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Tech4effect Project Report

Johanna Routa, Robert Prinz and Benno Eberhard (editors)

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Abstract

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The TECH4EFFECT project, funded by the "Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program", is an international research collaboration of 20 partners from science and industry. The objective of the project is to enhance efficient wood production, by adapting the management of European forests to the requirements of a modern bioeconomy, and to meet new challenges such as climate change. This publication provides an overview of Working Package (WP) 2 “Increasing access to wood resources”, which has the overall aim to increase the access to wood resources by identifying and promoting forest management practices that increase growth rates in the forests and achieve measurable improvements in the efficiency of forest operations.

The forestry sector, in general, is very traditional in decision-making, sustainable planning and applying management alternatives. WP 2 acknowledges this tradition and evaluates traditional techniques and establishes knowledge-based new principles. On this purpose, WP 2 addresses four main objectives: 1) the increase of the access to wood resources; in general, not the wood production itself is the problem, but the access to wood resources. 2) the efficiency-increase in silviculture; it basically is a traditional expression for the management of forest stands. 3) the accessibility increases in the forest supply service business structure. 4) the idea of upscaling the suggestions for improvement; it means to ensure a validity on a larger scale.

The first step in the process towards the realization of the mentioned objectives was an assessment of the existing key silvicultural systems in Europe (Task 1). Through this assessment it became evident that shortcomings and corresponding improvement measures in European forestry heavily depend on the existing tree species and the geomorphological circumstances, e.g. if a region is mountaineous or flat. The thereby identified potential for increased access to wood resources included two principal measures, an intensification of thinning and an enhancement of mechanization. It is apparent that in Northern European countries the degree of mechanization is already very high, and the main focus was on the intensification of thinning. In contrary, Central-, and Southern European countries have a different situation with a lower degree of mechanization, and therefore the boost of mechanization is the prevalent need.

In a second step, case studies for the implementation of the formulated potentials were carried out (Task 2). Case studies showed that schematic thinnings executed by fully mechanized harvesting systems (harvester-forwarder combination) are reasonable. This way the mechanization is not anymore, an auxiliary work step for the execution of silvicultural decisions but is an integral part of the silvicultural concept. This implies that a new conception of what silviculture is, is necessary, and that mechanization alternatives must be an integral part of silvicultural planning. The case studies on the business processes of silvicultural and harvesting services suggest that in wood mobilization gains regarding process interactions can be expected if small scale forest owners organize the management of stands by using public online business tools compared to the traditional direct inquiry alternative or when long-term forest management agreements are applied by forest owner associations ultimately providing the potential to increase planning horizons and the potential to reduce purchase lead times (Task 4).

The third step consisted in developing a harvesting-systems map for Europe. We considered in different harvesting systems, ranging from manual harvesting with chainsaw, semi-mechanized chainsaw-cable yarding to fully mechanized harvester-forwarder combinations. We developed a methodology to assess the most suitable harvesting system based on stand properties, terrain and road density, utilizing large-scale spatial-explicit stand structure maps. The upscaled harvesting-systems map showed the large potential for the application of fully mechanized harvesting systems on European scale (Task 3).

Keywords: Silviculture; mechanisation; thinning regimes; ecoregions; efficiency; wood mobilisation

Tiivistelmä

TECH4EFFECT on kansainvälinen tutkimusyhteistyö-hanke, johon osallistuu 20 partneria sekä tutkimuslaitoksia että käytännön toimijoita. Hanketta rahoittaa Bio-based Industries Joint Undertaking (BBI JU). Hankkeen tavoitteena on tehostaa puuntuotantoa mukauttamalla Euroopan metsien hoito nykyaikaisen biotalouden vaatimuksiin ja vastaamaan uusiin haasteisiin, kuten ilmastomuutokseen. Tämä julkaisu tarjoaa yleiskatsauksen työpaketin 2 ”Puuvarantojen saatavuuden parantaminen” tuloksiin. Työpaketin tavoitteena on lisätä puuraaka-aineiden saatavuutta edistämällä käytäntöjä, jotka lisäävät metsien kasvua ja parantavat metsäoperaatioiden tehokkuutta.

Metsäsektori on toimintatavoiltaan hyvin perinteinen toimiala. Työpaketin työ aloitettiin kartoittamalla perinteiset toimintatavat. Hankkeen aikana pyritään kehittämään uusia tietopohjaisia ratkaisuja. Työpaketti 2:ssa on neljä päätavoitetta: 1) puuvarantojen saatavuuden lisääminen; ongelmana ei ole itse puuntuotanto, vaan puun saatavuus 2) tuottavuuden kasvattaminen metsänhoidossa 3) metsäpalvelujen saatavuuden kasvattaminen ja liiketoiminnan kehittäminen 4) parannusehdotusten skaalaaminen suurempaan mittakaavaan.

Ensimmäinen askel tavoitteiden toteuttamiseksi oli olemassa olevien metsänhoitomenetelmien kartoittaminen ja arviointi Euroopassa (tehtävä 1). Arvioinnin aikana kävi selväksi, että puutteet ja ongelmat ja niihin kohdistuvat parannustoimenpiteet riippuvat käytettävistä puulajeista ja alueen topografiasta. Harvennuksien tehostaminen ja koneellistamisasteen nosto tunnistettiin ensisijaisiksi toimenpiteiksi puuraaka-aineen saatavuuden lisäämiselle. Pohjois-Euroopassa koneellistamisaste on jo erittäin korkea, ja siellä pääpaino on oikea-aikaisten ensiharvennusten ja taimikonhoidon tehostamisessa. Sen sijaan Keski- ja Etelä-Euroopan maissa koneellistamisaste on alhaisempi, ja koneellistamisasteen nostolle on todellista tarvetta.

Toisessa vaiheessa tehtiin tapaustutkimuksia havaittujen parannusehdotusten testaamiseksi (tehtävä 2). Tapaustutkimukset osoittivat, että täysin koneellisilla korjuujärjestelmillä (harvesterin ja kuormatraktorin yhdistelmällä) suoritetut harvennukset ovat perusteltuja. Koneellistaminen tulee integroida osaksi metsänhoitoketjua. Metsätalouden käsitys uudistuu ja koneelliset toimenpiteet tulevat osaksi suunnittelua alusta alkaen. Metsänhoito- ja korjuupalvelujen liiketoimintaprosesseista tehdyt tapaustutkimukset viittaavat siihen, että puun mobilisoinnissa voidaan odottaa merkittäviä hyötyjä prosessien välisestä vuorovaikutuksesta. Esimerkiksi digitaalisten palvelujen käyttöön siirtyminen ja pitkäaikaisten metsänhoitosopimusten käyttäminen lisäävät suunnitteluhorisonttia ja antaa mahdollisuuden lyhentää ostojen läpimenoaikoja (tehtävä 4).

Kolmannessa vaiheessa kehitettiin Euroopan hakkuusysteemi-kartta. Skaalattu kartta osoitti mm. laajan potentiaalin kasvattaa koneellistamisastetta Euroopassa (tehtävä 3).

Avainsanat: metsänhoito; koneellistamisasteen nosto; harvennukset; ekologiset alueet; puuntuotannon tehostaminen

Contents:

1. Introduction

The strategic objective of TECH4EFFECT Project is to improve the efficiency of European forest management by enabling data-driven knowledge-based revolution of the European forest sector while also providing key incremental improvements in technology. The overall aim of Work Package 2 (WP2) is to increase the access to wood resources by promoting practices that increase growth rates in the forests and to achieve measurable improvements in the efficiency of forest operations. This goal involves three main aspects:

1. The application of appropriate harvesting techniques – aiming at the promotion of mechanized systems wherever possible, and

2. The evaluation of appropriate silvicultural operations.

3. The demonstration of the importance of rational business processes in procuring or marketing services for silviculture, harvesting and wood purchasing.

Appropriate silvicultural measures are principally intended to increase wood production, maintain the biodiversity and resilience but also to enable and facilitate the use of efficient silvicultural and harvesting operations. The development of methods for increasing the wood production and optimizing the interface between harvesting technology and silvicultural procedures is the research emphasis of this work.

Task 1 focus on the evaluation of the current situation that means the currently practiced main silvicultural systems in the participating countries ("Where are we?"). On that basis the potential to increase wood production is identified. Task 2, as a consequence, aims at formulating research questions ("Where do we want to go?"), and at generating case studies and establishing case study areas, in order to clarify how the identified development potential can be materialized and defined research questions can be achieved ("How do we get there?"). This means that optimal combinations of silvicultural work steps such as choice of species and species mixtures, planting patterns, early operations, thinning regimes and definition of rotation length will be developed and assessed against their feasibility. Task 3 deals with the modelling of identified best practices, in order to make visible the consequences of the suggested improvements and to ensure their long-term effect. Task 4 concentrates on the improvement of the sequence of business processes within supply chains of forest based products and services in form of (business) tools for improved stand treatment and wood mobilization services ("How to improve business processes in procuring or marketing services?").

To obtain information about the current situation and to identify key silvicultural systems, the questionnaire for all partners involved in Work Package 2 was prepared. Information collected in the questionnaire was then made available to all project partners. Completion of the questionnaire was based on the use of already available data and expert knowledge. The applied solution allows for compiling the knowledge on specific conditions in different European countries. The results can be used by the project partners for country-wise publications describing key silvicultural systems. All partners who have filled out the questionnaire also described possible promising options to enhance productivity of silvicultural operations in their local conditions. This knowledge allows for describing trends and offers possibilities to improve the existing key silvicultural systems, in order to achieve this goal on the local and regional scale, as well as to prepare similar ideas for implementation in a European scale.

The working process in Task 2.2 is based on the results of Task 2.1. In context of that the following six key silvicultural systems for European forests could be identified: age class forest, continuous cover forest, shelterwood forest, coppice, coppice with standard, forest with exclusively commercial purposes ("short rotation", "plantations"). A further result of Task 2.1 was a rough evaluation of increase potentials for silvicultural practices in Europe. The aim of Task 2.2 is the evaluation and quantification of such increase potentials, by implementing case studies. Seven partner countries have realized twelve case studies in total. In the course of the generation of the case studies four focus groups of promising increase potentials for European forestry emerged:

1. to enhance mechanization in harvesting operations (three case studies),
2. to change and intensify tending and thinning practices (four case studies)
3. to adopt more appropriate methods in early operations and stand establishment (three case studies)
4. to demonstrate the importance of rational business processes in procuring or marketing services for silviculture, harvesting and wood purchasing (two case studies).

Two case studies from group 2 (tending and thinning) are realized by implementing harvesters. That means that they have a strong intersection with group 1 (mechanization), so that in five case studies the enhancement of mechanization is an essential topic. Therefore, a bottom line of the work in Task 2.2 is the observation that mechanization might acquire an increasing impact (feedback loops) on silvicultural goals and management strategies. Six ase studies conducted in Task 2.2 used models to assess future developments. Models used include forest growth and yield simulation tools (MOTTI, MOSES, SIMA, PP3, yield tables) and a process based forest ecosystem model. These models allowed for the estimation of the potential increase in biomass and timber products, and in the case of the process-based forest ecosystem the simulation of the effect of intensified silvicultural treatments under a climate change scenario.

Although models were extensively used the scale of the case studies remained on the regional level. Thus, the aim of Task 2.3 was to expand the results of the case studies from their regional to the larger scale. This was done by first mapping the spatial distribution of forest resources in Europe based on harmonized National Forest Inventory data, large scale net primary production (NPP) model outputs and remotely sensed data. In a second step the accessibility of these forest resources by different harvesting systems was assessed. The outcome is a 'Harvesting Systems Map for Europe' showing the potential area of application for different harvesting systems in Europe and the wood resources that can be obtained by each system. In our aim to promote more mechanized timber harvesting operations the map prioritizes more mechanized harvesting systems, if more than one system is applicable at a given site. This map was then used to assess the possible impact on wood resource accessibility by improving silvicultural practices and the harvesting systems involved. More specifically improvements suggested and evaluated in the case studies of Task 2.2 were up-scaled from their regional to the country or ecoregional scale.

Research has shown that considerable efficiency differences can exist between apparently similar supply chains. Mapping the business processes required in procuring services or forest-based products enables them to be systematically analysed, e.g. regarding the number of interactions of participating actors, and redundancies identified and eventually removed. Rauch and Gronalt (2005) showed in their study that the reduction of interaction cost of timber supply is a way to improve the availability of wood as a raw material.

Thus, the aim of Task 2.4 was to explore the suitability of IT-tools, internet-based applications and other interfaces that enable both the requisition and marketing of silvicultural and harvesting services in three Nordic countries (Denmark, Finland and Norway). Two case studies focussed on selected case-specific business processes between forest owners, forest administrators, service providers, and local Forest Based Industries (Finland and Norway).

