kind of world where the landowner is determining the optimal time to harvest. The difference is that now the landowner is incentivized to take into account the value of the carbon sink. Landowner should according to the optimality condition harvest when the total value of growth in wood production and carbon sink is equal to the opportunity cost of delaying the harvest revenues for one more period plus the interest cost of bare land.

Results of the model depend heavily on the carbon prices, and the discount rates. These are both assumed exogenous. When optimizing pure carbon sinks, rotation is longer the stronger we discount, and a zero-discount rate maximizes the average carbon stock in forests (see Section 5 and Appendix C for numerical illustration). When optimizing both wood production value and carbon sinks, same holds, although the effect of carbon sink on the optimal rotation vanishes when discount rate approaches zero. This implies that optimal rotation is discontinuous at zero discount rate.

A key takeaway comparing Korhonen and Tahvonen to Faustmann is, that wood production still is valuable - but not enough for us to neglect the carbon sinks. Hence, a proper way to approach forest sector emissions could be to treat them as any emissions. Instead of treating biogenic CO_2 as carbon neutral, should we be *color agnostic* [5] and tax it as other sources? If yes, policy should not be left halfway, but a forest growth subsidy should be put in place to ensure that everyone has the correct incentives.

Claims for optimal policy based on stand-level models are hardly sufficient. What about the wider-economy effects of biomass use? The models reviewed do not consider landowners' freedom to choose between agriculture and forestry, or wood production's effect to the broader economy. To support my case, a brief review of general equilibrium models is next given. More in-depth look to the models is provided in Appendix 2.

Models deriving optimal forest policies from social welfare perspective by Tahvonen (1995), and Lintunen and Uusivuori (2016) confirm the findings of the rotation models. The current status quo where biomass use is treated as carbon neutral may not lead to first-best optimal outcome. Considering the value of forest as a carbon sink, the optimal policy is to subsidize landowners for forest growth, and taxing emissions from harvesting. These models account for substitution effects (biofuels replacing fossil fuels) and the wood products' value as carbon storage. Where they are lacking, is accounting for the wider value-adding effects of the forest industry, and institutional constraints, which were described in the previous section.

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[5] *Color agnosticity* borrows from its usage in the energy industry, where it e.g. refers to preferences of hydrogen production method. Some have strict preferences for green or renewable hydrogen, others argue that blue (natural gas with CCS) is equally good as it is cheaper & more feasible, and are hence color agnostic.

Tahvonen (1995) studies the taxation of CO_2 on a national level using a dynamic general equilibrium model. Key takeaways from the contribution of Tahvonen are, that from social welfare perspective, considering the preferences of landowners, firms, and the government, it is optimal to increase the size of the natural carbon sink in the forest, as forests can store carbon. Based on the study, the current policy where biomass is considered carbon neutral may not lead to the first best solution. Instead, as in the simpler rotation models, carbon tax on biogenic emissions and a subsidy for forest growth could be more optimal. In a decentralized carbon market, countries with high forest resources (such as Finland) could receive net negative taxes (subsidies) for functioning as the lungs of the market.

Lintunen and Uusivuori (2016) builds on Tahvonen (1995) to examine a first-best optimal forest sector carbon policy. The authors use a very multi-faceted forest and energy sector model with a carbon cycle module and solve for a competitive equilibrium with carbon externalities. The authors emphasize that even if forests are a renewable resource, emission free use of biomass is still not warranted. Still, with the policy options based on the model proposed (subsidization of carbon removals and taxation of emissions), it is shown that it is optimal to increase wood use to improve social welfare. In their numerical solution, before wood use is increased, the proposed policies will lead to increased carbon sink and hence climate benefits, until a new equilibrium is reached.

What has been neglected thus far, is the possibility to use land for other things than forestry. Forest could be used for agricultural production, or even for solar or wind power generation. Lintunen and Uusivuori include an option for land-use change through allowing the landowners to choose between forestry and agriculture. The agricultural crops are consumed by the households in the economy. The authors also include detailed carbon stocks for carbon in atmosphere, forest biomass, wood products, and deadwood in soil. Households, firms', and social planner's (government's) objectives are considered (profits maximized). Again, the carbon tax is proved optimal, but only if accompanied with the forest growth subsidy.

According to Lintunen and Uusivuori, the optimal policy may be implemented either as a tax (prices), or by auctioning tradable pollution permits as in EU ETS (quantities). The point at which pollution is agreed to occur has implications for policy design, but in the paper's numerical results the accounting convention does not lead to different outcomes.

Reviewed models support the case of the stand-level models, the other even suggesting that taxing biogenic CO_2 could be beneficial for countries like Finland, with vast forests. Still, based on economics, it is difficult to give a general guideline for forest management which would apply for all forests or economies. Section 6 will discuss optimal policy more in detail, tying the results to the institutional background provided throughout the thesis. For now, let us go back to the stand-level world.

3.3 Deeper look into the forest in search for the costs of forest carbon removal

In this subsection, forest as a tool to control flows of CO_2 is further discussed. In Finland, thinning is a crucial part of forestry, and harvest residues are used for bioenergy. Deadwood's carbon storage is significant – even bigger than that of living biomass (Pan et al. 2011). To get more robust insights, more elaborated stand-level studies by Pihlainen, Tahvonen, and Niinimäki (2014), and Tahvonen, Suominen, Parkatti, and Malo (2024) are reviewed. Results from these papers indicate, that increasing the carbon storage would be a cost-efficient way to reduce the net carbon emissions of Finland. The results are used later on in section 5, where costs and benefits of natural carbon storage are compared to those of BECCS.

Pihlainen in his research on Scots pine stands (which take two thirds of Finland's forests) builds an empirically validated ecological-economic model to optimize timber and bioenergy production combined with carbon storage. Based on the model, Pihlainen et al. (2014) compute a cost function for carbon storage in Finnish Scots pine forests and show that increasing the carbon storage of the forests can be a cost-efficient abatement option.

While Pihlainen's model is in its interdisciplinary approach much more complex, it is still essentially an extension of Faustmann – it still considers maximizing the bare land value over infinite rotations, now also accounting for important factors previously neglected. In the model, trees in a stand are divided in different classes, each with different timber harvest value. These classes are saw log categories (high, medium and low grade), pulpwood categories (from tree tops and logs), and wood used for bioenergy (from harvest residues and waste wood). Harvesting does not lead to direct emissions, but the model takes the production and the carbon storage of dead organic matter and timber products into account.

Effects of carbon pricing are analysed through two systems: gross subsidies (assuming carbon release burden to fall on the sectors burning the biomass) and net subsidies (similar as a scheme implemented in New Zealand, omitting carbon storage of harvested wood products and assuming direct release to atmosphere at harvest). In both systems rotations become longer, but optimal thinning differs. Gross subsidy yields shorter rotations than net subsidy, explained by a higher effect of subsidy on land value in the gross subsidy system.

Different forest stands have different productivity levels, and react to carbon pricing differently. Poor sites' carbon storage increases more than good sites' storage. For different sites, optimal carbon storage allocation is solved by minimizing the costs of an additional discounted storage in a site, such that the storage target for that site is reached. Aggregating, total, and marginal cost functions for additional carbon storage are calculated. The costs of increasing carbon storage stay relatively low up to 104Mt/CO_2 (total cost under 1bn €, marginal cost under 20€). With gross subsidy, costs are lower.

Pihlainen finds that storing additional carbon in Finnish Scots pine stands has potential of 1,5-5,5Mtpa/CO_2 in marginal cost range of 6-92€/t, lower than the studies published before. The model does however assume bare land as the initial steady state, and hence results are underestimated. We would need to have information on the current stand age class distributions all over Finland to get absolutely perfect estimates.

Something neglected thus far, is the role of soil carbon, and the freedom to choose between different management regimes. Tahvonen, Suominen, Parkatti, and Malo (2024) model the optimal stand-level wood production and carbon sink, by including individual-tree models, soil carbon model, detailed wood production economy, and an intertemporal objective for both wood production and carbon sinks. Choices of the management regime (rotation vs. continued cover), rotation ages, and thinning timing are found by reinforcement learning, a machine learning technique which enables an agent to learn by trial and error.

Key results of Tahvonen et al. (2024) are, that carbon tax leads to rotation forestry with clear-cuts being more optimal versus continuous cover forestry. Thinnings are lighter and postponed, and rotations become longer. With higher carbon prices, only clear-cuts are practiced, and it may be optimal to utilize the forest only as a carbon sink in some cases. Still, the total carbon stock is maximized with longer rotations but continuing harvesting, in comparison to not harvesting at all. Carbon prices have positive effects on bare land value.

Different models for stand-growth are applied for robustness. As in Pihlainen, tops, branches, roots etc. are included. Deadwood is littered to soil, and the value of the soil carbon sink is included in the analysis, as well as its emissions. Also, the emissions from production and decay of the wood products are included. The products are divided in several classes. Everything is added to a single equation which has around 4000 state variables. A Markov Decision Process problem, the model is solvable with reinforcement learning.

Generally, increasing carbon price leads to large carbon stock increases. The results vary depending on the stand-growth model type. Introducing carbon price leads to a regime switch from continuous cover forestry (found optimal without carbon pricing) to rotation forestry and clear-cuts, with longer rotations and bigger trees, or in some specifications no harvesting at all. This is explained by carbon pricing's increasing effect on stand density and decreasing effect on natural regeneration. If carbon sinks were valued lower, there would be more sparse forests and more room for natural regeneration. Stronger discounting favours continuous cover, as replanting artificially becomes more expensive. With low carbon price (40€) and higher discount rate (3%), carbon stock may not be increased as harvesting is more profitable.

As before, valuation of wood production and carbon sinks depends on discounting and carbon price. With higher carbon prices and discount rates, carbon sink value of the forest exceeds that of wood production. Over one rotation, wood production value increases with rate of discount, and as the forest stand matures, it exceeds the carbon sink value. Stand bare land value is maximized at an early age, as trees grow faster.

Values of wood production and carbon sinks are utilized to compute estimates for additional discounted carbon sinks. With discount rate of 3% (1%), additional net sink of 50t/CO2 (200t/CO2) is feasible with an average cost of 16€/t (30-43€). Additional sink is 200-350t/CO2 with marginal cost of 100€/t.

The results confirm the case made by Pihlainen et al.: increasing the carbon storage in forests could be a cost-efficient method to reduce net emissions. In the baseline solutions reported in Tahvonen et al., bare land is assumed at time 0. This may be a concern for the accuracy of the estimates for the costs of additional carbon sinks. Still, they are a recent finding through very well-thought models. These estimates are set side by side with the marginal costs of BECCS in section 5. Tahvonen et al. (2024) also considers BECCS, and I will return to these results in Section 5.

In conclusion, this section reviewed relevant literature on economics of forestry. To lead us into the forest, the legendary rotation model of Faustmann (1849), and its extension Korhonen and Tahvonen (2023) considering the carbon sink service of the forest, were presented. With all their simplicity, these models provide a solid foundation for analysing the questions that Finland faces in the time of rising global carbon emissions. Results of general equilibrium models studying broader effects to the economy of the forests (Tahvonen (1995), Lintunen and Uusivuori (2016)) reach similar conclusions, supporting the case: Forests have a potential which is currently underestimated, as we are only valuing them as a timber resource. Going deeper into the forest, more elaborated stand-level models by Pihlainen et al. (2014) and Tahvonen et al. (2024) give us further insights to the tradeoff between wood production and carbon sinks. They show us that forests can be a cost-efficient tool to reduce net emissions.

Whether feasible, section 6 will discuss from policy perspective. For now, it seems that the EU and Finland have seemed to have given up on *improved forest management* as a way to mitigate climate change. Priorities have been shifted to other fronts. Carbon capture and storage, and carbon dioxide removals have seen a rise in popularity at least among the region's politicians. The new technology to abate CO_2 emissions may also influence the state of the forest's carbon sinks, and hence the net emissions of an economy. This should be a given thought when planning policies for the likes of bioenergy with carbon capture and storage, as will be further demonstrated in the next sections.

Next, the calm Finnish forest (or the endless swamp of the research studying it) is left shortly behind, and we change scenery. A longship takes us to the stormy North Sea, where the modern-day Vikings are making their money. An exciting new technology is introduced, and analyzed from economics perspective: that of industrial carbon capture and storage. When applied to bioenergy production, it could allow for generating negative emissions - removing CO_2 from the atmosphere. For this to become reality, we could need cooperation between the petroleum and forest sectors.

4 Technological sinks - Bioenergy with Carbon Capture and Storage

In this section, the necessary technical details, and a historical perspective of the development of industrial Carbon Capture, and Storage (CCS) is given. Thereafter, its subcase linked to forests, BECCS, is presented, and its complicated economics is discussed. The section is concluded with an economic model of the current value chain for CCS in the Nordics, and a discussion on how Finland is positioned with respect to it, to deepen the institutional background of the thesis.