2. Identified key silvicultural systems

2.1. Description of the questionnaire as a data source

The questionnaire was provided as an MS Excel spreadsheet with examples to illustrate expected results and guide the participants responsible for providing information. The spreadsheet contained 6 parts (sheets):

1. Contact – data of person responsible for filling-in the questionnaire in each country.
2. Silvicultural systems – the aim of this part was to cover the majority of managed forests in the respective country by describing key silvicultural systems. If available, potential options to enhance the productivity of particular silvicultural systems should be highlighted, expressed as forest increment (m^3/ha/year) or as machine productivity (m^3/hour). The number of silvicultural systems for each partner was not fixed. As a guideline, at least 80% of the managed forest area in the country/region should be represented by the described systems.
3. Case studies – provision of meta-information on case study areas. Already existing study regions could be chosen and used as case studies. If certain information was missing, project partners should collect additional data to fill the gaps.
4. Forest management, including early operations – the intention of this part was to describe the forest management systems/options and to cover the whole lifetime of a tree, from germination/planting to cutting. This part of the questionnaire tried to collect the most important systems across Europe. Involved partners were authorized to include individual systems, if needed to cover the specific features of their country.
5. Harvesting systems – the aim of this part was to capture the most important wood harvesting systems across Europe. Gathered data allowed the comparison of systems used for thinning and final harvesting. Systems – to be comparable – were defined by the same final product (e.g. logs stacked on forest road).
6. Sources – list of literature used to derive information for questionnaire.

2.2. Results of questionnaire – assessment of the current situation

2.2.1. Description of key silvicultural systems, key management options, main tree species and employed harvesting systems

Data collected by questionnaire are available for 9 European countries, which are delineated in Figure 1.

Figure 1. Countries with available data from questionnaire

In order to use consistent terminology, the key silvicultural systems described by the partners have been condensed in 6 categories, which are listed and described in Table 1. Please note that “Age class forest” is not necessarily connected with clear cut, since it can also be established by a sequence of small-scale-area removals (group cut, gap cut, opening up) in order to harvest mature trees as well as to promote regeneration and control the species mixture of regeneration. That means, “Age class forest” is used as generic category, and “Age class forest / clear cut” is a special characteristic. The detailed results on key silvicultural systems by country are shown in Table 1.

Table 1. Definition of key silvicultural systems

Silvicultural system	Description
Age class forest	Even aged high forest. One final cut (clear cut) or various final cuts (group cut, gap cut, opening up). With subsequent artificial or natural regeneration.
Continuous cover forest	Uneven aged high forest with final harvest of single trees ("Plenterwald" / target diameter system). With mostly natural regeneration.
Shelterwood	Even aged high forest. Sequence of final cuts for harvesting mature trees and establishing natural regeneration.
Coppice with standard	Middle forest with two layers: overstory (production of sawn logs) and understory (production of fuel wood, pulpwood).
Coppice	Low forest, vegetative regeneration.
Short rotation forestry	Intensively managed forest resulting from an artificial regeneration with control of the genetic resource.

Table 2. Questionnaire – Key silvicultural systems by country

Key Silvicultural system	Management system/options	Main tree species	Early operations	Employed harvesting systems	Covered forest area
Finland					
Age class forest	First thinning Intermediate thinning Clear cut	Scots pine	Soil preparation/stand establishment, natural regeneration	Harvester and forwarder	3% first thinning 18% intermediate thinning 26% final cutting
Age class forest	First thinning Intermediate thinning Clear cut	Norway spruce	Soil preparation/stand establishment, artificial planting	Harvester and forwarder	1% first thinning 6% intermediate thinning 33% final cutting
Age class forest	First thinning Intermediate thinning Clear cut	Silver birch	Soil preparation/stand establishment, artificial planting	Harvester and forwarder	1% first thinning 5% intermediate thinning 7% final cutting
	According roundwood trade 2015–2019.				

Norway

Age class forest	First thinning Intermediate thinning Clear cut	Norway Spruce	Artificial regeneration, weeding + precommercial thinning, 2 thinnings, clear – felling (medium to high site classes)	Harvester and forwarder	20%
Age class forest	First thinning Intermediate thinning Clear cut	Scots pine	Seed tree regeneration, tending, thinnings, clear-fellings	Harvester and forwarder	24%
Age class forest	First thinning Intermediate thinning Clear cut	Silver birch	Natural regeneration, 1 thinning, clear-felling	Harvester and forwarder	31%
Age class forest	First thinning, Intermediate thinning Clear – cut	Mixed Norway spruce + Scots pine	Weeding, 1(max 2) thinning, clear-felling, planting Spruce	Harvester and forwarder	4%
Age class forest	First thinning Intermediate thinning Clear cut	Mixed Norway spruce + Silver birch	Weeding, 1(max 2) thinning, clear-felling, planting Spruce	Harvester and forwarder	6%

Denmark

Age class forest	Clear cut stand wise or clear cut in strip or wedge patterns. Rotation age 40 – 150 years	Spruce – Fir – Pine – Larch – Douglas fir – Beech – Oak – Ash – Maple – Cherry – others	Normally planting, in fewer cases sowing either artificial or natural from a few left-over neighboring trees	Early thinnings: chainsaw or fellerbuncher – eventually forwarder – and chipper. Later thinnings: Harvester – forwarder and chipper. Final harvest conifers: harvester – forwarder or skidder (eventually winch supported) and chipper. Final harvest broadleaves: Chainsaw – skidder (eventually winch supported) / forwarder and chipper	66%
Shelterwood	Regeneration time up to 20 years	Beech (supplementary species e.g. Larch, Douglas fir, Sitka and Norway spruce)	Regeneration by seeds often combined with supplementary planting of other species	Early thinnings: chainsaw or fellerbuncher – eventually forwarder – and chipper. Later thinnings: harvester – forwarder and chipper. Final harvest: chainsaw – skidder (eventually winch supported) / forwarder and chipper	9%
Continuous cover forest	Reduced impact logging or group wise regeneration; “Plenterwald”	Beech–Oak–others		Chainsaw – skidder (eventually winch supported) / forwarder and chipper	8% (Becoming more common)
Coppice	Rotation age 40–50 years	Oak–Alder–Maple–Beech–Hornbeam–others		Chainsaw or harvester – forwarder – chipper	1% (Occasionally)

Coppice with standard	Rotation age under story e.g. 20 years. Standards e.g. 100 years. Additional standards are selected after each coppice operation.	Oak–Beech–Hornbeam–others		Chainsaw or harvester – forwarder / skidder – chipper	Very Rare
Short rotation forestry	Short rotation 10–20 years	Poplar		Chainsaw, harvester or feller buncher – chipper or forwarder–chipper	Becoming more common
Poland					
Age class forest	Clear cut, wide strip 60 – 80 m, strip 40–60 m	Scots pine	Soil preparation, natural regeneration + artificial from plantation, type of seedling: bare-rooted plant	Chainsaw-tractor, chainsaw-skidder, harvester-forwarder	48%
Age class forest	Clear cut, narrow strip 15–30m	Norway spruce	Soil preparation natural regeneration + artificial from plantation, type of seedling: balled and burlapped planting	Chainsaw-tractor, harvester - forwarder	
Age class forest	Clear cut, strip 40–60 m or narrow strip 15–30 m	Common alder	Soil preparation natural + artificial from plantation, type of seedling: bare-rooted plant	Chainsaw – tractor, chainsaw – skidder	

Shelterwood	Shelterwood cutting	Scots pine, Norway spruce, Pedunculate oak, Beech	Soil preparation natural + artificial from plantation type of seedling: bare-rooted plant, balled and burlapped planting	Chainsaw – tractor, chainsaw – skidder	40%
Continuous cover forest		Norway spruce, Silver fir	Natural + artificial from plantation type of seedling: balled and burlapped planting	Chainsaw-tractor, chainsaw-skidder	3%
Germany					
Age class forest, Continuous cover forest	Spruce forest type of the highlands	Norway spruce	Natural regeneration, plantation, stand establishment, opening-up, precommercial thinning	Harvester-forwarder, cut-to-length logging (CTL)	29%
Age class forest, Continuous cover forest	Mixed Spruce forest type of the highlands	Norway spruce, Fir, Beech, Maple, Larch, Pine	Natural regeneration, stand establishment, opening-up, precommercial thinning	Harvester-forwarder, CTL, partly felling by chainsaw	
Age class forest, Continuous cover forest	Spruce forest type of the lowlands	Norway spruce	Plantation, stand establishment, opening-up, precommercial thinning	Harvester-forwarder, CTL	
Age class forest, Continuous cover forest	Pine forest / type of the lowlands	Pine	Soil preparation, plantation, stand establishment, opening-up, precommercial thinning	Harvester-forwarder, CTL	23%

Age class forest, Continuous cover forest	Pine forest / type of the highlands	Pine	Plantation, stand establishment, opening-up, precommercial thinning	Harvester-forwarder, CTL, partly felling by chainsaw	
Shelterwood	Beech conifer forest type	Beech, Spruce, Fir, Douglas fir, Larch, Maple, Beech	Natural regeneration, additional plantation, stand establishment, opening-up, precommercial thinning	Chainsaw-skidder, partly big size harvester	17%
Shelterwood	Beech broadleaved forest type	Beech, Maple, Ash, Oak, Hornbeam	Natural regeneration, stand establishment, opening-up, precommercial thinning	Chainsaw-skidder, partly big size harvester	
Shelterwood	Oak broadleaved forest type	Oak, Lime, Hornbeam	Natural regeneration, plantation, stand establishment, opening-up, precommercial thinning	Chainsaw-skidder	9%

France

Shelterwood	Beech high forest, thinnings	Beech	Natural regeneration	Chainsaw-forwarder	9%
Coppice / Coppice with standard	Beech coppice	Beech	Natural regeneration (where possible to take advantage of local genetic adaption), natural regeneration by coppicing	Chainsaw (harvester used sometimes for industrial timber), forwarder or skidder	
Coppice with standard	Pedunculate Oak (private forest)	Pedunculate Oak	Natural regeneration (where possible to take advantage of local genetic adaption), natural regeneration by coppicing	Chainsaw (harvester used sometimes for industrial timber), forwarder or skidder	21%
Coppice with standard	Sessile Oak (private forest)	Sessile Oak	Natural regeneration (where possible to take advantage of local genetic adaption)	Chainsaw-forwarder	
Shelterwood	Pedunculate Oak / Sessile Oak (public forest)	Pedunculate Oak / Sessile Oak	Natural regeneration (where possible to take advantage of local genetic adaption), natural regeneration by coppicing	Chainsaw (harvester used sometimes for industrial timber), forwarder or skidder	
Coppice	Pubescent oak coppice	Pubescent Oak	Natural regeneration by coppicing	Chainsaw-forwarder	9%

Coppice	Sweet chestnut coppice	Chestnut	Natural regeneration by coppicing	Harvester and Forwarder. Chainsaw used when the wood quality is very good.	5%
Coppice	Evergreen Oak coppice	Holm oak	Natural regeneration by coppicing, sometimes sowing	Chainsaw (located usually in steep terrains) Forwarder, winch supported	4%
Shelterwood	Ash (usually mixed stands)	Ash	Natural regeneration (where possible to take advantage of local genetic adaption), natural regeneration by coppicing	Chainsaw (harvester used sometimes for industrial timber), forwarder or skidder	4%
Coppice	Hornbeam coppice	Hornbeam	Natural regeneration by coppicing	Harvester and Forwarder	4%
Age class forest	Poplars cleacut	Poplar	Soil preparation – full cleaning and ploughing (only in best cases), mulching, pruning	Chainsaw-forwarder (logs from 1,3m to 5m)/ harvester is used only when parcels have a lot of herbaceous vegetation	1%
Age class forest	Maritime pine clear cut (private forest)	Maritime pine	Soil preparation (full or strip ploughing, discing), plantation, 3 – 4 thinnings and clearings	Harvester and Forwarder (skidder for long trees)	7%
Age class forest	Maritime pine clearcut/selection cut (public forest), thinnings	Maritime pine	Soil preparation (full ploughing, strip ploughing, discing, etc.), natural regeneration	Harvester and Forwarder (skidder for long trees)	

Shelterwood	Scots pine mixed stands	Scots pine	Natural regeneration	Harvester and Forwarder (skidder for long trees)	6%
Age class forest	Norway spruce planted, 4 thinnings	Norway spruce	Piling before plantation	Harvester and Forwarder	4%
Shelterwood / Continuous cover forest	Norway spruce mixed stands (mountain), precommercial thinning, thinnings, opening up	Norway spruce	Natural regeneration, stand establishment	Chainsaw-skidder (gros bois, steep terrains)	
Clear cut / Shelterwood / Continuous cover forest	Silver fir mixed stands	Silver fir	Natural regeneration	Chainsaw-forwarder	4%
Age class forest	Douglas fir clear cut, 4 thinnings	Douglas fir	Piling before plantation	Harvester and Forwarder (skidder for long trees)	3%
Age class forest	Black pine clear cut, 4 thinnings	Black pine (laricio)	Piling before plantation	Harvester and Forwarder	1%

Austria					
Age class forest	Spruce clear cut, 2–3 thinning operations	Norway spruce	Planting and natural regeneration, weed control, tending	Chainsaw-cable yarder with processing unit, harvester-forwarder	50%
Continuous cover forest	Spruce-Fir-Beech forest	Norway spruce-Silver Fir-Beech	Natural regeneration and planting, weed control, tending	Chainsaw-skidder	10%
Shelterwood	Beech shelterwood	Beech	Natural regeneration, preparative cut with removal of bad individuals	Chainsaw-skidder, harvester-forwarder	10%
Shelterwood	Oak shelterwood	Oak	Natural regeneration, preparative cut with removal of bad individuals	Chainsaw-skidder, harvester-forwarder	2%
Italy					
Coppice	Coppice clear cut	Oak-Beech-Chestnut-Hornbeam-others	None	Chainsaw-mules; chainsaw-tractors with boxes; chainsaw tractor and trailer; chainsaw-excavator-forwarder; feller-buncher-forwarder; chainsaw-yarder	30%
Coppice	Coppice conversion	Oak-Beech-Chestnut-Hornbeam-others	First heavy thinning; following thinning operations until regeneration by shelterwood system or clearcut depending on species	Chainsaw-mules; chainsaw-tractors with boxes; chainsaw tractor and trailer; chainsaw-excavator-forwarder; feller-buncher-forwarder; chainsaw-yarder	10%

Shelterwood	Spruce-Fir-Beech forest	Spruce-Fir-Beech, generally mixed	Natural regeneration; ca. 2 thinning operations; preparation cut; seeding cut; removal cut	Chainsaw-skidder; harvester-forwarder; chainsaw-yarder; chainsaw-yarder-processor	10%
Age class forest	Spruce-Larch-forest /Gap cutting	Spruce-Larch-Pine (Scots and Mountain pine), pure or mixed	Natural regeneration; ca. 2 thinning operations; gap cut	Chainsaw-skidder; harvester-forwarder; chainsaw-yarder; chainsaw-yarder-processor	7%
Age class forest	Artificial pine forest /Gap cut – Clearcut	Austrian pine, Stone pine, Maritime pine	Manual planting, ca. 3 thinning operations, clearcut	Chainsaw-tractor; harvester-forwarder; feller-buncher-skidder	10%
Continuous cover forest	Spruce-Fir-Beech forest	Spruce-Fir-Beech, generally mixed	Natural regeneration; regular thinning of mature trees and dominated trees at 15–30 years intervals	Chainsaw-skidder; harvester-forwarder; chainsaw-yarder; chainsaw-yarder-processor	15%
Spain					
Continuous cover forest		Quercus ilex and Quercus humilis		Chainsaw-skidder, forwarder /chainsaw-horses hand forwarding	16% of forest area with tree cover (fcc> 5%) in Catalonia
Shelterwood / Continuous cover forest		Scots pine		Chainsaw-skidder, forwarder/chainsaw-horses	14%
Shelterwood		Aleppo pine	Tending		18%
Continuous cover forest		Black pine			8%

Coppice		Castanea, locally Quercus ilex		Chainsaw-skidder, forwarder	1% Castanea
Short rotation forestry	Clear cut	Fast growing tree plantations: Poplar, Platanus, conifers (Douglas fir, Silver fir, Cedar)	Soil preparation / stand establishment / plantation	Chainsaw-skidder, forwarder	2%
Continuous cover forest		Silver fir, Beech			3%
Continuous cover forest		Hardwood Quality timber (Juglans, Prunus, Quercus robur/ petraea)		Chainsaw-skidder, forwarder	

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2.2.2. Summary of key silvicultural systems by ecoregion

The summary of key silvicultural systems by European ecoregions (Table 3, Figure 2) was created according to “State of Europe’s Forest 2015” report and Tech4Effect questionnaire results.

Table 3. Summary of key silvicultural systems by ecoregions.

North Europe	
Main silvicultural system	Age class forest/clearcut
Main species	Scots pine, Norway spruce, Silver birch
Regeneration establishment and treatments	Soil preparation, natural regeneration, planting, weed control, thinning (2–3)
Main harvesting techniques	Harvester-forwarder (>90%), chainsaw-skidder
Central-East Europe	
Main silvicultural systems	Age class forest (clear cut, group cut), continuous cover forest, shelterwood
Main species	Scots pine, Norway spruce, Silver fir, Larch, Beech, Oak
Regeneration establishment and treatments	Soil preparation, natural regeneration, planting, tending, thinning (2–3)
Main harvesting techniques	Harvester-forwarder, chainsaw-skidder (tractor), chainsaw-cable yarder
Central-West Europe	
Main silvicultural systems	Coppice, coppice with standard, age class forest / clear cut, shelterwood
Main species	Oak, Beech, Maritime pine, Scots pine, Norway spruce, Sitka spruce, Chestnut, Poplar, Douglas fir, Silver fir, Eucalyptus
Regeneration establishment and treatments	Soil preparation (ploughing), mulching, natural regeneration (by coppicing), planting, tending, thinning, pruning
Main harvesting techniques	Chainsaw-forwarder (skidder), Harvester-forwarder
South Europe	
Main silvicultural systems	Coppice, shelterwood, age class forest (clear cut, gap cut), continuous cover forest, short rotation forestry
Main species	Oak, Beech, Chestnut, Hornbeam, Norway spruce, Pines (various: austrian, scots, maritime and umbrella the main ones), Hybrid poplar
Regeneration establishment and treatments	Soil preparation, natural regeneration, tending, thinning (2–3), pruning (hybrid poplar)
Main harvesting techniques	Chainsaw-mules, chainsaw-tractor, skidder or forwarder, feller-buncher-forwarder, harvester-forwarder, chain saw-yarder

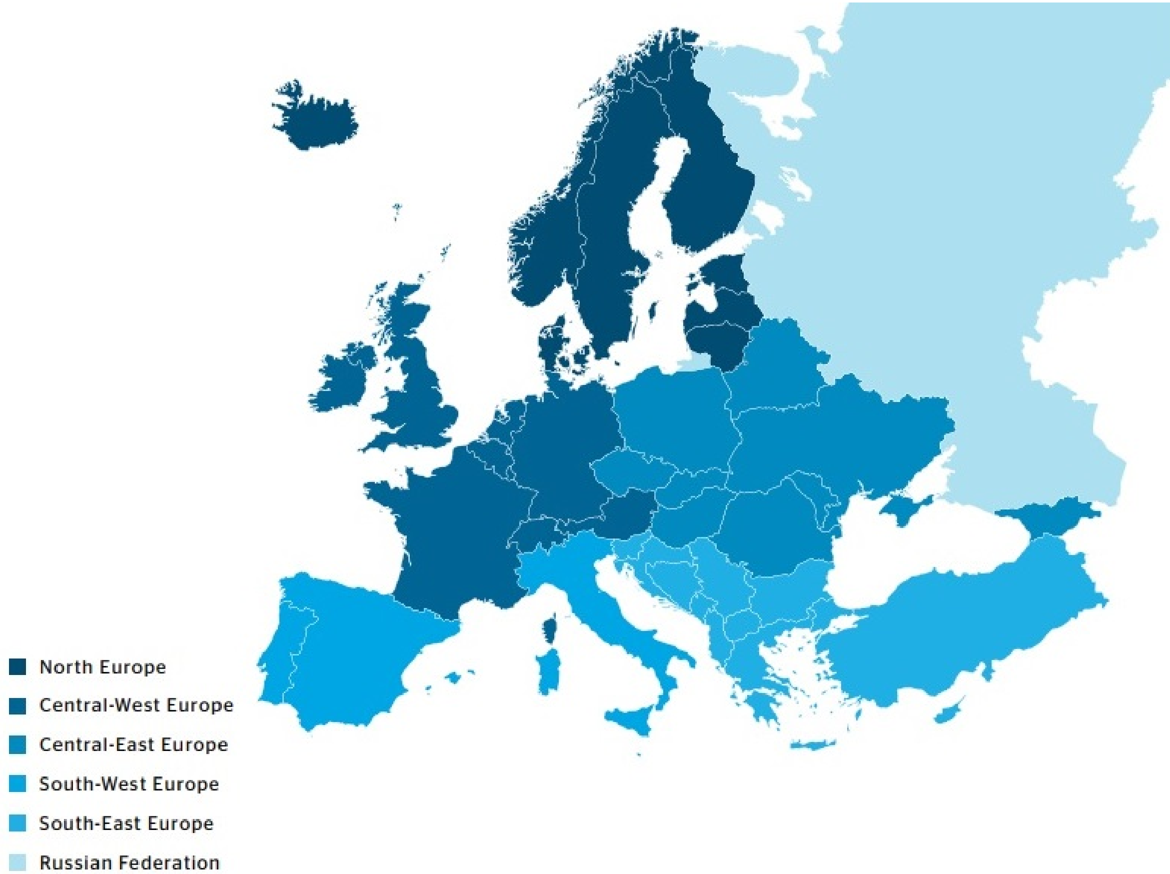


Figure 2. European forest ecoregions.

(source: http://www.foresteurope.org/docs/fullsoef2015.pdf).

The method of regenerating a forest stand after final harvest is one of the crucial issues for current and long-term forest sustainability. For comparative purposes a general overview on various practices by European ecoregions is provided in Table 4.

Table 4. Share of forest area (uneven-aged and even-aged) by regeneration types in the European regions, 2010 (source: http://www.foresteurope.org/docs/fullsoef2015.pdf).

Region	Natural regeneration and natural expansion		Afforestation and regera-tion by planting and seeding		Coppicing	
	million ha	% of forest area	million ha	% of forest area	million ha	% of forest area
North Europe	48.4	68	22.4	32	-	-
Central-West Europe	22.3	64	10.6	30	2	6
Cenral-East Eu-rope	16.1	52	13	42	2.1	7
South-West Eu-rope	26.1	86	3.3	11	1.1	4
South-East Eu-rope	19.9	72	4	14	3.6	13
Europe	132.8	68	53.2	27	8.8	5
EU28	98.5	68	38.8	27	5.4	5

3. Potentials for enhancing wood production

3.1. List of option by country

The potentials for enhancing wood production for different European countries were determined based on Tech4Effect questionnaire results. Within the variety of listed options for efficiency increase, we can identify a number of recurring issues.

Table 5. Questionnaire – Options to enhance productivity by country.

Country	Anticipated options to enhance productivity
Finland	• **Options for all listed silvicultural systems:** continuous mounding machines; reduction of seasonal variation of workload; systems assisting and guiding the operator; simplified forwarding operations; larger harvesting units (area).
Norway	• **Options for all age-class/ clearcut systems:** Improved stand density management strategies which includes: 1) appropriate initial planting densities, 2) increased amount of early stand tending's with guidelines on timing of tending and residual stand density, and 3) increased amount of mid-rotation thinning with guidelines on timing and residual stand density.
Denmark	• **Coppice:** Use of other tree species than poplar e.g. fast growing conifers; extending rotation age; regeneration by planting with regular intervals; coppicing is not an option; design of stand and forest infra structure; improved instructions; since management decisions at time may affect the productivity over time the time dimension needs to be addressed; technical efficiency achieved by high harvesting rates may contribute to high performance but compromise long term productivity and economic outcome. • **Even aged high forest (monocultures as well as mixed stands. Rotation ages 40–150 years):** Improved instructions; improved stand and forest infrastructure; thinnings: marking of trees for thinning and or later marking of future trees; power cultures – forced quality broadleaves (with high productivity rates in early stage of life cycle such as: *Acer pseudoplatanus, Prunus avium, Quercus spp., Fraxinus excelsior, Juglans spp.* with intensive management regime including pruning in order to produce high quality crop trees)-no thinning (optional in e.g. *Picea sitchensis* and *Abies grandis*) • **Even aged high forest (Beech shelter wood. Regeneration time up to 20 years):** Improved instructions; improved stand and forest infrastructure; marking of trees for thinning and or future trees – establishment of semi-permanent skidding roads. • **High forest (typically mixed stands. Becoming more common):** Improved instructions; improved stand and forest infrastructure; permanent skidding roads.
Poland	• **Clearcut:** Systems assisting and guiding the operator; mechanize harvesting and processing; optimize trail network to reduce damage at trees. • **Shelterwood/Continuous cover forest:** Mechanize harvesting and processing; optimize trail network to reduce damage at trees.