4.1 Carbon Capture and Storage - petroleum sector's solution to Paris

Carbon capture and storage (CCS) means capturing CO_2 from industrial sources, and storing it underground permanently in geological formations. Industrial carbon capture technology is in the literature often divided in three categories: pre-combustion, post-combustion, and oxy-fuel combustion capture. These all come with their own advantages and disadvantages and their practicality and costs depend on the individual process they are applied to. This thesis mainly considers post-combustion technology, as it is rather mature and applicable to current industrial processes. To build intuition, consider an industrial plant which generates energy. The plant needs to burn e.g. natural gas or biomass to do this, and a side product from the process is a highly polluting CO_2-intensive flue gas. By applying a carbon capture unit to the 'chimney' of the plant, CO_2 can be captured from the flue gas before it reaches the atmosphere. The capture unit in a way functions as a 'plug' or a 'filter' for the chimney.[6]

Storage of CO_2 is possible in for example saline aquifers and depleted oil fields. The ability of the storage to take in CO_2 decreases over time, as the CO_2 injection increases pressure in the storage reservoir. Perhaps the storage side could be modelled as petroleum production from a reservoir (see e.g. Hannesson, 1998), but in reverse. The petroleum industry is into CCS – akin to the theory of petroleum economics, the expertise of the professionals and companies in the field could be used almost one-to-one with CCS. Storage sites are rarely situated next to the industrial plants. Transport to storage by either pipeline, ships, or trucks is hence required.

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[6] Without technical background, I prefer not to go too deep into the actual mechanisms of carbon capture. Post-combustion capture is often done chemically by utilizing an amine-based sorbent. A recent master's thesis by Tognetty (2023) provides a comprehensive review of the different technologies, and further references.

Players in the oil and gas industry have been pioneers in the technology, showcasing that it is ready and safe. First scientific and commercial CCS project Sleipner was initiated by Equinor (then Statoil) in 1996. The Norwegian government imposed a tax on CO_2 in 1991 and has high requirements for the CO_2-intensity of natural gas allowed for export (maximum 2.5% while Sleipner field gas naturally contains up to 9%). CO_2 from the Sleipner gas has due to these reasons been purified by capturing the CO_2 directly from the gas, and injecting it into the deep saline aquifer Utsira under the Norwegian seabed. Sleipner has captured and stored around one million tons of CO_2 annually since it became operative (Lindberg, 2022).

Not only has the use of CCS been beneficial for the business of Equinor, but it has demonstrated, that there is potential in storing CO_2 underground permanently for hindering the catastrophic effects that rising CO_2 concentration in the atmosphere may have. Still, the amount of CO_2 stored by CCS (think Sleipner's 1Mtpa) falls short in comparison to the amount of CO_2 utilized (CCU) in industrial processes today. Largest global consumers are urea manufacturing (130 Mtpa) and EOR, enhanced oil recovery (70–80 Mtpa) (Kujanpää et al. 2023b). Appendix 3 provides more information about EOR and other CCU pathways.

Oil & gas industry is often accused of using CCS as a *red herring* to prolong the fossil era (Birol, 2023). Budinis et al. (2018) finds that gas and coal would be used by 200 EJ more annually in scenarios of wide-spread adaptation of CCS. This would lead to more emissions in the production of the fuels. Still, scope 3 emissions[7] account for 80-95% of the total life-cycle fossil fuel emissions (Wood Mackenzie, 2022). CCS could maintain the status quo in fossil fuel use. Yet, as a complementary option, it has an important role to play. Hard-to-abate industries such as cement, steel, and possibly pulp & paper, are relevant for CCS, as they have limited options for abating their emissions.

One key technical concern is the potential leakage of CO_2 at any part of the supply chain. My thesis is optimistic, and assumes no leakage. Using an integrated assessment model, van der Zwaan and Gerlagh (2008) finds that even with some leakage, CCS can be a valuable option for climate change mitigation. Furthermore, Paltsev et al. (2021) use the MIT Economic Projection and Policy Analysis model (a global multi-region multi-sector energy-economic model), and finds that global emission mitigation costs would be much higher without CCS.

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[7] Scope 3 emissions are those emissions which are not produced by a company, but the end-users of the products that the company produces. Scope 2 are indirect emissions produced by the company (related to energy use), and Scope 1 are emissions in direct control of the company.

4.2 Bioenergy with CCS (BECCS) - forest sector as remover of CO_2

Carbon Dioxide Removal (CDR) means capturing CO_2 from atmosphere and storing it permanently. Bioenergy with CCS (BECCS) is categorized under both CCS and CDR. BECCS means capturing CO_2 from combustion of biomass for energy generation combined with the permanent storage of the captured CO_2. The biomass can be derived from crops, trees, agricultural or forestry residues, and organic wastes (Bellamy et al. 2021). BECCS could in the big picture have very different meanings due to the different biomass sources for combustion available in different geographical regions.

In Finland, the main source for biomass would be the forest. In practice, Finnish bioenergy producers would capture the CO_2 which they produce by burning forest residues or wood fuels for energy. Thereby, the forest industry could effectively *remove* CO_2 from the atmosphere. As the plants have absorbed the molecules, capturing them makes BECCS carbon negative - or at least carbon neutral, if you ask the forest economists. Kujanpää et al. (2023) estimates the theoretical potential for carbon capture in Finland's coastal industry clusters to be up to 13,8Mtpa/CO_2 starting from the 2030s. Of this, 9,8Mt (71%) is biogenic.

While still unproven at scale, BECCS is currently the most cost-effective technology available for removing CO_2 from the atmosphere. Fajardy et al. (2021) use the MIT Economic Projection and Policy Analysis model, and finds that BECCS could reduce the costs of meeting stabilization targets. That straightforward it is not. There are major environmental and economic tradeoffs involved with large-scale BECCS deployment.

First, IPCC scenarios with higher probability of reaching the 1.5-degree target require BECCS removal of 12Gt/CO_2 per year (quarter of current total emissions). This would require a large amount of additional land to be concentrated purely on BECCS: additional land use required is estimated to be between 0.4 and 1.2 billion hectares of land, or 25-80% of the current global cropland (Fajardy et al., 2019). Land requirements pose a great challenge for global BECCS deployment, and Direct Air Capture (DAC) may prove in this aspect more viable. Smith et al. (2016) estimates DAC effects on land use to be negligible unless renewable power production requires much more land due to the higher energy use by DAC.

Second, if CO_2 is removed from the atmosphere at the cost of food production, the global food prices could increase. Fajardy et al. (2021) show that price increase in commodity prices including food is visible (4-5% higher in simulated 2100 vs. 2015), but limited given the scale of BECCS deployment. This is due to the rising global population balancing the situation, as agriculture will remain profitable due to high global food demand.

Third, CCS is a very energy intensive technology, and will lead to increase in demand for electricity. For BECCS globally this is not a major issue per sé – by definition, bioenergy is generated while biomass is combusted. In the Fajardy et al. (2021) model, 1.5- and 2-degree scenarios with BECCS lead to around twice as high energy generation as those without (relying on nuclear, CCS, wind, solar, and afforestation). Smith et al. (2016) find, that BECCS would generate 170EJ of energy in a year in 2100, while DAC would require 156EJ/year.

For BECCS, increased energy production and potential cost-effectiveness are strong arguments. However, the land-use and food price tradeoffs are challenging. In addition, Fajardy et al. (2021) does not consider the political feasibility or distributional issues. Largest amount of BECCS is simulated to happen in Africa, Eastern Europe, and Central Asia. Africa needs energy for its growing population, and has plenty fast-growing trees and oil fields. Yet, it has scarce economic resources today. In the increasingly divided world we would need a true global solidarity, and increased cooperation between people and industries such as those of petroleum and forestry, to make BECCS in any way relevant option going forward.

Let us go back to the Nordics, where such cooperations are already emerging (e.g., Scastone). In Finland, the potential and focus (at least for now) is in using BECCS to reduce the current industrial emissions - not in generating maximum amount of negative emissions. The Finnish existing industry needs to produce more energy (heat) to power the capture units. As was described in Section 2, Finnish industry plants mostly function on bioenergy derived from burning harvest residues and wood fuels. Hence, demand for them would increase.

Karlsson, Eriksson, Normann, and Johnsson (2021) investigate the relationship of biomass supply and large-scale BECCS implementation in Sweden, and finds, that targeting the pulp and paper (P&P) industry for BECCS results in significant additional biomass demand. This could limit possibilities for BECCS in regions where biomass is demanded also in other sectors than P&P. Northern Sweden's P&P plants are show to be more optimal for BECCS than the southern ones due to better biomass availability.[8] Use of biomass for energy could in the P&P plants studied increase by 40-63% of the current use. Results of Karlsson et al. could be assumed to generally hold for the Finnish case due to regional similarities.

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[8] Use of other wood fuels, procuring harvest residues outside the local region of the P&P plants, or importing biomass for energy generation could be options, but are not considered in Karlsson et al. (2021).

The additional biomass combustion increases the electricity production of the industrial plants. Electricity output could from the Swedish plants studied in Karlsson et al. increase by a total of 1,35TWh (around 8,5% of their current biobased energy use). This electricity can then be used to compress the CO_2 for transport, or be sold to the market, to mitigate the costs for capture. Energy required for CO_2-compression is not considered in the study.

For the individual factories, the energy intensity of the capture units leads to a tradeoff between production and capture rate. Karlsson et al. finds, that the Northern Swedish P&P plants can achieve a higher capture rate (81%) due to the better biomass availability. For Southern Swedish plants, lower capture rate designs are suggested, unless other biomass sources than local harvest residues can be used.

Rodriguez et al. (2021) studies the Swedish and Finnish company perspectives on BECCS qualitatively, by interviewing large-scale emitters of biogenic CO_2 in the countries. Four emerging tensions regarding BECCS are identified: (1) absence of reliable long-term policies; (2) limits to companies' climate change responsibility; (3) technical trade-offs of carbon capture; and (4) lack of customer demands for negative emissions.

There are no incentives for the Finnish forest industry to do BECCS with the current regulatory framework. The tax on biogenic carbon proposed in the previous section could work - but it could also be detrimental for the forest industry in the short run. Paying the high costs of BECCS alone, and compensating from production to power the capture units is not in its interests.

Given the summarized challenges can be solved, BECCS can become a potential tool for Finnish industries to reduce emissions. It could also prove to be a very efficient pathway to reach the national carbon neutrality targets for cases like Finland. As described in Section 2, forest industry emissions are remarkably high in Finland. Theoretically, there is a very high potential to reach large emission reductions by 'putting a plug' on few industry chimneys, instead of concentrating on hundreds of thousands of small chimneys and exhaust pipes. Hence, there is a high national interest for having the industry do this. From economics perspective, we should of course ask whether this is *cost-effective* compared to other abatement options. Market creation considerations are next discussed, in order to see what would be needed for BECCS, and more generally CCS, to become a reality.

4.3 Creating markets for (BE)CCS in the Nordics

Fitting capturers, transporters, and storers together is a difficult task, due to lack of incentives and coordination issues. In the industry, it is a common saying that there is a ’chicken and egg problem’, as nobody wants to be the first mover if there is no certainty about the others following. All parties in the value chain need each other – and they all need to make individual final investment decisions. No capture without storage, no storage without capture. Nothing without transport. It is a three-way street. All market participants need to at least break even by participating. This has until now been impossible, as cost estimates for the entire value chain of CCS have been higher than the carbon taxes (or in Europe the ETS).

CCS can be incentivized by *stick* policies like carbon taxes. The Norwegian sticks perhaps led to birth of the whole technology. The EU ETS allows for CCS - the industries which need to buy pollution permits for their emissions, can simply avoid this by capturing their emissions, and storing them permanently. On the other hand, there are currently no stick incentives for BECCS, as biogenic CO_2 is considered carbon neutral. This sets the bioenergy industry in a tricky situation, as it cannot benefit monetarily from doing BECCS, unless someone pays for their effort. Bilateral agreements between companies are taking place (e.g. Microsoft paying for Ørsted to offset their own emissions), but the scale is still small, and demand almost non-existent. EU Commission and Parliament have agreed to set a framework for voluntary carbon removal credits, but the legislation is still unclear. Even if the costs of ETS allowances have been high in recent years, and the future ETS prices are expected to be even higher, little investments in CCS have been made.

Alternative to *sticks*, the social planner may offer *carrots* for the emitters in the form of e.g. tax credits or subsidies. This is the preferred approach in the US. The Inflation Reduction Act gives generous tax credits of 85€/tCO_2 stored. In Europe, Norway has been leading the way in CCS market development, and the government is heavily subsidizing the process. In 2020, Norwegian government initiated the project Longship, aiming to demonstrate the first complete value chain of CCS. In it, emissions are captured from industries in Oslo fjord, and transported by ship to storage in Øygarden. The company doing the transport and storage, Northern Lights, is 80% subsidized by the Norwegian state. Longship is expected to become operational in 2025 (CCS Norway), and Northern Lights in 2024, with a capacity of 1.5-5Mtpa/CO2 for storage. Northern Lights has ordered 3 ships for transport (Northern Lights).

Figure 1: The Salop circle (Golombek et al. 2023)

Golombek, Greaker, Kverndokk, and Ma (2023) models the value chain by focusing on decisions taken by the market participants. Authors find, that due to network effects and market imperfections, such as market power, the market for CCS has not yet emerged. Providing incentives for the agents involved could help the markets surpass the tipping point.