Germany	• **Options for all listed silvicultural systems:** Opening-up; aligned harvesting techniques.
France	• **All broadleaves:** the main challenge in France is to increase mechanization of broadleaves with irregular shapes and very heterogeneous size as this resource is immobilized for decades. • **Mountain forest:** Many stands resulting from farming land abandonment or plantation for erosion prevention on steep terrain remain unused and is poorly managed and difficult to harvest. Use of appropriate machinery and active management is a way to increase productivity in these areas. • **Poplars clearcut:** Prunings are made not to enhance the productivity but to enhance the quality of the wood, then it will be better payed by the industrials, it improves profitability. Selection of the more pest resistant collection of clones is favoring production • **Pedunculate Oak coppice/Sessile Oak coppice/Pubescent oak coppice/Evergreen Oak coppice/Hornbeam coppice/Sweet chestnut coppice:** Some coppices can be very old (hundreds of years) or located in place not any more appropriate under changing climate. Regeneration with new material or enrichment and/or replacement by plantation is an option to increase productivity (for wood and fruits) • **Pedunculate Oak and Sessile Oak shelterwood:** The ONF (National Forest Office) applies active thinning regimes to enhance the wood production. • **Ash (usually mixed stands):** Big problem with dieback because of the *Hymenoscyphus fraxineus* (Chalara fraxinea) fungus, forest owners stopped investing in this species. • **Maritime pine clearcut:** Pruning is highly recommended when producing high wood quality to increase profitability, but not rewarded at the moment. Used of improved material with shorter rotation period is a way to increase productivity in a system already requiring active management. Some alternative thinning regime with high initial density and first thinning for biomass is considered to increase productivity. Additional resource for biomass use is more and more commonly harvested: stumps, branches. • **Scots pine mixed stands/Norway spruce mixed stands (mountain)/Black pine clearcut:** Limited management, the main challenge is to mechanize and renew old stand established for soil erosion protection but with a potential for timber. • **Douglas fir clearcut:** Sometimes there is a first thinning at the early plantation begging for enhancing the growth, Douglas fir wouldn't lose its mechanical properties. Pruning after the first thinning and another pruning when height is about 12 m (ideal cases) is a common way to increase profitability. Use of provenance adapted to drought is an appropriate way to increase productivity of lower stand suffering under climate change.

Austria	• Shelterwood (Beech, Oak): **Reduce rotation period to permit harvester use, introduce non-native conifers to enhance share of sawn logs.** • Clearcut (Spruce): **Large tree spacing to increase efficiency of thinning.** • Continuous cover forest (Spruce-Fir-Beech): **Optimize trail network to reduce damage at trees.**
Italy	• **Coppice:** Mechanized or semi-mechanized whole-tree harvesting for biomass production, rather than short-wood harvesting for firewood production. • **Spruce-Fir-Beech Continuous cover forest (continuous cover management, shelterwood cut)/Spruce-Larch-Pine even-age forest (gap cutting):** Mechanized harvesting and processing by introducing state-of-the-art cut-to-length logging technology (mechanized harvesting system in which trees are delimbed and cut to length directly at the stump); improve and automate yarding; effective biomass recovery. • **Artificial pine forest:** Increase mechanization of operation, by introducing mechanized cut-to-length logging and whole-tree harvesting technology.
Spain	• ***Quercus ilex* and *Quercus humilis*:** Use of skidding roads. • ***Pinus sylvestris*:** Application of tending and thinning on time. Timber quality classification on site and on-industry; apply ORGEST silvicultural models. • **Hardwood quality timber (*Juglans, Prunus, Quercus robur, Quercus petraea...*):** Increase the use of this silviculture in mixed stands.
Spain	• ***Quercus ilex* and *Quercus humilis*:** Use of skidding roads. • ***Pinus sylvestris*:** Application of tending and thinning on time. Timber quality classification on site and on-industry; apply ORGEST silvicultural models. • **Hardwood quality timber (*Juglans, Prunus, Quercus robur, Quercus petraea...*):** Increase the use of this silviculture in mixed stands.

3.2. Summary of mentioned options for enhancing wood production

Within the variety of listed options for efficiency increase, we can identify a number of recurring issues.

Issues regarding silvicultural activities:

- Tending and thinning: Effective and careful pre-commercial thinning; adaption of thinning regime by tree species (e.g. more thinning on *Quercus* spp., no thinning on *Picea sitchensis, Abies grandis*, possibly *Pseudotsuga menziessii* and mixed stands)
- Change of species (including non-natives?)
- Selection of appropriate provenances
- Adaption of thinning regime: more thinning on particular species, e.g. Oak, no thinning on particular species, e.g. Sitka spruce, Giant fir, possibly Douglas fir
- Change of rotation period: reduction in high forest (→ compatibility with mechanized harvesting techniques), extension in coppice (compatibly with the regeneration potential of the stumps)
- Genetic improvement of seedlings, high productivity clones
- Effective site preparation (drainage, ploughing)
- Effective and careful pre-commercial thinning and weed control
- Facilitation of N fixing understorey
- Forest fertilization on appropriate stands (applying strict economic and ecological criteria)

Issues regarding harvesting activities:

- Establishment of appropriate skidder trail networks (= corridor layout) and appropriate stand infrastructure (e.g. suitable size of harvesting unit)
- Enhanced mechanization of harvesting, processing and yarding procedures
- Promotion of tree marking for precommercial thinning in even aged high forest, development of supportive tools for tree selection done by harvester operator
- Selection of most favorable harvesting period (season), in combination with the selection of most favorable harvesting technique, in order to reduce soil and stand damages
- Effective biomass recovery all over Europe (e.g. whole tree method in coppice)

4. Results of case studies

Twelve case studies in seven partner countries have been done. In the course of the generation of the case studies four focus groups of promising increase potentials for European forestry emerged:

1. to enhance mechanization in harvesting operations (three case studies),
2. to change and intensify tending and thinning practices (four case studies)
3. to adopt more appropriate methods in early operations and stand establishment (three case studies)
4. to demonstrate the importance of rational business processes in procuring or marketing services for silviculture, harvesting and wood purchasing (two case studies).

Two case studies from group 2 (tending and thinning) are realized by implementing harvesters. That means that they have a strong intersection with group 1 (mechanization), so that in five out of twelve case studies the enhancement of mechanization is an essential topic. Therefore, a bottom line of the work is the observation that mechanization might acquire an increasing impact (feedback loops) on silvicultural goals and management strategies.

4.1. Enhancing mechanization

4.1.1. Case study Finland – Tending with Cutlink device

Johanna Routa, Antti Asikainen and Yrjö Nuutinen

Current practice / Need for improvement

Tending of seedling stands means cleaning the brush and thinning the stand to a suitable growth density. This is done to ensure that the seedlings get enough sunlight and space to grow well. According to National Forest Inventory data, there is an urgent need for tending seedling stands of at least 700,000 ha and a need for 1 million ha in next few years in Finland (Korhonen et al. 2017). The motivation for forest owners to conduct pre-commercial silvicultural operations is low due to the associated high costs. Especially the costs of tending and clearing operations after the regeneration of the stand have been increasing. In addition, the availability of labor is a restricting factor due to the high seasonality of silvicultural works.

In the 2000's several solutions for the mechanization of tending have been proposed. These are based on the use of harvester or a forwarder as a base machine. Typically, light weight base machines are favoured to reduce the hourly cost of operations and the impacts on the remaining seedlings. There has been a challenge with the high speed of the cutting device, which increases the risk of damages to the head and the ignition of forest fires when the circular saw or chain hits stones, for example. In addition, the chain can become dislocated due to bending forces caused by stumps.

Goals

Cutlink has presented a low RPM (number of revolutions) solution based on rotating cone-shaped shears that cut 50–100 cm wide corridors between and around seedlings. In this study, the productivity of mechanized tending with Cutlink´s device compared to manual tending was evaluated in spruce seedling stands in central Finland (Figure 3). The productivity, fuel consumption and quality of the seedling stand after the operation were measured. In early tending the productivity of motor manual tending was notably better than when using the Cutlink device. Crucial factors for the competitiveness of a mechanized alternative include the annual working hours and finding suitable working areas for the machine. Additional work for the device and base machine can be found also in the clearing of forest roadsides. The aim of this study was to compare the productivity of mechanized tending with the Cutlink device to manual tending in spruce seedling stands in central Finland.

Figure 3. Motor-manual tending and mechanized tending using the Cutlink device were compared in a field experiment.

Achievement of goals / Future practice

We compared the productivity of mechanized tending with a Cutlink device to manual tending in spruce seedling stands in central Finland (Figure 4). Motor manual tending was noticeably faster and the quality of the work was better than with Cutlink. The average productivity of motor manual tending was 0.23 ha h^{-1} and with the Cutlink device it was 0.11 ha h^{-1}. However, the test period was on average 35 minutes, and the work efficiency of motor manual work will certainly decrease after continuous work of several hours. We conducted all motor manual tests on the same day and observed that in the last section the difference was the smallest between motor manual tending and the Cutlink device.

The conditions in the experimental stand were slippery, and the quality of the work of the Cutlink device was not very good; very small birch seedlings were difficult to cut with device. The blades were sharped during the test, but the cutting of small birches was still very difficult. With Cutlink the removal was smaller than the number of remaining seedlings, so the quality of work was not acceptable in all blocks. In general, work quality of mechanized tending is lower than in motor manual tending and there have been reported damages to remaining trees (Rantala and Kautto 2011, Sandström et al. 2011).

Impact on stand development, forest products, costs

However, the Cutlink device was found to be very reliable and its technical availability was exceptionally good considering its development stage. There weren´t any interruptions during the tests. The availability of labor can be a restricting factor due to the high seasonality of silvicultural works and we need new solutions. The share of mechanized tending will increase in the future; the challenge is to improve the productivity bringing it up to a cost-efficient level. Possible solutions could include automation, sensor technology and machine vision. In addition, the selection of the right stands and training of the operators are crucial for improving mechanization. One new method is silver leaf fungus (Chondrostereum purpureum) treatment, which prevents the pruning of deciduous trees. Combining fungus treatment with mechanization improves the cost efficiency of the operation. The other new promising technology is uprooting. The mechanical solution for this is the Naarva uprooter (Pentin paja Oy) which uproots the deciduous trees from a conifer sapling stand. Efficiency of this method is crucially dependent on how well the need of later pre-commercial thinning after uprooting is prevented.

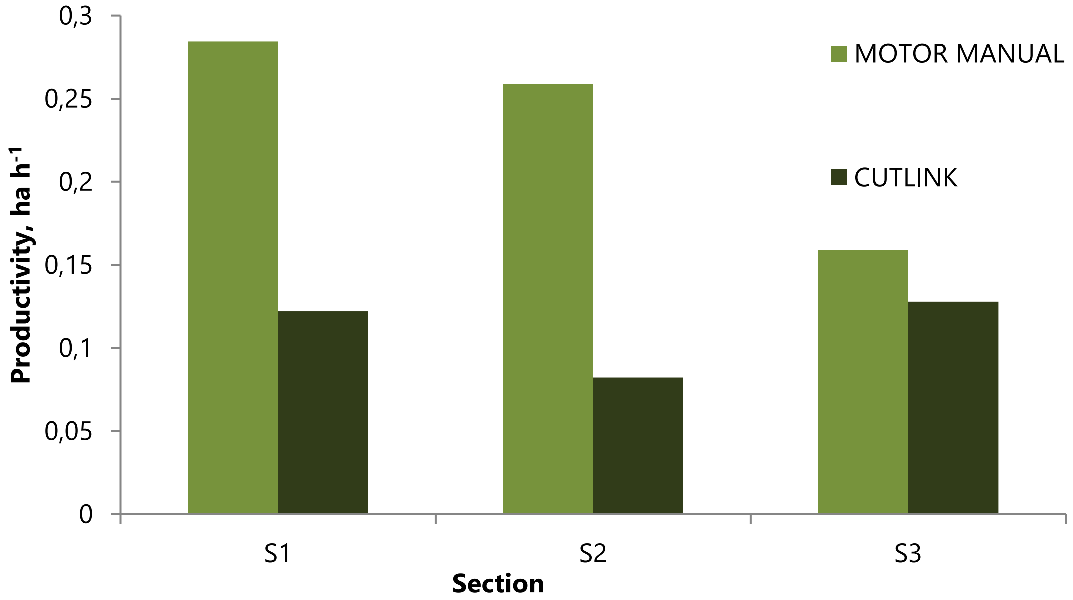


Figure 4. Productivity (ha h^{-1}) of motor-manual tending and Cutlink device in average of each section.