Authors model the value chain using Salop circle model, often used in industrial organization economics to analyze consumer preferences by geographic location. In Golombek et al., CO_2 capture plants ('customers' of the CO_2 storages) are uniformly distributed around a circle, with potential terminals (initially none) located between them evenly to reduce transportation costs. Storage is located in the centre. See Figure 1 for a simple illustration.

Capturing plants are subject to a Pigouvian carbon tax correcting for the negative externality of emissions (by assumption EU ETS). Capturers can avoid this tax by installing a capture unit to their plant and transporting emissions to terminals. Golombek et al. derives equations for the total costs of investments in CCS for the capture facilities, including transport to terminals. The terminals in hand must pay a fee for the storage operators for depositing the CO_2. The equations are then used for deriving socially optimal outcome – the cost-minimizing amount of carbon capturing plants, and terminals.

Different market structures are studied, by calculating market clearing equilibria for the cases of government regulated storage, storage with monopoly power, and cartel (integrated storage and terminal). Each of these are analyzed as multi-staged games within the Salop model, assuming all investments happen simultaneously. In all cases, investments in carbon capture are lower than in the social optimum.

Comparing total costs to social costs, regulated storage fairs best, followed by cartel and monopoly storage. In regulated storage, the terminals have more market power. This may lead to suboptimal number of terminals due to excess entry. In the cartel case, the integrated cartel's market power results in higher costs and fewer investments. Monopoly storage leads to higher costs for capturers and terminals. No investments occur at tax lower than 60€/tCO_2, although it would be socially optimal to invest if the tax exceeds 56€/tCO_2. Higher taxes might still not lead to investments. Markets may in other words be in a state of *excess inertia*.

Different options for the policymaker to correct for solving the key issues are proposed. Offering a subsidy for capturers in the cartel case would lead to first-best outcome, as without it the capturers would face a non-competitive market price. This subsidy should be increasing with the Pigouvian carbon tax. In the cartel case, no tendering of terminals is needed as the profit-maximizing cartel builds the optimal number of terminals. In regulated storage, could an entry tax be imposed to prevent excess entry.

Limitations of the Golombek model is that it is static, and a fixed carbon tax is assumed. EU ETS's volatility has hindered CCS investment, contrasting with the more stable 85$/t$CO_2$ tax credit under the US Inflation Reduction Act. At the time of writing, the ETS price had dropped to a 3-year-low 56€/tCO_2). Even if the ETS future expected price is higher than the current one, it does not give confidence for investors to risk their money. High interest rates, and geopolitical risks have further discouraged investment.

The model is a simplification but captures the essential dynamics of the CCS value chain. Potential CO_2 capturers are as in Golombek et al., distributed around the North Sea. They are in general located close to industrial clusters such as Teesside or Humber in the UK, and the terminals in the most feasible cost-optimal locations from them. From these clusters, the economies of scale linked to the terminals (transport) are particularly relevant.

Storage sites have been announced in Norway, Denmark, and the UK, both offshore and onshore – also outside the simple North Sea Salop circle. Particularly Equinor has high ambitions, targeting a storage capacity of 35-50 Mtpa. Equinor will initially do the transport with ships, but also a CO_2-pipeline from Belgium to Norway is being planned. The company could currently be seen as the cartel of the Golombek model. The company is amassing market power but is unlikely to have total monopoly, due to interest from other players.

To summarize, Golombek et al. highlights that CCS markets are currently stagnant, due to market imperfections and coordination problems. Even if investments in technology would be socially optimal, little is being invested today. Government intervention may be necessary to overcome the barriers. The wording 'socially optimal' should be interpreted cautiously, as the model does not consider alternative emission reduction methods.

4.4 Linking Finland in the value chain - what would BECCS cost?

Total costs of (BE)CCS consist of fixed capital expenditure (CAPEX) for the infrastructure required (capture units on the capture side, pipelines/ships on the transport side, drilling injection wells on the storage side), and variable operational expenditure (OPEX). To conclude this section, the costs for the case of BECCS in Finland are analyzed, in preparation for next section's comparative analysis. Capture and transport costs are given more treatment.

For the marginal costs for the entire value chain it is difficult to give general estimates, as the costs depend on the industrial process, transport method, and storage site. Generally, fossil CCS is more mature and cheaper than BECCS. Marginal costs for the whole value chain can be as low as 20€/tCO_2 in the case of fossil fuel CCS, and up to 400€/tCO_2 for BECCS. According to Kujanpää et al. (2023a), there are several industrial plants in Finland, which could currently do BECCS at a cost of 120-150€/tCO_2. Cost estimates of the report are indicative, based on general estimates from Kearns et al. (2021).

Capture costs may be calculated by multiplying an estimate for the capture of bioenergy by a scale factor to approximate costs specifically for the Finnish bioenergy plants. For exact costs of BECCS in Finland, a detailed data from all industrial plants would be needed. A comprehensive model for BECCS costs specifically in Finland is out of the scope of this thesis.

The capture of the molecules is the most cost-intensive part of the value chain. Applying a capture unit requires high upfront investment in the capture unit and energy generation. Most of the variable costs are typically due to increased energy consumption, and/or operating a new unit for energy generation specifically for the needs of the carbon capture. *Ceteris paribus*, the capture costs are inversely related to the partial pressure of CO_2 in the flue gas. In pulp and paper industry, flue gas is of atmospheric pressure (101 kPa), whereas the partial pressure of the CO_2 in it is low (16 kPa). This leads to higher energy requirement to separate the molecules from the gas, hence higher costs. [9] Kujanpää et al. estimates capture costs to be 72,8€/t for a bioenergy plant with emissions of 300ktpa, and a 90% capture rate. After capture, the molecules need to be compressed in case of ship transport. Kujanpää et al. estimates compression to cost roughly 20€/t for the same bioenergy plant as above.

Transport and storage cost much less, but they can have very high fixed costs, if a new pipeline or ships are built. Transport of the CO_2 from Finland to the potential storage sites

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[9] See Kearns et al. for a more detailed technical description of partial pressure, and how it affects the costs.

would most likely happen with ships. Transport costs are the higher, the higher the geographical distance is. Sharing transport infrastructure lowers the costs for the whole value chain per capture unit. Swedish government report (SOU 2020:4) estimates transport costs for different Swedish plants considering BECCS, and estimates the shipping costs to be 13-26€/tCO_2[10]. Much more expensive than that can shipping not be from Finland.

Even if cost-wise the shipping distance would not make pivotal difference, the time for transport is a key factor to consider. The ships of Northern Lights will have cargo tank volumes of 7500m^3, with cargo density of 1100kg/m^3. A ship will be able to transport 8,25t/CO_2 at once. With ship speed of 14kts, transit time from Kemi to Aarhus is 2 days and 18 hours, whereas from Kemi to Bergen the transit is 3 days and 19 hours. If we reserve one day for loading and deloading (discharge rate for Northern Lights ships is 800m^3/hour), one ship is able to make approximately 52 journeys to Denmark, but only 40 to Norway. A ship to Denmark would be able to transport 429ktpa/CO_2, whereas a ship to Norway only 330ktpa.[11] Shipping emissions are also lower in the case of Denmark.

For annual BECCS of 10Mt, with the shipping capacity of 429kt per ship, some 24 ships would need to be built. If we assume ship cost of 50 million euros, the upfront CAPEX would be 1,2 billion euros. If higher ship cargo capacity is possible, less ships would be required, and Norway as a storage option could be more viable again. Transport terminals have been suggested to be built in coastal cities of Kotka and Pori (e.g. Kujanpää et al., 2023). However, transport from inland to these terminals would increase the costs, and there are still no concrete plans on how the transport would be implemented.

Kujanpää et al. uses general estimates from the literature for the storage costs (18€/t + 8€/t for shipping deloading and pipeline transport to storage). Combining this with the Swedish report estimates, we would get shipping and storage costs of 31-52€/t. This is in line with the Northern Lights targets transport and storage cost of 30-55€/t.

Marginal cost for the whole value chain of BECCS in Finland is in Kujanpää et al. estimated to be 119-230€/tCO2 or 117-172€/tCO2 with shared logistics. Weighted averages of these costs are used as benchmarks for BECCS costs in the next section. The eventual decommissioning of the infrastructure and the risk that the assets become stranded should be taken into account in the analysis, although are out of the scope of this thesis.

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[10] 150-300 SEK converted to EUR with an exchange rate of 0,087 (rate of 10.4.2023).

[11] Data from publicly available Northern Lights FEED report (Equinor), and Searates Cargo Calculator.

5 Carbon removal through forests versus BECCS - numerical and comparative analysis

The stormy North Sea proved to be a busy place. As the previous section shows, there is a multitude of moving pieces to consider before (BE)CCS can become a reality. In theory, it could be an efficient way to significantly reduce Finland's emissions. However, effects of harvesting on the forests' natural carbon sinks should not be forgotten about. In this section, we hike on the *fjells* of Fennoscandia, and look at both the storages in the forest and the bottom of the sea at the same time, to understand the results of the previous sections better.

The potential of doing BECCS in scale in Finland is analyzed from two viewpoints. First, in the more demanding part of the hike, BECCS is connected to the forest economics research, to see what BECCS would mean for the forest use and hence the net carbon sinks. Second, having reached the peak of the *fjell*, the costs and benefits of BECCS are compared with those of enhancing forest carbon storage.

5.1 BECCS through the lens of forest economics

Here I apply the model of Korhonen and Tahvonen (2024) to the case of BECCS, and show that forest rotations may remain short if we capture the carbon from bioenergy generation. In other words, the profitability of harvesting could remain high, which could reduce the natural carbon sinks. Tahvonen et al. (2024) finds, that BECCS does indeed increase wood production value of the forest. Compared to the business as usual case, BECCS could have an increasing effect on net carbon sinks. Results are, however, sensitive to the model parameters such as carbon price, discount rate, and timber price. In Tahvonen et al. (2024), increasing carbon price leads to carbon sink value of the forest dominating the wood production value. Hence, BECCS offers an additional tool for carbon removal, but unlikely replaces the natural forests' carbon sinks as an economically important climate mitigation tool.

Let us first go back to the simpler stand-level world. In the model by Korhonen and Tahvonen, the landowner maximizes the value of the bare land, taking into account both the value of wood production and the value of carbon sink. Equation for the landowner's optimization problem was as follows (see Section 3 and Appendix 1 for more elaborated technical details):

$$W(t) = V_w(t) + V_c(t) = \frac{pf(T)e^{-rT} - c}{1 - e^{-rT}} + \frac{\tau\theta\omega[\int_0^T f'(s)e^{-rs}ds - \beta f(t)e^{-rT}]}{1 - e^{-rT}} \tag{2}$$

An interesting case arises, if we assume that the emissions from bioenergy use can be avoided with BECCS. As better explained in Section 3, in the carbon sink value term ($V_c(t)$) the parameter β is equal to the present value of CO_2, which in hand comes from $\alpha/(\alpha + r)$, α being the rate of decay of harvested biomass. All harvested biomass is not used for bioenergy generation, but let us consider a case where it is. If we apply CCS to bioenergy generation, the rate of decay of the biomass is not relevant to consider. If we can capture and permanently store all emissions, α goes to 0, and hence β goes to zero. This would lead to the whole second term of the carbon sink value function vanishing. In other words, the social costs of CO_2 emissions would not affect the landowner's optimization anymore:

$$W(t) = V_w(t) + V_c(t) = \frac{pf(T)e^{-rT} - c}{1 - e^{-rT}} + \frac{\tau\theta\omega[\int_0^T f'(s)e^{-rs}ds]}{1 - e^{-rT}} \tag{5}$$

BECCS leads to a case where the landowner maximizes the sum of net harvest revenues and the present value of gross sink. If carbon taxes can now be avoided, will harvesting become relatively more profitable, which leads to shorter rotations. This is possible, but quite tedious to prove analytically, so I took a numerical approach, in footsteps of Tahvonen, Korhonen, and Laukkanen (2024)[12].

Assume $p = 33$, $F(t) = (200+750e^{-0.01t})*(1-e^{-0.05t})^8$, $c = 1100$, $r = 0.02$, $\tau = 56$, $\omega = 1.9$, $\theta = 0.733$ [13] Equation (5) becomes as follows. See Figure 2 for a visual illustration:

$$= \frac{33 * 500(0.4 + 1.5e^{-0.01t}) * (1 - e^{-0.05t})^8 * e^{-0,02T} - 1100}{1 - e^{-0,02T}}$$

$$+ \frac{56 * 0,7 * 1,9[\int_0^T f'(s)e^{-0,02s}ds - 0,15 * 500(0.4 + 1.5e^{-0.01t}) * (1 - e^{-0.05t})^8 * e^{-0,02T}]}{1 - e^{-0,02T}}$$

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[12] The case is taken directly from the exercises and lecture slides of the Advanced Natural Resource Economics course at University of Helsinki, prepared by Korhonen, Laukkanen, and Tahvonen in 2024. I applied the model by including the new BECCS case with β=0, which results in equation (2) becoming (5). Costs of BECCS are neglected for simplicity.

[13] p =timber price, $F(t)$ =forest growth function, t =time, c =regeneration cost, r =discount rate, τ =social valuation of carbon, ω =biomass expansion factor, θ =CO_2 per m^3 biomass. Values for $F(t)$, ω and θ are borrowed from the aforementioned lecture slides, originating from empirical estimates. $\tau = 56$ was the social cost of carbon in Golombek et al. (2023). Rest of the parameters were randomly chosen, but were tested for robustness. See Appendix C for these 'robustness checks' or additional results.

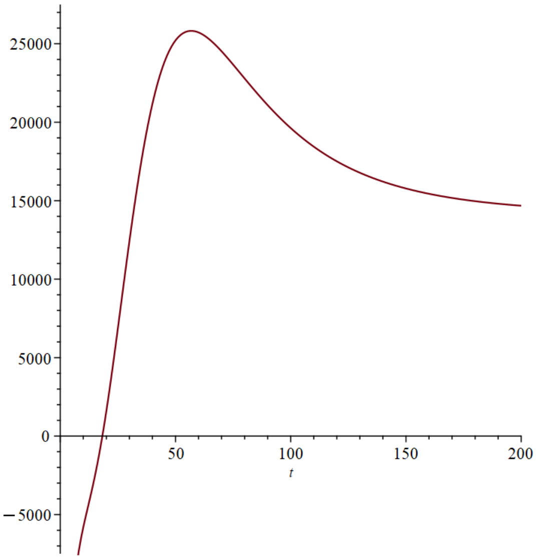

Figure 2: Korhonen and Tahvonen (2023) applied: Equation (5) optimized in Case of BECCS. X-axis depicts time in years, y-axis value of the function in €.

Figure 2 depicts the monetary value of the forest land through time. As forest grows, the value of the forest land first increases at a rapid pace. It reaches maximum at 56.8 years. If the forest is left standing after this, its value declines. Hence, it is optimal to harvest at 56.8 years.

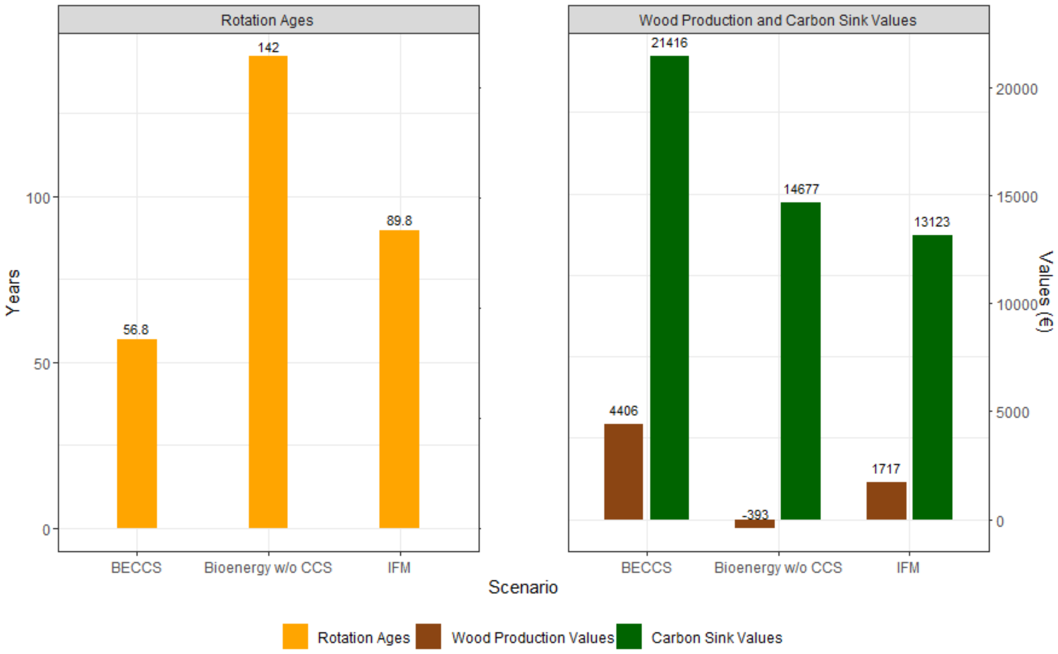

Figure 3: Base case numerical results.

Figure 3 visualizes the optimal rotation ages and corresponding bare land values in each scenario chosen for the analysis[14]. BECCS is in Equation (5) optimized with $\beta = 0$. Bioenergy without CCS is Equation (2) optimized with high β. IFM stands for Improved Forest Management, and is Equation (2) optimized, β set at 0.88. Left-hand graph depicts the optimal rotation age of the forest. Right-hand graph depicts optimal bare land carbon sink and wood production values of the forest land. Maximizing the above function with respect to the decision variable T, the optimal rotation for the whole equation becomes 56.8 years. The maximum sustained yield rotation ($F(t)/t$)) is 57 years, more or less equal to the 'BECCS rotation age', implying that BECCS could get us very close to carbon neutrality from stand-level perspective. Carbon sink value of the forest (21416€) nevertheless dominates the wood production value (4406€) by a large extent.

In addition to BECCS leading to shorter rotation, the effects on land value are remarkable. Applying BECCS could lead to higher forest land values, and this could imply higher costs for the taxpayers. Effects of increasing carbon prices have even stronger effecs on land values, as reported in Appendix C.

In case of improved forest management, results are as follows. If we take a case where β is high, yet not 1, as if we are producing pulp or paper (0.88), and we maximize the original equation (2), the optimal rotation becomes 89.8 years. Bare land value for wood production becomes 1717€ and for carbon sink production 13123€. Rotation ages are longer, but harvesting still takes place. Land values are not as high with BECCS, which could imply lower cost for taxpayers.

Let us for illustration use equation (2), and set value of β close to 1 to demonstrate what happens if bioenergy is produced without BECCS. The optimal harvest should happen at 142 years (wood production and sink value maximizing rotation age). Value of timber production turns negative (-393€), whereas the carbon sink value is strongly positive (14677€). It would be more optimal to keep the forest standing because of the sink value, than harvesting for bioenergy use. Yet, even if the rotation age becomes very long from a single landowner perspective, harvesting does still take place in this specification.

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[14] Business as usual (BAU) case is not reported in the graph. Applying $\tau = 0$, the carbon sink value of equation (2) vanishes, and we are left with the Faustmann formula. Optimizing equation (1) with the parameters used in (5), optimal rotation age becomes 50.23 years, and wood production value 4598. Since I assume that we value carbon, and I am interested in finding which of the two key methods is more optimal for reaching Finland's targets, BAU is excluded. Bioenergy without CCS is reported for illustration.

Varying the model parameters has little effect on the optimal rotation age in the BECCS case. As the Karlsson et al. (2023) in the previous section showed, BECCS leads to increase in biomass demand. This could lead to an increase in the price of timber, which in hand would make harvesting more profitable. In my numerical example optimal rotation indeed becomes shorter with a higher timber price, but only slightly. Increasing discount rate, has similar effect on the optimal rotation age. Significantly increasing the carbon price moderately increases the rotation age. Even if carbon taxes are very high, keeping forest standing longer is less profitable than harvesting, as the carbon taxes (assumed to bind biogenic emissions) can be avoided with BECCS. See Appendix C for illustrations of the 'robustness checks'. Even if rotation age is robust in BECCS case, it proves sensitive with other parameter values, as do the pure land values in all cases.

BECCS was analyzed here through a highly simplified model. A more detailed stand-level model is required to get more robust takeaways. The previously introduced Tahvonen et al. (2024) build such a model, and consider the case of BECCS. The model was the one that included tree size structure, soil carbon model, wood production economy, option for different management regimes, thinning and harvesting times, and stochasticity in growth and natural disasters. Agents were trained by reinforcement learning (see Section 2 for a detailed review).

In Tahvonen et al. (2024), BECCS is applied to bioenergy generation from harvest residues. Similarly as in the numerical case I made above, flow of emissions from the harvest residues is in Tahvonen et al. set to 0. In general, carbon stock in products and BECCS storage increases boundlessly, and net carbon sinks increase. As could be predicted from the simpler model by Korhonen and Tahvonen, BECCS unambigously increases wood production value. Still, its effect on net sinks and optimal harvesting depends heavily on the level of carbon price. In the business as usual case with 0 carbon price and a positive discount rate, BECCS does lead to an increase in the net carbon sinks (42% and 20% with r=1% and r=3%).

Model of Tahvonen et al. is more sensitive to the model parameters, than my numerical illustration. If carbon price is increased to 100-200€/t, average wood production decreases with carbon price, and it becomes more optimal to store carbon in forests, regardless of BECCS. Still, harvesting takes place, albeit rotations being very long. Discount rates have a noteworthy effect on the wood production values. With 1% discounting, wood production values are strongly positive, but they turn negative with 3% discounting.

In the current state of world, where biogenic emissions are not taxed, BECCS could indeed lead to a scenario, where the net carbon sinks are much higher. Biomass demand is expected to increase due to wood production becoming more valuable, but BECCS allows for keeping the net emissions in control - and even decreasing them (if we do not consider its effects on timber prices). From climate mitigation point of view, it could be a much better option than the current one with high amount of logging and emissions.

Still, it is unclear whether adding BECCS to the current world would lead to the best solution - at least if considering the costs. In my very simple application of Korhonen and Tahvonen, as well as in Tahvonen et al. (2024), BECCS is assumed to be free, which is far from truth. In the real world, the landowners are not the ones paying for BECCS, unless we think of forest companies who source the wood fully from their own forests (unrealistic).

Same increases in net carbon sinks could be achieved by *improved forest management*, improving the carbon sinks in forests. In the next subsection the costs and benefits of enhancing the forest carbon storage are compared to BECCS.

First, some concluding discussion to the inclusion of BECCS to the stand-level models is given. In these models it is the landowner who is subject to taxation, *and* who receives the subsidies for growing the carbon sink. If it is not the landowner, but the bioenergy generating firm, who pays the taxes, the landowner's optimization problem would be the same (5) with or without BECCS. Perhaps future research could look at BECCS in cases of net and gross carbon taxation as Pihlainen et al. (2014).

Limiting the stand-level models, is them assuming exogenous and constant timber and carbon prices. As BECCS leads to increase in wood production value (Tahvonen et al., 2024) and biomass demand (Karlsson et al. 2023), this could lead to different scenarios due to the effects on timber prices. Carbon prices are not constant, but volatile as the EU ETS has shown. As BECCS could be included in ETS, this could have implications for the ETS prices. Future research could look into including BECCS in a general equilibrium approach such as that of Lintunen and Uusivuori (2016), and introducing uncertainty in the carbon price.

Whether simply assuming zero emissions in the stand-level framework is enough, is another question. BECCS could require a new theory of its own. The 'new theory' could be still thought from the Faustmann perspective of a landowner maximizing the value of the bare land, or a forest company maximizing its profits. The landowner or the firm could have options for harvesting and producing bioenergy with or without BECCS. Timing is key - it is likely that there is an optimal age for BECCS, which maximizes the economic value given the resource scarcity. Perhaps the theory could include a broader set of agents, than the foresters. As was demonstrated in the previous section, the value chain for BECCS requires also the storers and transporters, who need to make a profit with their business. Perhaps this would require a step out from the Faustmann world towards a general equilibrium model.

The hike up was not easy, but the analysis clarified us something. BECCS could be a way to increase net carbon sinks. It could however lead to shorter rotations, which could be problematic if we consider factors such as biodiversity. Discount rates and carbon price level are important in the analysis. Increasing (introducing) carbon prices for biogenic emissions could lead to an increase of similar magnitude in net carbon sinks with or without BECCS.

5.2 Costs and benefits of forest storage enhancement versus BECCS - case of Finland

This subsection sets forest storage enhancement side by side with BECCS. The two methods of emissions abatement are compared, taking into account their costs and benefits, specifically in the case of Finland. Main finding is, that costs of BECCS are considerably higher than those of practicing improved forest management. BECCS could be politically easier to implement, but given the challenges in market creation, it is easier said than done. These two options are however not mutually exclusive. Forest sinks could first be enhanced to achieve higher national net emissions, and thereafter BECCS practiced with a lower economic cost.

Costs: Improved forest management is cheaper

Let us summarize the costs for both options. For forest storage enhancement or *improved forest management*, estimates from Pihlainen et al. (2014) and Tahvonen et al. (2024), which are a result of rigorous economic modelling, are used as benchmarks. For BECCS, the cost esimates are taken from the report by Kujanpää et al. (2023a), which provides more of an indicative rough benchmark, based on a report by Global CCS Institute (Kearns et al., 2021). Both estimates were presented in Sections 3 and 4, but their origins are briefly repeated here.

Pihlainen et al. finds that storing additional carbon in Finnish Scots pine stands has potential of 1,5-5,5Mtpa/CO_2 in marginal cost range of 6-92€/t. The authors reach this estimate by multiplying the annual cost of additional storage (found by using a model) by discount rate of 3% (present value of additional storage can be treated similarly as a constant perpetuity). If we take the simple average of the upper and lower bounds of the marginal cost range, we get an estimate of 49€/t. Reducing the net emissions by 5,5Mt would cost 269,5 million euros. Pihlainen et al. is from 10 years back, and assumes bare land as the starting point of their model, which undervalues the costs to some extent. However, the simple average marginal cost I used could be quite conservative. Weighted average cost could be lower.