Proper stand management has long-term effects on stand development and, subsequently, on the profitability of forest management (Huuskonen and Hynynen 2006). It is extremely important to increase the knowledge about the importance of early cleaning and pre-commercial thinning among the forest owners. In practice we need to achieve a level, where machines are faster and cost effective compared to motor-manual work. Mechanizing the silvicultural work improves the safety at work and decrease the physical stress of the workers. In addition, we need change the operation culture to favor more mechanization in the early phases of forest development.

Routa, J., Nuutinen, Y. and Asikainen, A. 2020. Productivity of mechanizing early tending in spruce seedling stand. CROJFE 41: 1–11.

4.1.2. Case study Italy – Mechanized harvesting in coppice with standard

Carolina Lombardini and Raffaele Spinelli

Current practice / Need for improvememt

Approximately 16% of all productive forests in Europe are classified as coppice, covering a total area of ca. 23 million ha. These are mainly located in the far west, south and south-eastern parts of the continent. Over half of European coppice forests are situated in industrialized countries, such as France (6 Mi. ha) and Italy (3 Mi. ha).

Foresters are very much concerned that mechanized cutting may produce significant stump damage, with negative effects on regeneration in terms of stump mortality and shoot growth. For this reason, mechanized cutting is forbidden in many areas (most of Italy, i.e. ca. 3 million hectares) and manual cutting is required.

If a way can be found for introducing mechanized cutting to coppice forests, one may obtain significant benefits in terms of:

- increased competitive capacity of wood products from coppice, due to a dramatic reduction in supply cost
- increased wood supply at a landscape level, because the increased efficiency will make it cost-effective to harvest a large number of stands that are not currently harvested due to the high cost of manual cutting
- guarantee that coppice management is maintained on many sites where it may soon disappear due to abandonment and natural conversion into a poor quality high-forest, which is a marked benefit if we agree on the economic, environmental and cultural value of coppice forests, as advocated by COST Action Eurocoppice
- dramatically reduced fatalities in forestry work, since fatal accidents most often occur during manual felling (expected reduction at about 4:1, according to Bell and Grushecky 2006)

Figure 5. An overview of the study area.

Goals

The case study aims at determining with scientific methods if mechanized cutting results in an increased mortality of the coppice stools and a reduced resprouting vigour in surviving stools.

Data were sourced as follows:

- the crucial element here is to determine whether the mechanized cutting of coppice stumps in traditional coppice operations may affect coppice regeneration, and to what extent. The null hypothesis is that it does not. In order to determine that CNR has established an experimental site near Tarquinia
- social data, and namely: operator safety, operator comfort and employment. These were derived from existing bibliography on the subject;
- economics (esp. harvesting cost with the two systems): these data were derived from the large database made available through COST Eurocoppice.

Figure 6. Cutting by chainsaw (left) and by disc-saw (right).

Achievement of goals / Future practice

Preliminary results indicate that mechanized harvesting does not result in an increased stump mortality and/or a reduction of resprouting vigour.

At the same time, harvesting cost is reduced by at least one third, which dramatically increases the financial viability of coppice management and may motivate owners to better care for their coppice forests.

Finally, all references indicate that mechanization may allow reducing severe accidents which may be already enough of a good reason for a decisive shift towards mechanized harvesting.

Impact on stand development, forest products, costs

The introduction of mechanized felling to coppice operations generates a large potential for technology and knowledge transfer across Europe.

The size of these effects is dramatic. In Italy alone, we are talking about almost 3 Mi ha (45% of the national forest surface) that suffer from a principle exclusion from the benefits of mechanized cutting because they are classed as coppice!

Avoiding the abandonment of coppice stands contributes to the improved stability of European forests, because coppice stands should be either maintained under coppice management or intentionally converted to high forest, but not abandoned. Abandonment generally leads to degradation and wildfire damage, especially in the face of climate change.

Furthermore, this study represents a fundamental contribution to the current scientific debate about the strategy to follow with coppice forests, which has always been very strong in Southern Europe and has been recently revived by COST Action Eurocoppice

Figure 7. Measuring resprouting vigor: count of all sprouts, determining height and diameter of the five tallest sprouts.

4.1.3. Case study Poland – Mechanization of thinnings in conifer forests

Arkadiusz Gruchała, Karol Bronis and Michał Zasada

Current practice / Need for improvement

One of the most important processes in Polish state forests is the mechanization of fellings (including tending and finall cutings), especially in the most important coniferous forests. Taking into account the role of Task2, the objectives of this study were: (i) comparison of mechanised (harvester), mixed fellings (harvester and chainsaw) and manual (chainsaw) in relation to species structure, type of fellings and site conditions; (ii) comparison of skidding trail network for analysed harvesting types; (iii) analysis of marking trees according to analysed harvesting types and (iv) assessment of factors affecting the possibility of mechanised fellings.

Goals

Alluding to the fact that the largest number of harvesters in Poland operate in the north-west and north Poland, the case study was carried out in Polanów Forest District. The territorial range of this area equals 327 km^2. In total, forests in this forest district occupies 16 195 ha, including 7 875 ha (50%) of Scots pine stands. The volume of timber resources in analyzed area is 4.1 million m^3, while the average volume of growing stock of all stands equals 253 m^3/ha. As a part of activities carried out during the case study, an analysis was aplied for all stands harvested in 2018 (in total 141 stands). These were different stands from the point of view of the species composition, growing conditions and harvesting activities carried out.

In order to achieve the goals of the case study, two main data sources have been used:

I. Data from Information System of State Forests (SILP) providing description of stands including: stand structure (e.g. age, species structure and site tipes defined in the Table 6), type of the management system (e.g. clear-cut, shelterwood), type of fellings, the quantity (m^3) and costs (EUR) of fellings.
II. Questionnaire addressed to forest managers, which contained questions for each stand related to: skidding trail network (width, distance between trails), type of tree marking and factors affecting the use of the harvester.

Table 6. Description of analysed site (habitat) types.

Bśw	fresh coniferous forest	Bb	bog (pine) forest
BMśw	fresh mixed coniferous forest	Lśw	fresh deciduous forest
BMw	moist mixed coniferous forest	LMśw	fresh mixed deciduous forest
BMb	mixed coniferous bog forest		

Achievement of goals / Future practice

All analysed fellings were carried out with three methods: (i) mechanized harvesting with the use of harvesters – 13.5% of total fellings; (ii) mixed (harvesters and chainsaws – 29.1%) and (iii) manual (only chainsaws – 59.1%). The results obtained in this case study in relation to the analysed tree species indicated that, for both coniferous and deciduous species, with the eception of larch (2 stands only), manual harvesting dominates (Figure 8). Moreover, the largest share (nearly 25%) of mechanized harvesting, has been recorded for Scots pine. Interestingly, deciduous tree species (birch, beech) were in some cases also felled with harvesters. The share of mechanized harvesting for these tree species was about 7%

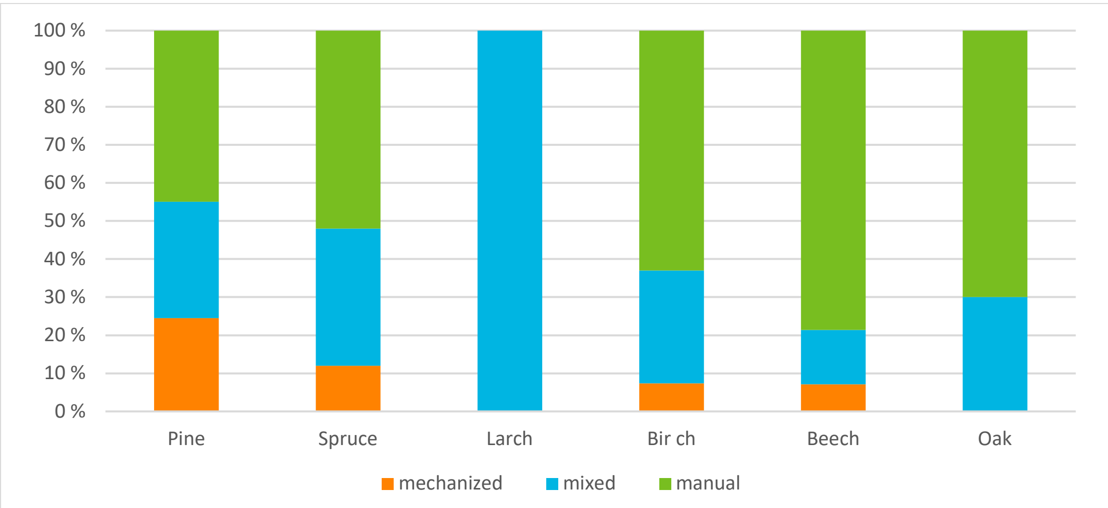


Figure 8. Share of analysed harvesting methods in relations to tree species.

Harvesting in the analysed forest district concerned mainly pre-final fellings – nearly 60% of those type of activity were carried out in 2018. At the same time, manual harvesting was carried out in all categories of fellings, while mechanized and mixed methods were used only in the case of tending and clear-cut system (Figure 9).

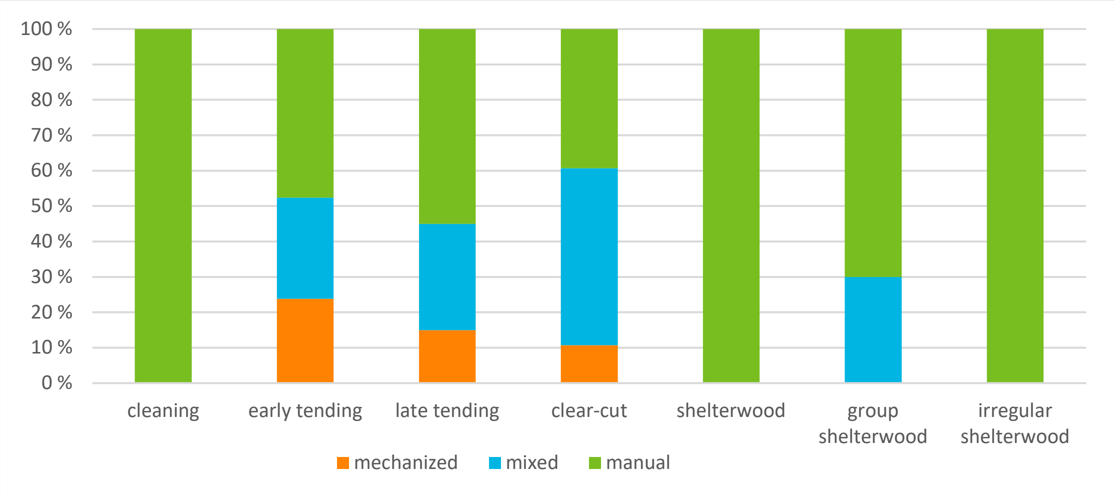


Figure 9. Share (%) of all types of harvesting achieved in 2018 according to analysed types of fellings.

Considering all analysed felling methods from the site type point of view, manual harvesting is present in all site types (Figure 10). While mixed harvesting is used in case of three site types, although in a size reaching even over 30%. Mechanised fellings does not occur only in the case of one site type (BMw – moist mixed coniferous forest) and its share for coniferous sites reaches even 50% (e.g. Bśw – fresh coniferous forest).

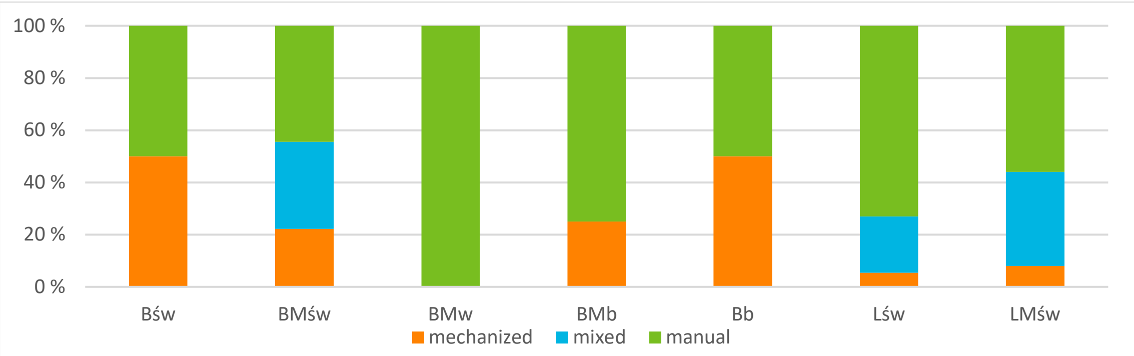


Figure 10. Types of felling according to site types.