Tahvonen et al. find that with a 3% discount rate, an additional sink of 50t/CO_2 per hectare can be obtained with a cost of 16€/tCO_2 on average. With the additional sink of 50t from Tahvonen et al., 37Mt of additional storage would be in reach with the average cost of 16€/tCO_2. Reducing net emissions by 37Mt would cost 592 million. If we only reduce emissions by 5,5Mt as in the earlier case, costs would be 88 million euros.

Kujanpää et al. (2023) presents indicative cost estimates for BECCS, based on general estimates from Kearns et al. (2021). Capture costs are calculated by multiplying a specific estimate for the capture of bioenergy by a scale factor to approximate costs of the Finnish bioenergy plants. Marginal cost for the whole value chain of BECCS in Finland is in the report estimated to be 119-230€/tCO_2 or 117-172€/tCO_2 with shared logistics. Let us consider the case of shared logistics. Weighted average for it is 133€/tCO_2. With this marginal cost. Considering only the industrial plants with 100% biogenic emissions, the weighted average stays almost the same, being 134€/tCO_2. Removing 5,5MtCO_2 would cost 737 million euros.

	Scots pines (2014)	Whole forestry land (2024)	BECCS (2023a)
Cost/MtCO_2	49€	16€	134€
Cost/5,5Mt	269,5M€	88M€	737M€

Table 1: Marginal cost estimates (Pihlainen et al., Tahvonen et al., Kujanpää et al.)

Costs of removing 5,5Mt/CO_2 with BECCS is based on the above estimates much more expensive than reducing net emissions by investing in natural carbon sinks.

Sweden is planning to go big with BECCS. A government report (SOU 2020:4) proposes a set of complementary measures to help the country reach its net zero targets by 2045. The report's proposed targets for 2030 and 2045 are to reach emission abatements of 3,7Mt and 10,7Mt/ respectively. These complementary measures are BECCS, forest carbon sinks, and verified emission abatements in other countries. For 2030, BECCS is set a target to account for 50% of these measures, and for 2045 its target is 25-100%.

Swedes are planning to do BECCS partly with taxpayer money. The report estimates a government subsidized abatement of 1,8Mt/CO_2 to cost 1,5-2bn SEK, roughly 130-170M €.[15] Sweden will subsidize BECCS with a reverse auction, to make sure that an adequate amount of support is given to the most cost-optimal projects. The Swedish report expects BECCS to be feasible with a cost of maximum 1100SEK/t, which is around 94€/t. Some of the report's cost estimates are referred to come from personal discussions with industry experts. Shipping and storage costs are also set a low requirement of 250-500 SEK. As Section 4 showed, storage side has high fixed costs, and is unlikely that they will do their part *pro bono*.

Either way, the cost of 170 million for 1,8Mt is less, but not far off from my simple calculation of 734 million for 5,5Mt. Seems like still, enhancing the forest carbon sinks could prove much cheaper - and the Swedish report could be greatly overestimating its costs. Furthermore, the effect of harvesting on carbon sinks is neglected in the report, and the whole value chain of forestry and BECCS is not considered in the analysis.

Something important to note is that the cost estimate for BECCS above is a financial cost, and not an economic cost. If instead we talk about *economic costs*, BECCS would actually prove costlier. Economic cost includes the financial cost, and the opportunity cost - what else could have been done instead of BECCS. The marginal cost estimate above does not consider the time value of money. This leads us to a discussion of the benefits of the different options.

Benefits: either likely yields more climate benefits than the do-nothing scenario

The two ways to reduce national net emissions are related, as same forest could be used for both at different points in time. This means that BECCS is actually costlier than the financial marginal costs imply, if we take into account the opportunity cost of not using the biomass burned as a natural carbon storage. Still, even if improved forest management seems like a no-brainer in the shorter term, it is complicated due to uncertainty and institutions. As is BECCS, due to the market creation challenges. Climate change further complicates the analysis, and could make either of the options more 'beneficial'.

Climate change as itself is not beneficial for anyone, and either of the options could be effective ways to mitigate it. A short-term benefit for Finland would be, that both options could

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[15] The cost estimates are net of possible EU level support, I suppose this would mean the EU Innovation Fund, which is currently supporting e.g. the Stockholm Exergi BECCS project.

efficiently help the country reach its ambitious net zero targets. In long-term perspective, learnings from doing something home could be leveraged globally, to mitigate climate change, and perhaps even make money in the process.

What if we postpone harvesting timber for wood production and bioenergy generation? If the forest is kept standing for longer, it absorbs more CO_2, and stores it in biomass and soil. In a later point in time, harvesting of the same forest could yield larger climate benefits due to carbon absorption, even if it would not be economically optimal (see my numerical analysis). I am now assuming, that the emissions would be captured (CCS applied) and no emissions would be generated. Perhaps this scenario could also result in monetary benefits, if the costs of BECCS go down, as they tend to do with new technologies over time.

Opting for *improved forest management* could be better for Finland's economy, considering the costs. In addition, avoiding the potential high price tag for not reaching the LULUCF targets could result in substantial economic benefits. Albeit, due to uncertainty, effects on forest industry, and forest industry's effects on the national economy, this is hard to prove.

Reducing harvesting would also result in biodiversity benefits, at least in the short run. These benefits would be undermined by harvesting the forest at a later point in time.

Benefits of BECCS are its certainty, easier accounting, and perhaps better political feasibility. Monitoring the state of the forests and their net emissions is more difficult and subject to inaccuracies, than counting the exact emissions from a single point source, an industry chimney. Forest abatements are highly uncertain due to uncertainty in forest growth, damage risk, and the possibility for illegal logging.

Payers of the forest sink enhancement would be the taxpayers, unless the private sector is provided incentives to offset their emissions, or a tax on biogenic emissions would be imposed (next section discusses the policy implications further). 88 million is not a very large sum of money for abating 5,5Mt of emissions, but public resources are scarce.

BECCS, in hand, may not be paid totally by the taxpayers, although I am assuming it would first be. Given the potential integration of BECCS to the carbon markets, and a potential credit system for negative emissions, could BECCS become a reality with 0 taxpayer money. That is still a scenario waiting to happen, and could without improved forest management still be costly for the taxpayers, as forests carbon sinks would be neglected. Going back to Golombek et al. and the lack of incentives and demand for BECCS, taxpayer money is probably going to be needed for market creation, as in the case of Sweden. How much? That is the big question.

The hike is approaching its end. To conclude, my numerical analysis suggests that BECCS could be a way to at least reach carbon neutrality in today's forestry. A more elaborated analysis by Tahvonen et al. shows, that net carbon sinks could be increased with BECCS compared to business as usual forestry. However, it could still be more optimal to store carbon in the forests, due to significantly lower costs. Postponing harvests today and conducting BECCS in the future are not mutually exclusive options. Either or both could in the end prove good options due to the large potential climate benefits.

6 Policy recommendation and discussion

A discussion from a policy perspective next given. Reviewing policy implications of technological sinks inevitably leads us to a discussion on optimal forest management. That, in hand, leads us to a general discussion on the use of land and public finances. Based on the quantitative and qualitative factors considered, I recommend a policy which enhances natural carbon sinks in the short run, even if difficult to implement due to institutional constraints. BECCS has potential, and I recommend keeping the door open for it, for the long run.

Let us start by discussing the new and exciting technological sinks. Factors for Finland doing BECCS are existing forest industry with high level of biogenic emissions, and political will to reduce these emissions without hurting the competitiveness of the industry. Factors against, are long distance to storage sites whose capacity is limited, high costs, and lack of incentives. A major disadvantage of Finland is the lack of its own geological storage.

Whether the Finnish companies considering CCS are in contact with the potential storers and transporters is not public information. How much the Finnish companies or government are willing to pay for the transport infrastructure, and whether there is available storage capacity in the first place, are key questions affecting the individual investment decisions.

Lead times to complete industrial projects of the caliber we are talking about are long. The Finnish government has stated that the aim is to start doing BECCS already before 2030. The political process is proving slow, however. Sweden has got its 3 billion euro reverse auction scheme approved by the EU commission (Energimyndigheten). Sweden shares many similarities with Finland, such as vast forest resources and established industry. Swedes are also closer to the storage sites in Norway and Denmark. Finland would need a similar political agreement to allow for CO_2 transport between countries. If BECCS becomes something that is pursued, reverse auctioning could be the most efficient way to incentivize BECCS, as it by design leads to outcomes where the government subsidizes the most cost-efficient projects.

Economics is all about tradeoffs and opportunity costs. What else could be done than BECCS? Forests' carbon sinks could instead be enhanced. According to economic theory reviewed, if biogenic emissions were taxed, the forest rotation ages would become longer, leading to lower net emissions. Given the institutional constraints, and short-term effects on profitability of the forest companies, this is not a popular choice for policy, however optimal from economics perspective.

Also improved forest management would require an incentive scheme in place. An alternative to taxing emissions could be to tax landowners more heavily for harvesting and to provide subsidies for forest growth. Foresters could be compensated for the revenues they lose if they do not harvest. This thesis does not go deeper into the practical details of such a policy. An overview of different options is provided in the report by Soimakallio and Pihlainen (2023). For a detailed review on policy design, see also Gren and Aklilu (2016).

Why is today's policy then not considering the value of the carbon sinks? One reason is the large role of the forest industry in the Finnish society, and its hypothetical function as a tool to distribute income in the country. The benefits from the revenue for government from taxing CO_2 are perhaps not deemed large enough to outweigh the added value of forest industry for the national economy (especially for the economies of rural areas). The general equilibrium models reviewed in section 3 (and Appendix 2) do not consider the value-adding effects of the forest industry, or its distributional role in enhancing social cohesion. Such thing as *social cohesion* is, if not impossible, at least *very* hard to include in a quantitative analysis.

Public resources are scarce, and it would prove unpopular to implement a policy which would lead to a transfer from deforested regions to afforested ones. While in the EU context the LULUCF regulation takes forest land into account in today's climate policy, it does it in a way which favours the countries which have cut down their forests a long time ago. Reference levels were set according to the states of forests in 00s. This has led to a system, where every country has their own reference level, and some countries are in a more favourable situation only because of the state of their land in the arbitrarily selected reference periods.

If biogenic CO_2 was taxed globally, the transfers between countries would be noteworthy[16]. Finnish forests are dense, and a hectare has 122 cubic meters of wood on average (Luke, 2019-2021 data). Finland has 26,3 million hectares of forest land, of which 20,25 million ha (77%) is suitable for forestry. This makes the total amount of wood in Finnish forestry land around 2,5 billion cubic meters. If a cubic meter stores around 1t/CO_2, the total storage of Finland would be 2,5Gt/CO_2. With carbon prices of 100€/t this carbon storage would be valued 250 billion euros, almost equalling the country's GDP. Forest growth removed 8Mt/CO_2 in 2021 (Statistics Finland). The forests (or landowners) are hence now doing (temporary) carbon removal for 'free' although that could be seen worthy of 800 million euros.

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[16] To be fair, so are today's transfers between countries with and without hydrocarbon reserves.

Instead of compensating for all storage or all harvest, an additionality principle could be applied. This means, that compared to some baseline, the absorbed additional CO_2 could be subsidized. Perhaps the LULUCF is trying to accomplish this, although it takes into account also other land than forest land. General value of land and the land use opportunity costs become key factors to consider in a complete analysis, which my simpler cost-benefit analysis of the previous section neglects.

Tahvonen and Rautiainen (2017) show that subsidizing additional carbon storage in forests would not lead to distortions to land-use in general in a simple stand-level framework. However, a market-level vintage model analysis shows that this may lead to distortions in land-use allocation and rotation age. The authors argue that this could still be a good second-best policy to consider. If complete tax neutrality (no distortions) was the aim, the authors propose a tax on land whether it was used for forestry or agriculture.

Let us not forget, that in Europe, agriculture is a subsidy dependent sector. Due to the Common Agricultural Policy, up to third of EU budget could be going to agriculture, often for agriculture with high emissions (e.g. cattle production). Economic cost of forest removals in Europe could hence be much lower than today considered, if we take money for it out of agriculture subsidies. Pihlainen et al. (2014) shows, that the marginal costs of storing carbon by afforestation increase in the land value of agricultural land. If the carbon price was 40€/t, it would be optimal to shift from farming to forestry if the value of the agricultural land was less than 7300€/ha (at the time of the paper, land values were generally higher than that). It is argued, that if we control for agricultural subsidies, it would be optimal to do afforestation at the expense of agriculture with a carbon price of 40€/t.

Due to low popularity, this may be out of reach. European farmers have been very vocal in their demonstrations in the past year. In addition, the effects for food markets of such a policy ought to be considered. If European food production decreases, and as a result global food prices increase, this would not lead to very pleasant outcomes. Neither does a warming climate due to high emissions, to be fair.

Further concern for policy is the possible anticipation from the landowner side. As mentioned in the review of Pihlainen et al. (2014), New Zealand has a system where forest emissions are included in the local ETS. Before they were included, this led to a dramatic increase in logging. Policy should be a 'surprise' to be effective, which is difficult to achieve, as the governments prefer to be coherent in their decision-making to remain popular.

There is a risk that the policymakers decide to tax all carbon without subsidizing forest growth. The consequences would be catastrophic for countries and regions for whose economies forestry is important. At least in the short run. While wood production has economic value, it may not be the most productive option for an economy. For example, the production of a semiconductor (pulp) for export in Finland may not be the most productive use of capital and labour. Yet, productivity considerations are out of the scope of this thesis.

It is unlikely, that a first-best optimal combination of taxes and subsidies is feasible. After a more careful analysis has been conducted than what this thesis accomplishes, and a global agreement on what is to be done is reached, become the main questions - how is all of this implemented, and who will pay? Whatever the solution, whatever the direction set for the world from above: cooperation is going to be needed. Cooperation between different countries and sectors, such as that proposed between forest and petroleum sector in this thesis. A proper global solidarity needs to be established going forward.

Long story short, I recommend Finland to conduct *improved forest management* in the short term. It can do it by implementing a policy which incentivizes enhancing the forest carbon sinks in the short term. The same forests that are left unharvested could later be cut, and CCS applied to the process of bioenergy production - perhaps even lower financial cost due to technology development. This could give Finland large savings both due to lower investments in technological sinks in the short term, and a higher chance to meet the EU LULUCF requirements. Economic costs would be lower in comparison with the BECCS pathway, as my cost-benefit analysis in last section showed.

Against this option speak the forest industry of Finland, and the lack of political will to regulate the industry. There is also a considerable uncertainty in emissions reductions due to factors such as climate change's effects on forest growth and damages, and difficulty in monitoring if compared to BECCS. Payers virtually being the Finnish taxpayers is also something swinging the bell to the way of BECCS, which could be easier to sell to private investors in the near future. Hence, BECCS has its benefits, and could especially in the long term be a very relevant option for countries like Finland and Sweden, which will try it first.

Before concluding, I feel the urge to give my final thoughts on forest economics and rotation models, the cornerstone of this thesis. Rotation modelling is an intuitive way of describing the economics of the forest. Managing forests by clear-cutting is still the status quo in commercialized forests in Finland. However, rotation forestry has very severe consequences for biodiversity. An optimal policy would of course not neglect biodiversity. The policy recommendation stated above would be a better option from the biodiversity perspective.

One option is to manage the forest continuously, letting trees grow at different ages, and allowing for some decay. This has been argued to lead to high grading of the forest: if only the best trees are cherry-picked for harvest, only the worst are left behind. Still, some research has shown that continuous cover forestry can be more optimal than rotation forestry (see e.g. Assmuth and Tahvonen, 2018). Other studies (e.g. Tahvonen et al., 2024) report results where rotation forestry still prevails as the most optimal from economics perspective. Continuous cover forestry could provide an option where we could harvest for wood production, and value the forests function as a carbon sink, without compromising from biodiversity.

Climate change is already happening, complicating the analysis. Assmuth and Tahvonen argues that continuous cover forestry could even be a more resilient management form, as climate change has increased uncertainty and risks for damage. In the analysis of this thesis, climate change's effect on forests was not considered. The previously referred Swedish report discusses these effects in a great detail. Warmer climate has a positive effect on forest growth. Yet, climate change could also lead to extremely dry or wet periods, more frequent forest fires, storm damages, and increased incidence of pests and disease. Forest damages have been on the rise in Europe since the 1970s, and there are some alarming signs also in the Finnish forests. European spruce bark beetles have been particularly damaging for the Norway spruce. Whether this issue is caused by the climate change, and not by for example growing too homogenous forests, is another question.

7 Conclusion

Carbon sinks may be divided into natural carbon sinks, and technological carbon sinks. The main focus of this thesis has been the Finnish forest, which can be used both as a natural sink, and as an ingredient for technological carbon removal by Bioenergy with Carbon Capture and Storage. My thesis emphasizes, that BECCS as a carbon removal method is linked to the forest sinks, which should be considered when designing policy. Based on a numerical analysis, and a simple cost-benefit analysis, I recommend that Finland opts for enhancing the natural carbon sinks in the forests in the near future.

Applying BECCS, rotation ages may remain short and bare forest land values rise, as my numerical analysis shows. A more elaborated stand-level analysis by Tahvonen et al. (2024) shows, that BECCS increases net carbon sinks in the business as usual case where forest carbon emissions are not subject to tax, and the interest rate is positive. Limitations of stand-level analyses are, that results are sensitive to the model parameters (discount rate, carbon and timber prices), and that the cost of BECCS is not incorporated in the models.

Landowners or forest companies could benefit from BECCS, but this could come at a high cost, as my analysis shows. Even if the case for enhancing natural carbon sinks is arguably stronger, also BECCS could provide an efficient alternative to bring down the emissions of Finland. Forest industry emissions in Finland are high, and there is political will to implement BECCS. Scale of removal potential is non-trivial considering national net zero targets. Against BECCS speak the lack of incentives, as well as the potential storage site scarcity, and other market creation challenges, such as coordination problems and slow political processes.

To end on a positive note, with all the challenges related to BECCS extensively described in this paper, it is a new technology providing carbon removal opportunities already in the near future for countries like Finland, blessed with vast natural forest resources, and an established forest industry. BECCS could provide exciting business opportunities for the Finnish industry globally, given the incentives for it are established.

Before that happens, remain the natural carbon sinks a cheaper way of reducing net emissions both in Finland and globally. Not logging down the forests at current pace could lead to large savings from the Finnish national economic perspective. More critically, it could give us an overtime to think about how we together can develop all-round feasible, fair, and effective methods to save the climate, to leave a better environment for tomorrow’s beings.

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A Korhonen and Tahvonen (2023)

Let W be the landowner's maximization problem, a sum of the values $V_w + V_c$ of wood production value and net carbon sinks. Let τ equal social valuation of CO$_2$, θ the quantity of CO$_2$ per m^3 of biomass, β the present value of CO$_2$ emissions from harvested wood per m^3 (equal to $\alpha/(\alpha + r)$, where α is the rate of decay of harvested biomass), and ω the biomass expansion factor for including e.g. branches and roots. Problem is written as:

$$W(t) = V_w(t) + V_c(t) = \frac{pf(T)e^{-rT} - c}{1 - e^{-rT}} + \frac{\tau\theta\omega[\int_0^T f'(s)e^{-rs}ds - \beta f(t)e^{-rT}]}{1 - e^{-rT}} \tag{2}$$

Wood production value (V_w) is the equation (1), the good old Faustmann rotation function. In carbon sink value (V_c), the numerator's first term represents the present value of gross sink, and the second term the present value of emissions.

First order optimality condition for the function above is:

$$W'(t^*) = V_w'(t^*) + V_c'(t^*) = 0 \tag{3}$$

, where:

$$\begin{aligned} V_w'(t^*) &= \frac{e^{-rt}}{1 - e^{-rt}}[pF'(t) - rpF(t) - r\frac{-c + e^{-rt}pF(t)}{1 - e^{-rt}}] \\ &=> [pF'(t) - \frac{r[-c + pF(t)]}{1 - e^{-rt}}](e^{rt} - 1)^{-1} \end{aligned}$$

$$\begin{aligned} V_c'(t^*) &= \tau\theta\omega[F'(t)(1 - \beta) - r\beta F(T) - \frac{r[\int_0^T F'(s)e^{-rs}ds - \beta F(t)e^{-rt}]}{1 - e^{-rt}}(e^{rt} - 1)^{-1}] \\ &=> \tau\theta\omega[F'(t)(1 - \beta) - \frac{r[\int_0^T F'(s)e^{-rs}ds - \beta F(t)]}{1 - e^{-rt}}](e^{rt} - 1)^{-1} \end{aligned}$$

Equation 3 can then be manipulated to get the equation (4) with economic interpretation showed in text, by adding back the terms that were removed in the last phases of the equations above. Consider first $V_c'(t*) = V_w'(t*)$:

$$\tau\theta\omega[F'(t)(1-\beta) - \frac{r[\int_0^T F'(s)e^{-rs}ds - \beta F(t)]}{1 - e^{-rt}}](e^{rt}-1)^{-1} = -[pF'(t) - \frac{r[-c + pF(t)]}{1 - e^{-rt}}](e^{rt}-1)^{-1}$$

Multiplying both sides by $e^{rt} - 1$ to clear the denominators:

$$\tau\theta\omega[F'(t)(1-\beta) - \frac{r[\int_0^T F'(s)e^{-rs}ds - \beta F(t)]}{1-e^{-rt}}] = -[pF'(t) - \frac{r[-c+pF(t)]}{1-e^{-rt}}]$$

Shifting terms with F'(t) to LHS and terms with $r/(1 - e^{-rt})$ to RHS and factoring out respectively.

$$F'(t)[\tau\theta\omega(1-\beta)+p] - \frac{rF(t)}{1-e^{rt}}[p - \tau\theta\omega\beta] = \frac{r}{1-e^{rt}}[\tau\beta\omega\int_0^T F'(s)e^{-rs}ds - c]$$

Shifting all to the LHS:

$$F'(t)[\tau\theta\omega(1-\beta)+p] - \frac{rF(t)}{1-e^{rt}}[p - \tau\theta\omega\beta] - \frac{r}{1-e^{rt}}[\tau\beta\omega\int_0^T F'(s)e^{-rs}ds - c] = 0$$

In (3), -rpF(t) and $r\beta F(t)$ were removed for simplicity, so they are added back.

$$F'(t)[\tau\theta\omega(1-\beta)+p] - \frac{rF(t)}{1-e^{rt}}[p-\tau\theta\omega\beta] - \frac{r}{1-e^{rt}}[\tau\beta\omega\int_0^T F'(s)e^{-rs}ds - c] - rpF(t) + r\beta F(t) = 0$$

Recall $W(t) = \frac{pf(T)e^{-rT}-c}{1-e^{-rT}} + \frac{\tau\theta\omega[\int_0^T f'(s)e^{-rs}ds - \beta f(t)e^{-rT}]}{1-e^{-rT}}$
Finally:

$$[p+\tau\alpha\omega(1-\beta)]f'(t) - r(p-\tau\alpha\omega\beta)f(t) - rW(t) = 0 \qquad (4)$$

B Broader economy models for forestry

Net national emissions, CO_2 taxation and the role of forestry (Tahvonen, 1995)

Tahvonen (1995) studies the taxation of CO_2 on a national level using a dynamic general equilibrium model. Key takeaways from the contribution of Tahvonen are, that from social welfare perspective, it is optimal to increase the size of the natural carbon sink in the forest, as forests can store carbon. Based on the study, the current status quo where biomass is considered carbon neutral may not lead to the first best solution. Instead, carbon tax on biogenic emissions and a subsidy for forest growth could lead to a more optimal solution. In a decentralized carbon market, countries with high forest resources could receive net negative taxes (subsidies) for functioning as the lungs of the market.

Here, I describe the model setup, but save the reader from the equations used. In the paper, carbon flow is considered to consist of accumulation of carbon in living forest biomass and soil, and its release to atmosphere to happen due to harvesting. Forest growth is assumed to be strictly concave: growth rate is monotonically slowing down as the forest matures (simplifies the picture a lot as often the growth is assumed convex-concave, or assigned an empirically estimated growth function). Part of the sequestered carbon is assumed to be absorbed in soil through first becoming dead organic matter. Carbon tax is assumed to be exogenous and constant for simplicity - and it is also applied to biogenic CO_2 emissions.

The economy is modelled through general equilibrium setup, where the economy has the choice to use biomass as a fuel or create wood products from it. An alternative option is to use fossil fuel at its own price. Net payments in the form of tax are given by the international carbon tax rate multiplied by total consumption of fuels and wood products net of carbon stored in products and soil. Economic production function is a function of capital, biomass, and fossil fuel. It is assumed to be strictly concave and increasing in all arguments. The arguments are not perfect substitutes, but some room for substitution is allowed. Social planner maximizes a strictly concave utility function such that marginal capital equals the production function net of consumption, fossil fuel production, and taxes.

The optimal outcome found from the exercise above is found to be feasible by implementing a tax on all carbon emissions at the international rate τ, and subsidizing forest sector and individual forest owners at the rate of $\tau\mu F(x)$, where $\mu \geq 1$ is the share of the total amount of carbon in biomass and soil, and $F[x(t)]$ the growth function of the harvestable biomass. This result is proved by the construction of a model economy that consists of a representative forest owner, a representative firm, and the government. The forest owner maximizes their utility by allocating capital between consumption and savings and harvesting the forest by taking in account the carbon stored in it, as it is subsidized by the government. The firm maximizes its profits and pays carbon taxes for its production. Comparing the necessary conditions of the planner's problem with those of the forest owner and the firm, it is found that the decentralized solution with the proposed taxation/subsidy program equals the Pareto optimal solution of the social planner.

The paper is concluded with a remark that emissions from wood can differ by utilization method. Biofuels emit CO_2 to the atmosphere immediately, pulp and paper are slowly decaying but generally assumed to have a half-life of 2 years, and in construction the CO_2 is stored for longer. The tax should according to Tahvonen be τ for bioenergy production and $\alpha\tau$ for other use, $\alpha \leq 1$ being the share of CO_2 sequestered in wood products. In the future, perhaps the first best optimal bioenergy production tax could also become $\alpha\tau$, if the carbon is captured and transported for permanent storage.

While emerging from a very simple model (yet more elaborated than the rotation models), the optimality of the taxation is interesting, as today the status quo at least in the European context is that wood use is carbon neutral and need not be taxed. Neglecting the natural carbon sink in devising methods and incentives for CO_2 abatements, we may end up doing something that is far more costly and ineffective as the optimal.