Mechanised harvesting was observed in age classes from 2 to 6 (age from 20 to 120). For 2 age class (age from 20 to 40) the share of mechanised harvesting reached level above 30%. For classes 3 to 6 (age from 40 to 120), the share of mechanized harvesting did not exceed 10%. The mean area of stand cut by harvester equals 2.36 ha. However, for both: mixed and manual method this area was noticeably greater (3.40 and 3.34 ha, respectively). The average volume of harvested timber depending on the harvesting method was as follows: for mechanized harvesting – 166.06 m^3/stand, for mixed harvesting – 320.60 m^3/stand and manual – 245.25 m^3/stand. Again, the lowest value for mechanized harvesting is unexpected. The cost of timber harvesting for the mechanized method ranged from 7.21 to 8.14 EUR/m^3. In the case of mixed and manual extraction, costs ranged respectively from 7.91 to 8.14 EUR/m^3 and from 6.94 to 8.14 EUR/m^3 (PLN/EUR exchange rate of 4.30 PLN for 1 EUR was used).

It should be noted that slight differences in achieved costs for analysed harvesting methods are related to the way contracts are concluded between Polish State Forests and private forest companies that provide services in the field of timber harvesting.

Questionnaire addressed to forest managers

As a part of research, questionnaire addressed to forest managers responsible for direct supervision over the implementation of the harvesting process, was also developed. The first question for planned harvesting concerned preparation of skidding trails network (skidding trails width and distance between them). Skidding trails were always prepared for mechanized and mixed harvesting. The width of trails ranged from 3 to 5 m. The 5-meter skidding trails were created only for mechanized harvesting, while 3.5-meter for mixed method. The most common skidding trails width was 4-meter – used in all harvesting variants. The distance between skidding trails varied from 20 to 30 m. For mechanized harvesting typical distance was 20 and 30 meters.

Respondents were also asked about tree marking – if and how the trees to be cut were marked. Only in case of 7% of analysed stands harvested manually forest managers did not mark trees for harvesting. However, for mechanized harvesting, two-sided trees marking has always been done. On the other hand, in the case of mixed and rest of manual harvesting, trees were marked on one or two sides. In the context of tree marking, respondents also specified the time devoted to this activity. In the case of mechanized harvesting, the respondents mainly pointed out the time from 10 to over 20 seconds per tree. However, in the case of mixed harvesting, it was mainly less than 10 seconds or up to 20 seconds per tree. The last question concerned factors limiting mechanized harvesting. The respondents indicated seven factors of different origin (Figure 11). Main barriers in the use of this method turned out to be the topography (over 40%), species composition (over 30%) and site wetness (over 15%).

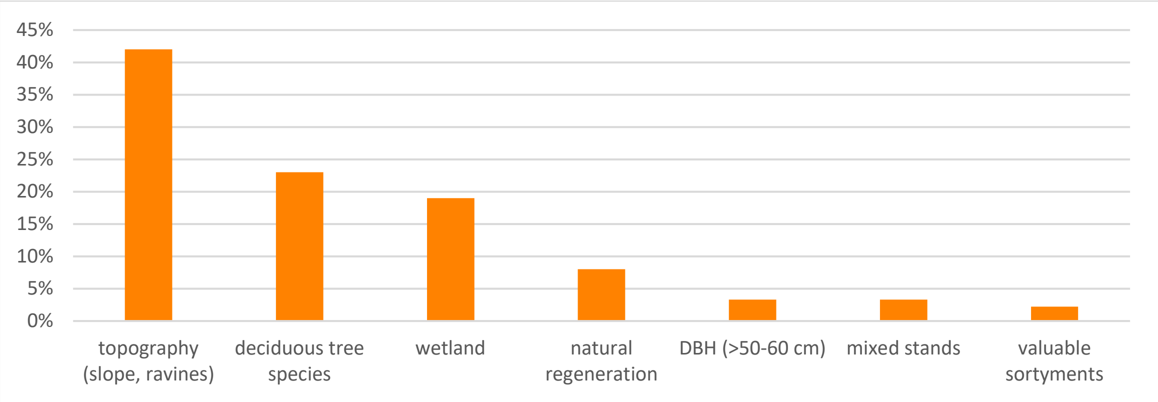


Figure 11. Factors limiting mechanised harvesting.

Impact on stand development, forest products, costs

- Mechanised and mixed harvesting is mainly applied to conifer forests, hovewer the role of deciduous species inrease.
- In the mixed harvesting method, particular emphasis is placed on the use of harvesters and minimizing manual harvesting.
- Site type (except site wetness) does not constitute a significant limitation of mechanized harvesting.
- Apart from standard activities in the form of designation of skidding trails, no additional activities are performed in case of mechanized harvesting. The skidding trails network is usually not specially adapted to the mechanized harvesting.

- The profitability of mechanized harvesting is related to the area on which it is made. In our case study, this area was small (2 hectares on average). It means that the whole analyzed forest disrict was not particularly prepared for mechanised harvesting. It is required to start coordinated long-term activities, which in consequence leads to an increase in the average harvesting area.
- Costs of harvesting only slightly differ between individual methods and stands. This is mainly due to the way in which the Polish State Forests contract timber services. Private companies present a price of 1 cubic meter of timber for so-called harvesting packages. These are groups, usually of dozen of stands, often with significantly different structure (e.g. age, species structure or site conditions) included in one or several organizational units. This solution equalizes the level of defined costs for different harvesting methods. Moreover, the business risk is borne primarily by the recipient. Individual contracting for each private company could significantly change this situation.
- Respondents indicate a number of factors limiting mechanized harvesting. Among them, natural factors dominate – e.g. the topography, which is difficult or impossible to change. However, some of pointed factors such as: small amount of wood, species composition, natural regeneration can be modified to increase mechanized harvesting.

4.2. Intensifying tending and thinning practices

4.2.1. Case study Finland – Corridor thinning

Johanna Routa and Yrjö Nuutinen

Current practice / Need for improvement

Every year, young Finnish forests are thinned less than their silviculture need would require. According to National Forest Inventory data, the current area of belated first thinnings is 800,000 ha and for dense energy wood thinnings 400 000 ha. So, there is an urgent need for first thinnings of 1.2 million ha in next few years in Finland (Korhonen et al. 2017) and in Sweden the productive forest area in need of immediate pre-commercial thinning amounts to 1.4 million ha (Forest Statistics 2018). Thinning wood is underutilized, partly due to the associated high harvesting costs and low income from first thinnings. Small stem size, low removal per hectare, high number of remaining trees and dense undergrowth means low productivity. For the current traditional selective thinning method cutting accounts over half of the costs from stump to the roadside storage. In addition, the availability of labor is a restricting factor due to the high seasonality of silvicultural works. To make bioenergy derived from young forest stands economically competitive, the costs of harvesting must be reduced and the biomass yield per ha must be high. Nowadays, almost 100% of cuttings in Finland and Sweden are mechanized.

Goals

In the Nordic countries several different cutting techniques have been launched, during the last decade, to increase harvesting productivity in young stands. Until now, the most successful method for small-diameter thinning has been cutting with multi-tree harvester head. However developing harvester technology alone hardly provides sufficient productivity jump. In addition, further investigations are needed to develop the work method itself.

According Jylhä et al. (2011) and Pasanen et al. (2014) profitable mechanized energy-wood harvesting comes about through stand having a large enough stem size and thinning removal, which also increases the proportion of commercial wood. The most important work process for developing thinning method is the boom movements which takes most of the working time. Conventional mechanized first thinning systems suffer from low productivity in young dense stands; in Finland, they are only profitable in stands with high standing volumes and harvested tree volumes greater than 50 dm^3. In Nordic countries mechanical boom corridor thinning (BCT) method for energy-wood thinning has been studied as a future alternative to selective thinning. Previously BCT is a thinning method for young dense stands, in which the trees are harvested in narrow (~1 m wide) corridors, aligned to the strip-road and with a length corresponding to the crane's reach (~10 m). According to Bergström & Di Fulvio (2014) BCT is a cost-potential harvesting operation method that allows flexible use of different thinning patterns. The long-term effects of BCT on stand structure, growth and thinning removal have been investigated by Isomäki & Väisänen (1980), Mäkinen et al. (2006), Karlsson et al. (2012) and Ulvcrona et al. (2014). The results indicate that the growth loss caused by BCT compared to selective thinning is not significant and could be compensated by decreasing harvesting costs. According to Witzell et al. (2019) BCT could increase the uneven stand structure and thereby support the biodiversity. However, there is a need to get more information about BCT's effects on harvesting, timber production and logging damage.

In our study we use term corridor thinning (CT). The main goal was to develop the idea of CT to find a cost-effective operator-friendly working method in the Finnish cutting environment which at the same time meets the recommendations of good forest management. The productivity of CT compared to traditional selective thinning method was clarified.

Achievement of goals / Future practice

The first thinning treatments were studied in three field experiments (Figure 12):

- Stand 1) Scots pine stand (*Pinus sylvestris* L.), age 35 years, with no undergrowth
- Stand 2) birch stand (*Betula pendula* Roth and *B. pubescens* Ehrh.), age 25 years, with rich undergrowth
- Stand 3) pine stand (*Pinus sylvestris* L.), age 24 years, with little undergrowth

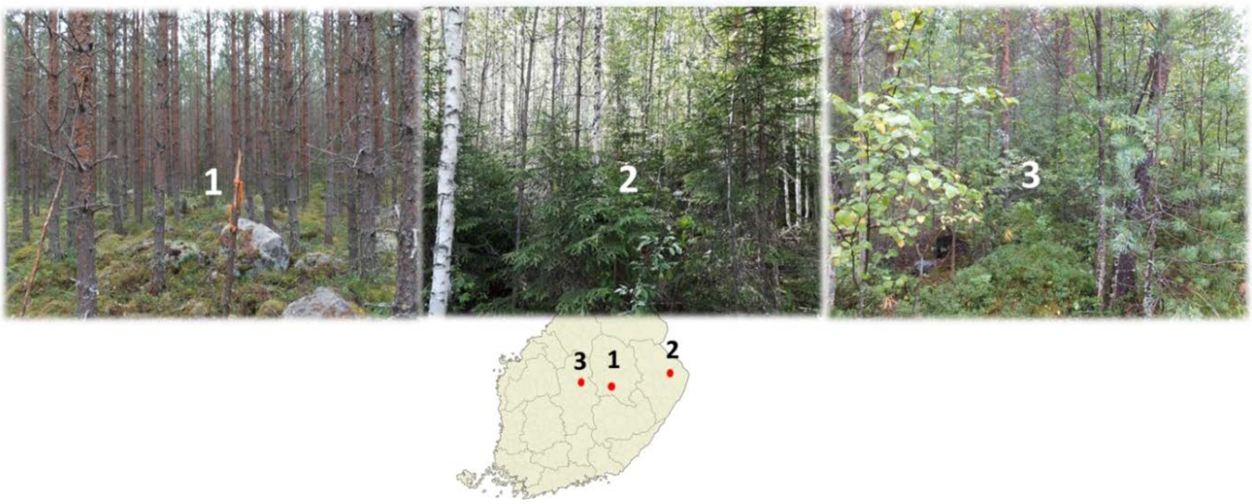


Figure 12. Study stands.

During the experiments the researcher and the operator together developed the working method from fully systematic CT to operator-based CT where the operator plans the position of the corridors according to standing trees (Figure 13). Data were collected in total from 44 treatment plots. The size of the plots was 20 m x 50 m (1000 m^2). The productive working time with all delays excluded of each plot was from 30 min to 1 hour. A time-and-motion study was carried out in each plot by video recording of the work performance of the studied treatments using the continuous timing method. From the video, the work elements of the operation time of each studied treatments were determined. The durations of the work elements were also analyzed. To investigate the effects of stand density, undergrowth and tree size on productivity the trees on the plots were measured before and after the test cutting. The output was recorded through the harvester's on-board production statistics system (volume and dimensions of each tree, as recorded by the computer).