Deriving optimal policies (Lintunen and Uusivuori, 2016)

Lintunen and Uusivuori (2016) examines a first-best optimal forest sector carbon policy. The authors use a very multi-faceted forest and energy sector model with a carbon cycle module and solve for a competitive equilibrium with carbon externalities. The authors emphasize that even if forests are a renewable resource and their absorption of carbon makes them carbon neutral, emission free use of biomass is still not warranted. Still, with the policy options proposed (subsidization of carbon removals and taxation of emissions), it is shown that it is optimal to increase wood use to improve social welfare. In their numerical solution, before wood use is increased, the proposed policies will lead to increased forest growth and hence climate benefits, until a new equilibrium is reached.

Lintunen and Uusivuori base their model on that of Tahvonen (1995), and enrich it by an age-structured forest resource model with option for land-use changes, and a detailed carbon cycle segment including stocks for carbon in atmosphere, forest biomass, wood products, and dead organic matter stocks of forest soil. Market level effects (endogenous input use and pricing) are introduced. Biomass is subject to Pigouvian tax. The model is closed and no carbon leaks out of it. Again, I present the model but refer the readers to consult the original paper for deeper insights into the technical details of the work. Detailed look into the model is interesting, as the model considers so many aspects of the forest and the economy.

Authors model the **land** as a parcel which is always used. The landowner is free to choose between agriculture and forestry. Landowner's harvesting decisions are modeled as shares of clear-cut area at the beginning of a period for different age-classes of the forest. Afforested land area variable introduces land-use change into the model. Negative sign of the variable indicates whether deforestation is taking place. Forest growth is determined by aging of the stand and resulting volumes. Roundwood harvest generates residues. Agricultural land produces constant crops, which are harvested each period.

Biomass carbon stock is divided into roundwood and non-roundwood biomass in the forest, and a parameter converts the volumes into CO_2 equivalents. This stock depends then on growth of the forest and harvesting. Harvest residues not collected for energy use turn into dead organic matter (DOM), become soil, and eventually the carbon stored in it leaks into atmosphere gradually – speed of leakage depends on decay class. DOM is assumed to not affect biomass growth, and biodiversity aspects are abstracted from. Long-lasting wood products (logs) increase harvested wood product stock (HWP), which decays into atmosphere slowly. Short-lasting products (pulpwood) are considered essentially instantly leaked into atmosphere (reasoned by the fact that the half-life of paper products is two years, and the model has time period of five years).

The **carbon cycles** between the renewable biomass and the atmosphere. In the paper two accounting conventions are considered - the one proposed by Tahvonen (roundwood emissions emitted at point of emission), and the IPCC convention accounting which follows the carbon stock changes (roundwood emissions emitted at moment of harvest). Landowners' decisions regulate flows of forest carbon.

The economy is modeled as follows. All production is consumed. Households consume food and an aggregate good. Food is measured in units of agricultural land and the good by its production level. Inverse demand functions for both are positive and decreasing, meaning that the goods' prices are determined endogenously. The aggregate good is produced by a representative firm using non-renewable raw material (e.g. cement), energy (fossil and wood fuels), and roundwood as inputs. The roundwood is divided into two classes by the lifetime of their carbon storage – long lived (logs) and short-lived (pulpwood).

In **competitive equilibrium** firms and landowners maximize profits. Firms optimize their input use in good creation and energy production sequentially, and all markets are cleared every five years. Landowners maximize the net present value of their land area. Prices are exogenous to, and certain to the landowners. Discounting is used and interest rate is positive. Harvesting and regeneration have constant costs – residue collection has convex costs depending on decay class, and is constrained as it is not technically feasible to collect all of it. The negative externality of CO2 emissions is ignored by the firm and the landowner, and a climate policy is designed to internalize the externality.

Benevolent social planner takes into account social welfare and the externality of CO_2 emissions. Authors propose that the solution to the problem of the social planner is equal to the competitive equilibrium only if utility functions represent gross consumer surplus. Non-regulated market does not maximize social welfare as agents ignore the **emission externality**. The marginal harm from CO_2 emissions is measured by the **social cost of carbon**, denoting the marginal social cost of atmospheric emissions. The cost can be expressed as the net present value of marginal damages from a unit of emissions. The different carbon stocks (DOM, HWP) have individual estimates for their social cost through the shadow prices of the stocks (in case of DOM for each decay class). The relative social cost of both is calculated as a ratio of them and the immediate release of carbon. With a couple of assumptions, the general equation for relative social cost for a carbon stock can be derived. Results from this equation are that even if the DOM and HWP stocks are harmful to society due to their eventual emission to atmosphere, they can still be utilized. The former reduces social costs from wood residue use in energy production, and the latter postpones the emissions into future and reduces the present value of the social costs from the emissions.

Optimal input use policy is modelled as a **Pigouvian tax based on the social cost of carbon and an input use based effective emissions factor**. Pulpwood and roundwood have zero emissions factor in the IPCC convention, as the emissions are counted already at the harvest. As the emissions factors of wood product industry and harvest residue use depend on the carbon stock's relative social costs, the log use leads to a gross subsidy under the IPCC accounting, which increases according to wood stored in the wood product industry. If the storage has a lower relative social cost, subsidy is higher. The harvest residue combustion emission factor and the social cost of the DOM stock are negatively dependent of each other. Hence, the more harmful the decaying carbon stock, the lower the costs from its use in energy production. With lower interest rates, postponing emissions has a minimal effect on welfare.

Tax above is optimal only if accompanied by **forest management policy** for landowners, subsidizing removals (forest growth) and taxing emissions (harvesting). Policymaker buys (or rents?) the carbon stored captured by the forest to incentivize the landowner to store CO_2. This should lead to a decrease in harvesting and longer rotations. Then the landowner buys the carbon back as he/she is willing to harvest through paying the harvest tax. A separate tax based on the DOM stock social cost is paid by the landowner for the non-roundwood biomass, as the harvest residues are first converted in DOM stock – this decreases profitability of harvesting.

Numerical solutions illustrate the effect of an unanticipated implementation of the policy change above. Two DOM stocks decay in 10 and 100 years. Final good is specified a Cobb-Douglas production function and energy inputs are assumed to be perfect substitutes. Different social costs of carbon are specified (15€/tCO_2 vs. 30€/tCO_2). Model is calibrated for a small economy with vast forest (e.g. Finland) and solved with 5-year period length. Results of the first 300 years are shown. Optimal policy decreases emissions. With lower social cost of carbon, no permanent reductions are achieved. With higher one, emissions reductions are high during the first 80 years, and phase out after that. Emissions are reduced through reduced harvesting (increased rotation age) and afforestation of agricultural land. Then harvests start to increase to match the growth in volume. Logs are preferred to pulp. Residue utilization increases – more for the faster decaying residues, as their climate impact is lower. Roundwood replaces fossil fuels in energy production after 40 years as it becomes cheaper, which leads to weakening of the biomass sink.

The model of Lintunen and Uusivuori paints a truly comprehensive picture of the complexities of designing forest policies, and what details are to be taken into account. It also considers different accounting conventions, and finds that end results do not differ - even if we are not in the first-best world of Tahvonen and van Kooten et al. we may still have hope. Regardless of the accounting convention, the authors propose a way to increase carbon sequestration by subsidizing forest growth in line with the aforementioned papers.

Lintunen and Uusivuori jump from assumption to another, but somehow keep the forest standing (at least for 80 years). Limitations of the model are many, however, as the world is simplified in many aspects. Labour and capital are not included. The closedness of the model is also a major limitation, as the forest sector in case of Finland for example uses some imported wood. While these models include economy-wide effects, they simplify in other aspects. Tahvonen (1995) considers different wood products, but does not consider deadwood or harvest residues. While the more elaborated Lintunen and Uusivuori (2016) considers deadwood and harvest residues, it does not consider silvicultural practices.

Still, this is a leap towards more realistic modeling of the world. The Natural Resources Institute of Finland (Luke) uses even more complex general equilibrium models to make sure they get everything necessary from state of carbon sinks to the industry dealings and labour markets included in the analysis.

C Robustness tests for the numerical results

This section visualizes the results obtained by optimizing Equations (2) and (5) with different parameters as in the base case reported in Section 5. The composition of the model and the base case is explained in detail in Section 5, and are not repeated here.

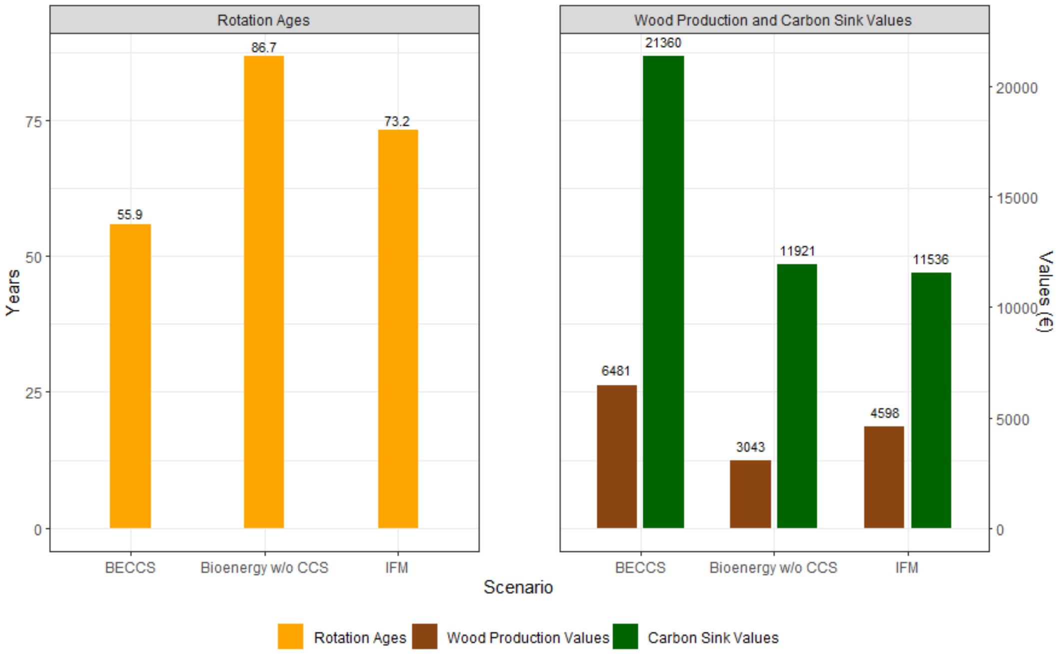

Figure C1: Results with higher timber price

Increasing the timber price from 33€ to 44€, harvesting becomes more profitable. Effect of the price increase on BECCS rotation age is small, but in the two other scenarios, optimal rotations become much shorter. Wood production value of the forest increases in all cases, while carbon sink values decrease slightly.

Doubling the interest rate from 0.02 to 0.04, results are as follows. In case of BECCS, harvesting remains optimal, and the optimal rotation age reduces slightly from 56.8 years to 55.4 years, close to the case of higher timber prices above. Bare land values reduce to 286€ for wood production and to 8149€ for carbon sink production. For cases of Bioenergy without CCS, and Improved Forest Management, the effects of interest rate increase are more dramatic. It is now never optimal to harvest the forest for bioenergy. For improved forest management, raising interest rates more than doubles the rotation ages from 89.76 to 235.2 years. Bare land values reduce from the base case. Wood production values become negative.

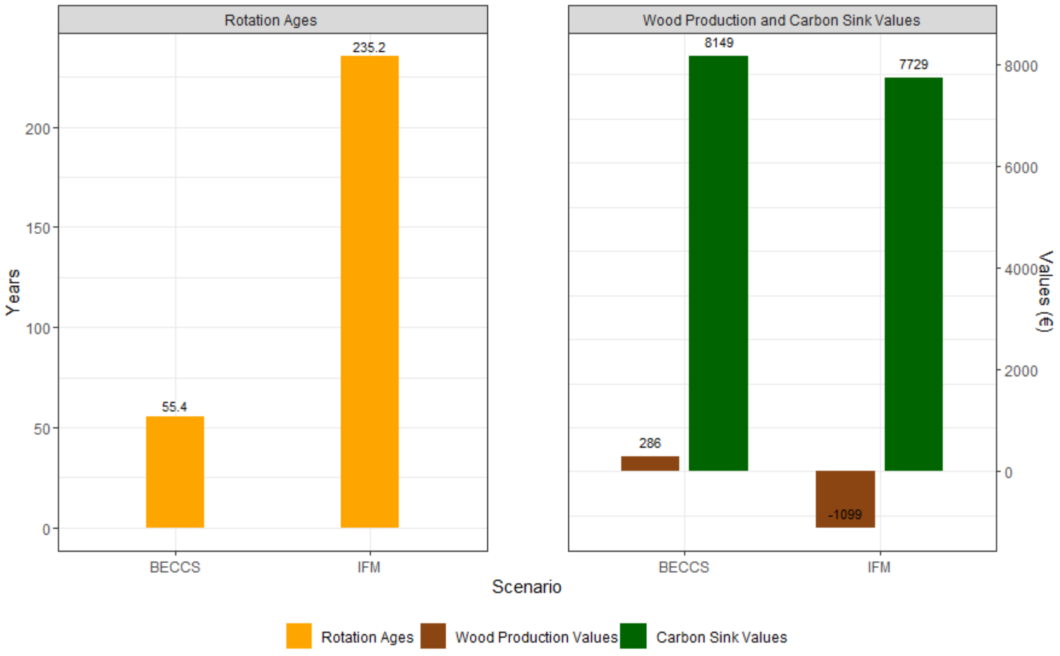

Figure C2: Results with higher interest rate.

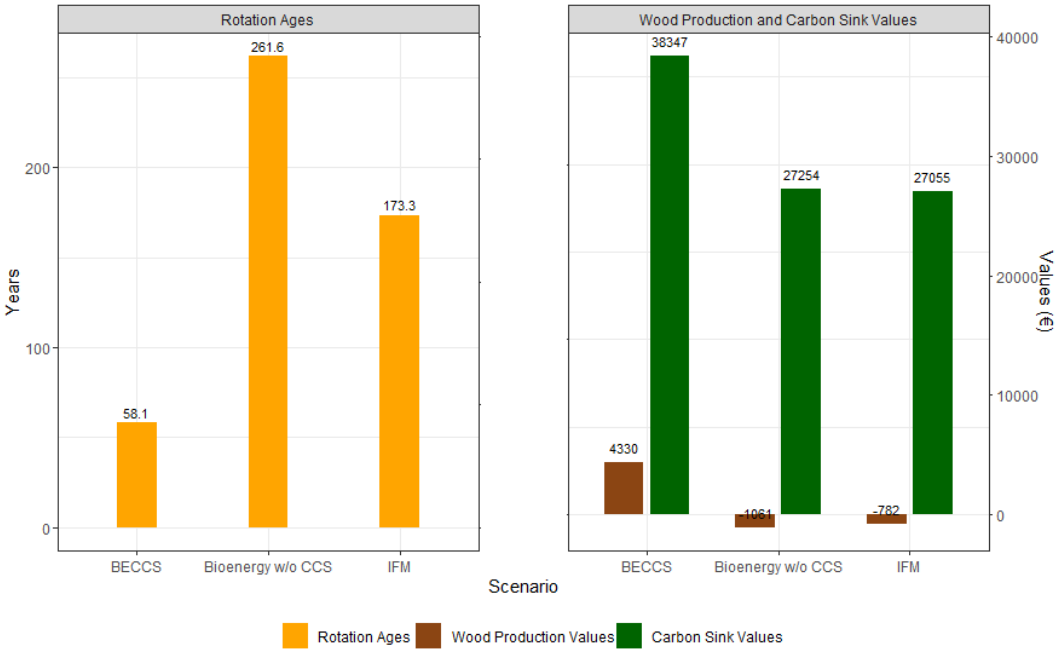

Figure C3: Results with higher carbon price.

Increasing the carbon price from 56€ to 100€, we get the following. Rotation ages increase unambiguously. Applying CCS to bioenergy production, rotation ages remain short, increasing by 1.3 years from the base case. For bioenergy withough CCS, and improved forest management, higher carbon taxes result in nearly doubling of rotation ages. Reason is evident from the wood production and carbon sink values graph. Carbon sink values of the forest increase substantially in all cases due to the higher carbon tax. Wood production values become in fact negative with carbon tax of 100€ in these scenarios. In case of BECCS, wood production value of the forest remains at a similar level, reducing by 1.7%.

In conclusion, varying model parameters has a small effect on BECCS rotation ages. For other variables of interest (rotation ages in cases of bioenergy without CCS and improved forest management, as well as bare forest land values in all cases), varying the parameters changes the results significantly. In short, higher timber prices make harvesting more profitable, whereas higher interest rates and higher carbon prices prolong the rotation ages (with the exception of rotation ages becoming shorter with higher interest rates in case of BECCS).

D Pathways for CCU (Hepburn et al., 2019)

Relevant for the case of Finland is the case of CCU, carbon capture and utilization. As Finland does not have a storage itself, usage of CO_2 as a feedstock could be one option for climate change mitigation. CCU would also logically fit into the general strategies of Finland in becoming a forerunner in circular economy. Effectiveness of CCU depends on the application. Generally, CCU does not necessarily lead to any climate benefits when all direct and indirect effects are taken into account. This section briefly summarizes a paper by Hepburn et al. (2019), which reviews ten different pathways for CCU, a topic related (though not synonymous) to carbon sinks. The paper is discussed from the Finnish perspective.

Hepburn et al. considers CCU to be a process where CO_2 is used to produce economically valuable products, whether it originally came from fossil flue gases, from the atmosphere, or from land-based processes (much like my thesis has considered BECCS where the original source of the CO2 is the Finnish forest). The ten pathways for CCU identified in the paper are: (1) CO_2-based chemical products, including polymers; (2) CO_2-based fuels; (3) microalgae fuels and other microalgae products; (4) concrete building materials; (5) CO_2 enhanced oil recovery (CO_2-EOR); (6) bioenergy with carbon capture and storage (BECCS); (7) enhanced weathering; (8) forestry techniques, including afforestation/reforestation, forest management and wood products; (9) land management via soil carbon sequestration techniques; and (10) biochar.

Of these pathways, some (1, 2, 3) *cycle* the CO2 back into the atmosphere in a rather quick schedule. This does not provide a permanent carbon removal, but could reduce the industrial emissions due to industrial carbon capture. Closed pathways (4, 5, 6, 7) store the carbon permanently in litosphere, deep ocean, or in built or natural environments. Open pathways (8, 9, 10) are somewhere in the middle, providing large removal potential in natural systems like biomass and soil, though with a risk of leakage back to the atmosphere.

My thesis has analyzed and touched upon CO_2-EOR (5), BECCS (6), and forestry (8), but these are by no means the only ways to store or use CO_2. Nor are the pathways identified by Hepburn et al. (2019), as the field is constantly evolving. The paper proposes that creating products from concentrated CO_2 could in the short term leverage the industrial capture of flue gases following fossil fuel extraction and combustion. However, in long term the so-called CO_2-loop should be closed, should we want to reach net-zero emissions.

Next, I summarize and discuss the different pathways' scale and economics from the Finnish perspective. BECCS and forestry are analyzed in earlier sections. Hence, I give treatment to CO_2-EOR, chemicals, synthetic fuels, concrete building materials, land management, and biochar. For other options, see Hepburn et al.

CO_2-Enhanced Oil Recovery (EOR)

In EOR, CO_2 is injected into oil reservoirs, leading to higher oil production. Vast majority of CCS projects globally involve storage of CO_2 in order to enhance oil production (Kearns et al.). In many EOR projects in the US, CO_2 is not captured but comes from natural CO_2 fields and is transported via pipeline to the oil fields. While CO_2-EOR can utilize and store CO_2 permanently, it potentially has a negative effect for the climate due to the emissions from the end usage of oil.

Hepburn et al. (2019) states, that CO_2-EOR could lead to genuine CO2 emission reductions depending on emissions intensity of counterfactual (what would have happened if CO_2-EOR was not conducted) and on the relevant inefficiencies (waterbed effect, the practice leading to more emissions elsewhere or later). If the CO_2 utilized in EOR comes from a fossil power plant, it provides no CO_2 removal, but can lead to emissions reductions. Biogenic CO_2 used in EOR could in theory lead to removal, but a careful life-cycle analysis is needed to verify this. The storage side could be modelled as the forest: we may think that the geological formation has an oil production value and a storage value. Currently, as with wood production from a forest, the oil production value of the reservoir dominates. CO_2-EOR could be a move towards *improved reservoir management*, although in the short run it could lead to slightly increased emissions. Adequate taxation could be designed to ensure optimal outcomes.

Norway is an oil-producing country, which has led to concerns on whether CCS is lobbied by the Northmen in order to be able to increase oil production (see e.g. Rodriguez, 2023). In Norway, the captured CO_2 is not used for EOR, nor does it seem likely that it would be used, given the reduced importance of oil to the Norwegian economy, and increasingly higher sustainability concerns in the country. CO_2-EOR may even lead to conflict with Norway's natural gas business. For example, in Snøhvit CCS project, the captured CO_2 was briefly injected back to where it came from, to the gas reservoir. This led to the need to capture an increasingly higher amount of CO_2 from the gas, to meet Norway's export requirements, until the practice was abandoned (Teknisk Ukeblad, 2013).

Chemicals

CO_2 can be transformed into various chemicals efficiently. The production of urea falls under this category. Urea is produced from ammonia, which in hand is generated by an energy intensive Haber-Bosch process, requiring a lot of energy, today provided by natural gas or coal combustion. Hydrogen could in the future replace these fuels. As was mentioned before in the thesis, it is currently by far the most upscaled CCU application, as 130Mtpa/CO_2 is consumed by it (Kujanpää et al., 2023a). Urea production is commercially viable, with a breakeven cost of 100USD per tonne, and a high demand as fertilizers are needed for producing food. Urea is used also for production of AdBlue, needed for running modern diesel motors (Nieminen, 2022). Producing 'clean urea' could be a path for CCU in Finland in the future. However, while circular, the utilized CO_2 in fertilizer and AdBlue releases back to the atmosphere within days or instantly. According to Hepburn et al. increasing urea production may have a negative impact on climate change due to the production of a potent N_2O gas.

Another possibility could be to produce polymers from CO_2. Global potential for CCU in polymer production is estimated to be 10-50Mtpa/CO_2 in 2050 (Hepburn et al.). CCU-polymers could be used in packaging to reduce petrochemical industry emissions - polymers could be used as well in construction, household goods, electronics, and vehicles, where the lifespan of the products would be much longer than in packaging. Tognetty et al. (2024) identifies construction polymers to be a mid-term approach. Some commercialized cases exist, but clearer regulation and subsidies appear to be required from the industry point of view.

Synthetic fuels

Synthetic fuels, such as methanol, methane, and Fischer-Tropsch fuels using CO_2 as feedstock could be the among the most promising paths for CCU in the near future. Hepburn et al. estimates the potential for these fuels to be 1-4.2Gtpa/CO_2. These fuels could be deployed in the existing transport infrastructure. It is unlikely that all of transport in the world can be electrified. Especially maritime, aviation, and heavy trucks will likely require other solutions.

Tognetty (2024) identifies methanol production as a potential short-term approach. Methanol is already used as a feedstock in various products in the market. Yet, producing it from CO_2 is not currently economically viable, although it is technologically mature. Perhaps the most relevant case for Finland could be captured CO_2 combined with hydrogen to produce e-fuels, as there is a boom in the country for creating infrastructure for hydrogen production and transport. EU level regulations and targets for the transport fuels (carbon pricing in ETS2, tax incentives for Renewable Liquid and gaseous fuels of Non-Biological Origin for aviation and maritime, as well as targets for increasing their use) could be something in favour of the synthetic fuels pathway. Yet, there is uncertainty with regards to the economic viability of carbon capture and hydrogen production in the case of Finland. For hydrogen production, low energy prices are needed. The high demand not only in Finland, but also in Sweden due to the steel industry's plans to electrify their processes with hydrogen use, could be a challenge for the synthetic fuels pathway in Finland.

Concrete building materials

While essential for the modern society, concrete is perhaps the most destructive material on earth. According to Lehne and Preston (2018), cement production accounts for around 8% of the global CO_2 emissions. Capturing CO_2 from the emissions intensive limestone calcination process, and utilizing it as a cement curing agent could be a potetial tool to reduce the emissions. Hepburn et al. estimates the potential to be 0.1-1.4Gtpa/CO_2 in the long term, with breakeven costs of 30-70USD/t.

Tognetty views concrete as a long term option. CCS could be a more viable option for the cement sector in the short term. For Finland, the lack of storage is problematic, and compared to the global scale, the Finnish concrete emissions are low (1,6%, according to Betoni). A Finnish start-up Carbonaide has made great progress in developing a technology for mineralizing CO_2 to concrete, which could in theory turn concrete from a carbon emission source to a carbon sink. In favour of the concrete pathway is the fact that concrete can store carbon for a very long time compared to the other pathways, leading to potentially larger climate benefits.

Soil carbon sequestration and biochar

CO_2 taken up by land becomes either utilized if it increases agricultural output, or removed, if it is permanently stored in soil. Hepburn et al. estimate potential for soil carbon sequestration techniques on croplands and grazing lands to be 0.9-1.9Gtpa/CO_2 by 2050, and the potential for biochar to be 0.2-1Gtpa. Breakeven costs estimated are 20-90USD/t and 60-70USD/t respectively.

Biochar is an ancient process which has been used by indigenous groups in the Amazon (Pratty, 2023). It could lock CO_2 emissions for millions of years. In it, instead of letting biomass decay and release carbon back to the atmosphere, it is heated up and turned into biochar. This product can also improve the nutritional value of the soil and its water retention potential, acting as a *sponge* (Carbo Culture, 2023). If biochar increases yields in tropical biomass, Hepburn et al. estimate that due to reducing land requirements, this could result to cumulative net emission benefit of 180Gt/CO_2 by 2100.

Biochar comes with its risks, though, as it could for example act as source of contaminants, increase nitrous oxide emissions, or have unwanted effects for the soil pH values (Six, 2014). Biochar production produces an excess heat, which in the Finnish context could be used for district heating.