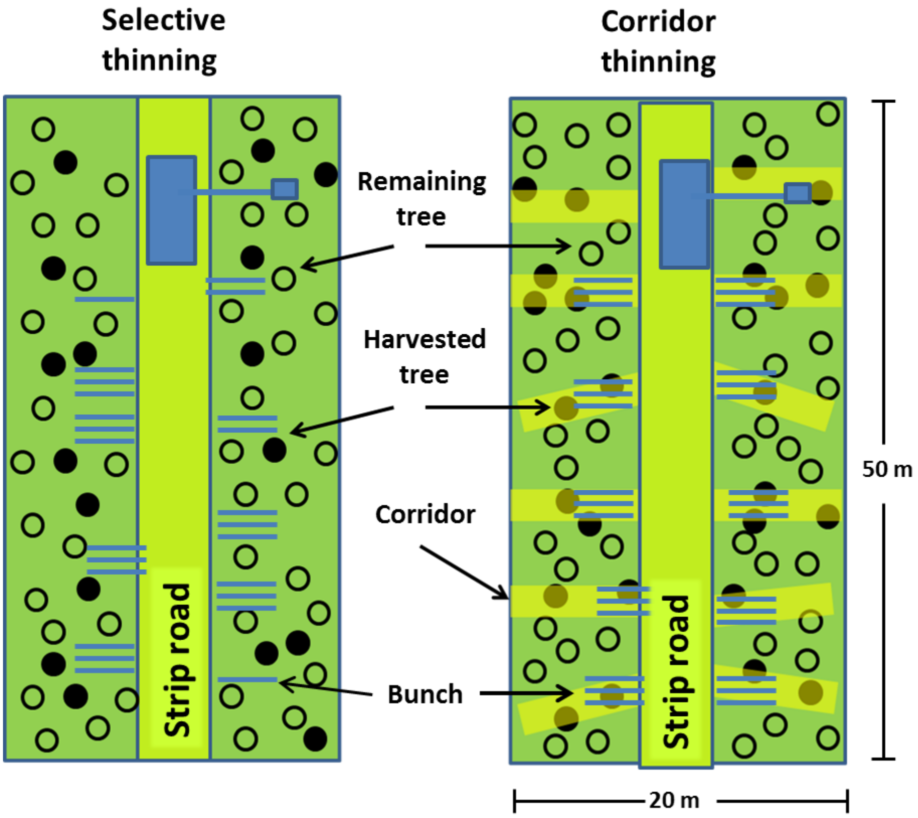


Figure 13. Schematic description of the plot of operator-based corridor thinning and selective thinning methods used in the treatment plots.

Impact on stand development, forest products, costs

In stand 1 with no undergrowth, the observed productive machine hour, PMh, of corridor thinning was on average 41% higher than for selective thinning and 7 % higher in stand with little undergrowth. In stand 2 with rich undergrowth, corridor thinning productivity without pre-clearing was 15% higher than for selective thinning and respectively 34% higher than with pre-clearing (Figure 14).

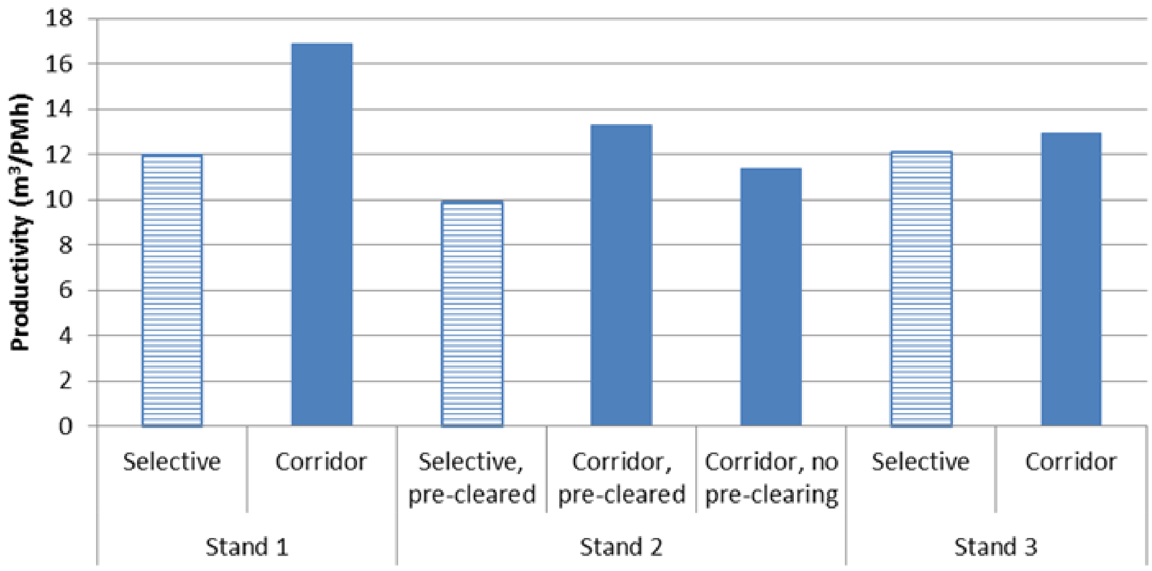


Figure 14. Productivity of thinning treatments in the three different study stands.

In stand 1, the average time consumption of effective work time excluding delays was 8% higher in corridor thinning (17.4 sec/tree) than in selective thinning (19.0 sec/tree). In selective thinning, moving the boom (work elements *boom out* and *positioning the boom forward*) was 24% slower than in corridor thinning. Felling the tree was 9% slower for selective thinning than for corridor thinning (work elements *felling* and *felling over 4 m*). The total time consumption of work elements of bringing top to the strip road, moving tops and branches and bunching the logs was 31% slower in selective thinning than in corridor thinning (Figure 15).

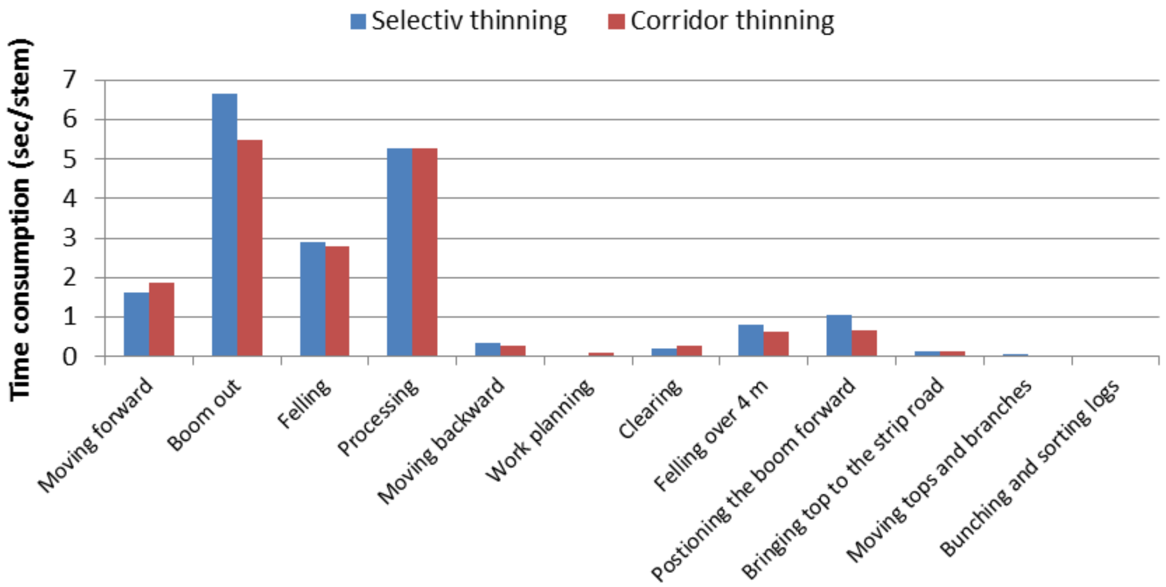


Figure 15. Average time consumption structure of work elements of effective work time (E_0h) in stand 1.

In Figure 16, the average volumes of removed trees are described by ratios. The reference value (100) is the mean volume of selective thinning of each treatment. In Stand 1, the mean size of removal in corridor thinning was on average 20% higher than in selective thinning and respectively in stand 3 8% higher. In stand 2, corridor thinning with no pre-clearing increased significantly more (17%) the removal size than corridor thinning with pre-clearing (8%).

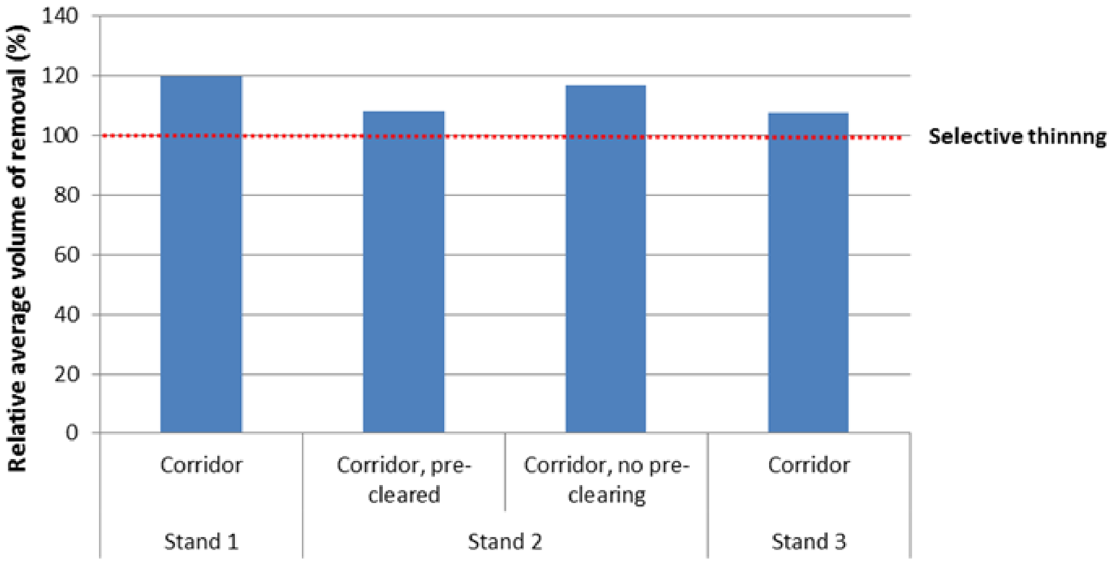


Figure 16. Relative volumes of harvested trees per treatments in stand 1, 2, and 3.

In our study, the CT method was developed in three different working environments: no undergrowth, little undergrowth and rich undergrowth. The operators of our study were experienced in traditional selective thinning method. They had no previous experience with CT. During the project the CT-method was gradually developed while training the operators. The development of the method involved active interaction between the operators and the work-study-researcher. The most important finding was that undergrowth is much less disadvantage in CT for harvester's felling head than in selective thinning: by CT it was possible to harvest the stand 2 with rich undergrowth without pre-clearing which gives cost savings from 300 to 400 € per hectare of pre-clearing. In stand 1 the productivity jump of 41% would bring 3 €/m^3 cost saving compared to selective thinning. Furthermore, in this case, if needed, clearing of undergrowth is possible to conduct after thinning which is easier and more cost-effective than before thinning. Saving the rich undergrowth leaves for the future operations options to grow uneven and two-storied forest to increase the biodiversity and carbon sinks of forests. On this basis we could the new thinning method *climate thinning*.

In CT operation, the standing trees did not hinder moving the boom as much as in selective thinning which accelerated the operation of CT. Removal of logging residues and arrangement of finished logs also took significantly less time in CT. In CT, increasing size of removed trees compared to selective thinning improves the productivity, which is an advantage of CT, especially in unmanaged forests with small stem size.

4.2.2. Case study Finland – Regional effects of timing of seedling stand tending

Johanna Routa, Saija Huuskonen and Soili Kojola

Current practice / Need for improvement

The objective of tending of seedling stands, including early cleaning and precommercial thinning, is to achieve the best possible return on investments made in the forest regeneration stage. Currently in Finland, however, tending treatments are conducted in much smaller areas than recommended in silvicultural guidelines. According to the forest inventory data, there is an urgent need for tending of seedling stands in at least 700 000 ha (around 18% of seedling stands) and a need for tending in 1 million ha in the next few years in Finland (Korhonen et al. 2017). The motivation of forest owners to conduct pre commercial silvicultural operations is low due to associated high costs. Especially the costs of tending of seedling stands and the costs of clearing operations after regeneration have been increasing. In addition, the availability of labor can be a restricting factor due to the high seasonality of silvicultural works. Thus, there is an obvious need to improve practices to reduce costs of tending and on the other hand to demonstrate positive effects of tending on the future incomes for the forest owners and society.

Goals

In young seedling stands, abundant fast-growing hardwoods create need for early cleaning to control the competition, and in subsequent years also precommercial thinning is generally needed to control the overall stem density in a stand. Removing hardwoods and other competing vegetation from young stands increases the growth of the released trees and enhances the yield of commercial wood.

In practice, hardwoods are often removed too late to gain the full benefit from the work. Therefore, in addition to implementation of tending in itself, it is important to pay attention to timing and intensity of treatments. The timing and intensity of tending affect the yield and quality development of young stands and, furthermore, the timing and profitability of the first commercial thinning (Huuskonen and Hynynen 2006). Because unwanted trees often grow strongly in the seedling stands, the cost of tending increases with time. According to Kaila et al. (2006), a two-year delay can increase the cost by 8–42%.

The aim of this study is to analyze the larger scale effects of tending of seedling stands to forest growth, forest developing, total production, share of timber assortments, and further, on the profitability of the forest management. The differences between seedling stands with right-time tending, late tending, or no tending were examined by the means of simulations and scenario analysis. Right-time tending means the treatments applied according to silvicultural guidelines (Rantala 2011). The Finnish National Forest Inventory data from two (former) Forest Centre areas were used to represent current status of the seedling stands and future developments of the stands in different scenarios were predicted with Motti simulator (Hynynen et al. 2014).

Achievement of goals / Future practice

Our results underlines at the regional level the importance of the right-time tending of the seedling stands, and thereby confirm the earlier published stand-level results concerning the positive effects of tending. Success or failure in the management of seedling stands has long-term effects on stand development and, subsequently, on the profitability of forest management (Huuskonen and Hynynen 2006). It is extremely important to increase the knowledge about the importance of early cleaning and precommercial thinning among the forest owners.

Impact on stand development, forest products, costs

According to our results, more valuable and earlier harvesting removals were reached in the 100 year scenario including right-time tending than in the other scenarios. Tending of the seedling stands induced earlier first commercial thinnings than growing the stands without tending due to the faster diameter development of the retained trees after treatment. Right-time tending also led to a higher sawlog yield compared to the scenario of later precommercial thinnings (later treatment was applied in 1.5 m higher stands stage than suggested in the silvicultural recommendations) or a scenario, where early cleaning and precommercial thinning were not applied at all. Without any tending treatments sawlog yield was 18% lower than with the right-time treatments (Figure 17). The net present value of the forest management from 100-year scenario period (with interest rates of 0, 2 and 3%) was the highest in the scenario including right-time tending (Figure 18). Same scenario also resulted in the earliest final fellings, because the stand diameter development was the fastest. However, the total harvesting removals including energy wood were the largest in a scenario, where no tending was applied.

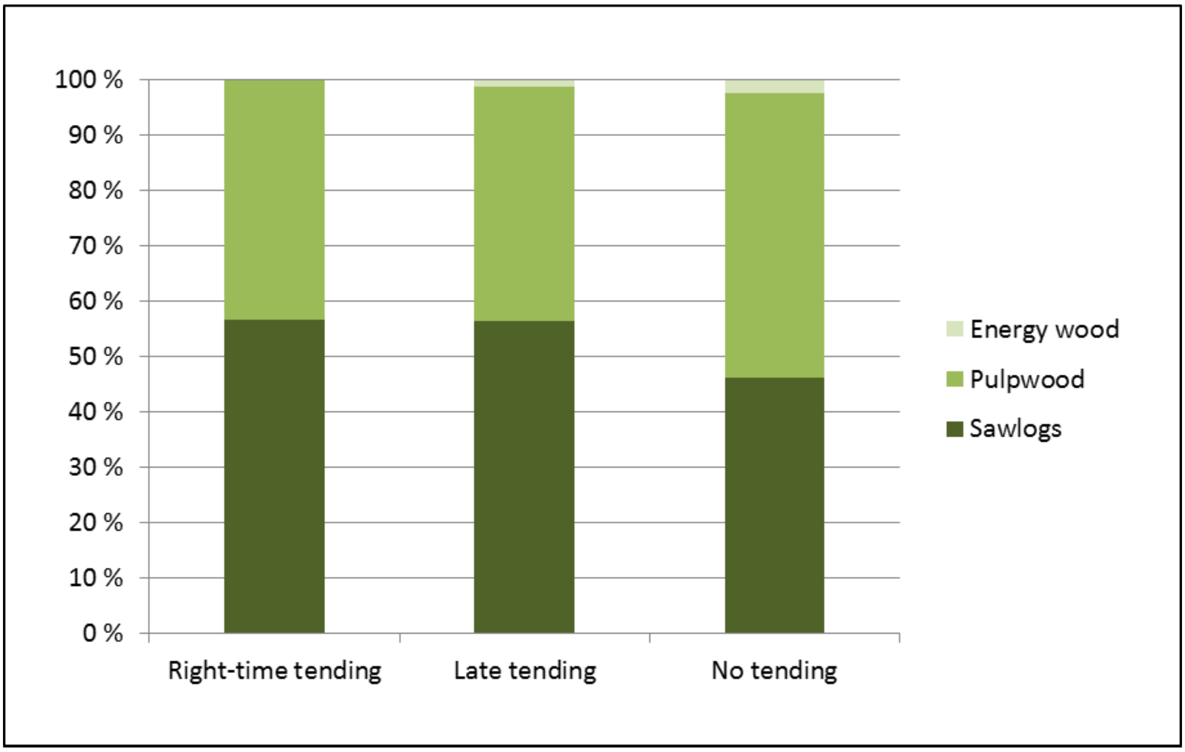


Figure 17. Structure of harvesting removals (%) in different 100-year scenarios.

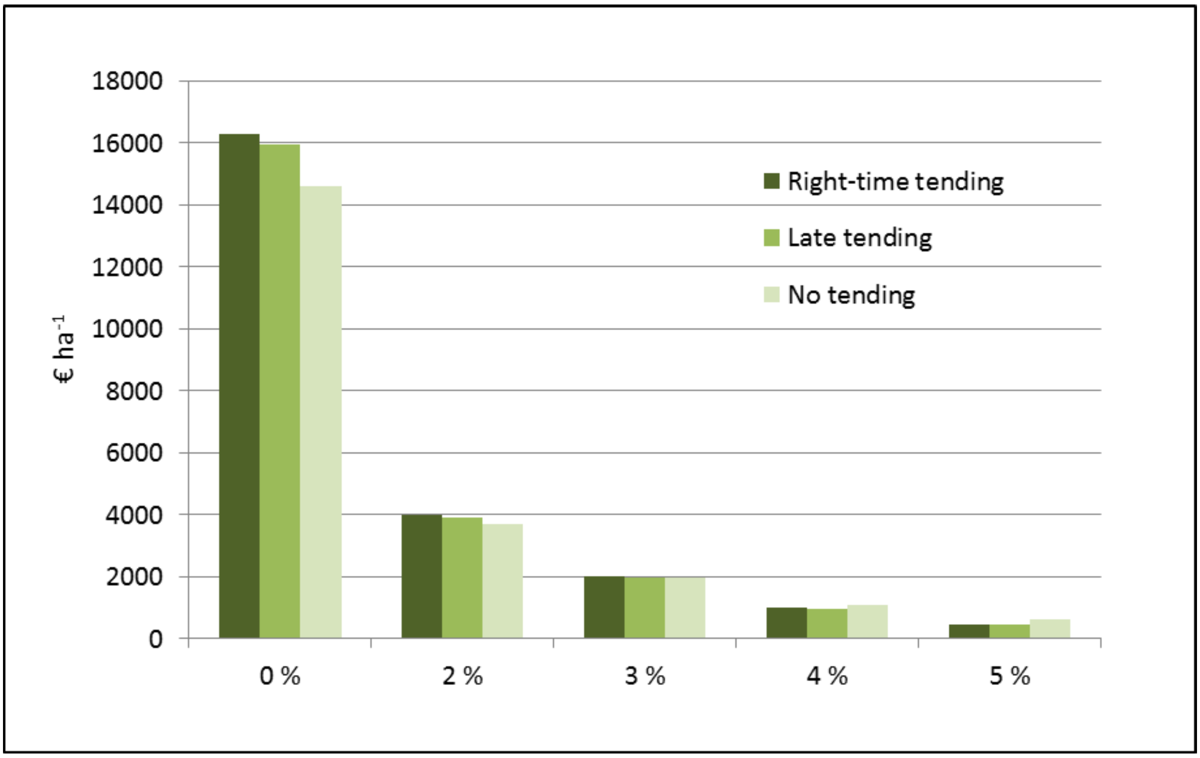


Figure 18. Average net present value (€ ha^{-1}) from 100 year period in different scenarios.

Haikarainen, S., Huuskonen, S., Ahtikoski, A., Lehtonen, M., Salminen, H., Siipilehto, J., Hynynen, J., Korhonen K.T., Routa, J. 2020. Does it matter to carry out juvenile stand management? – Regional effects of tending on wood production based on scenario analysis. Manuscript.

4.2.3. Case study Austria – Effects of thinning by tree marking vs harvester selection

Benno Eberhard

Current practice / Need for improvement

It is broadly recognised that tree marking has a significant influence on the development of forest stands, including the stand structure and the subsequent value of the remaining trees (Vitková et al., 2016). The scope of thinning in Austria is widely considered in removing trees in favour of valuable future crop trees. This implies that the main purpose of thinning is not the current utility of the removed trees, but the further development of the remaining trees (Dengler, 1935; Neumann, 2003). This is being executed in a two-step approach: First a forest manager marks the trees, and after occurs the harvesting operation. This method definitely is considered as a highly professional procedure. The general opinion in Austria is that previous tree marking by forester is a key requirement for the management of forest stands (see Frank, 2008). Yet it is time – and money consuming (Kellogg et al., 1998), and this is the reason why the forest owners often concentrate on good stands and on older stands, in order to make the thinning operations profitable.

As consequence, numerous stands where thinning is recommended, remain un-thinned, and the thinning residues accumulate. In Austrian forests noticeable thinning residues can be met. In the national survey of 2009, the NFI Austria aimed at assessing all stands with thinning residues. In order to process and neutralize these residues, the NFI recommended for forests with commercial purpose an annual initial use of 9 million m³ (tending 0.4 million m³, regular thinning 7.7 million m³, thinning residues 0.9 million m³) for the upcoming 10 years. This corresponds to 37% of total felling. But in reality the annual amount of initial felling was 3.3 million m³, which corresponds to only 13% of total felling (https://bfw.ac.at/rz/wi.auswahl the question arises if the first step, i.e. the tree marking by foresters before thinning, is necessary.

Goals

In our study we aim at assessing the effect of thinning by tree marking in comparison with thinning without previous tree marking, which means that the harvester driver himself is responsible for the tree selection before thinning. Both of the groups involved in our investigation, the foresters as well as the harvester drivers, are very experienced. By executing the instructions of the foresters for many years, the harvester drivers have internalised their principles. Hence when they work autonomously, they adopt the same silvicultural aspects like the foresters. In other words, they try to imitate the foresters.

The special approach of this study consists in doing the investigations on the same stands respectively. That means that first a forest manager does the tree marking, followed by all required examinations, and after occurs the harvester operation on the same stand, again followed by all the required measures. This is practicable by providing the foresters with removable ribbons for the tree marking (Figure 19).

At the same time we concentrate not only on the situation immediately after thinning, but also on the long term effects of the two thinning variants, by using the single tree-based growth simulation software MOSES (Hasenauer, 1994; Thurnher et al., 2017). This way we compare the two mentioned thinning alternatives with two further variants, random thinning, and no thinning, which is the zero variant. As a measure for the stand-stability we take the ratio between height and diameter of a tree (HD-ratio), the productivity is expressed as the stem volume in m³. For the assessment of damages, we define two categories: i) stripping damages, and ii) the collective category Other damages, which includes forked tree, broken tree top, red rot and harvesting damage. For the simulation in MOSES we define a growth period of 50 years.

Figure 19. The foresters are provided with removable ribbons. This allows us to make a direct comparison of the tree marking by foresters and the tree selection by harvester drivers at the same plots respectively.

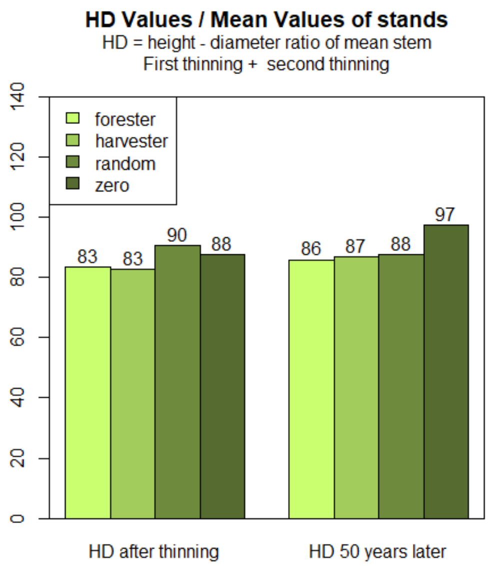
The study was carried out in 8 Norway spruce stands in Austria, located on the border between Upper Austria, Lower Austria and Czech Republic. The operations included 4 stands with first thinning, and 4 stands with second thinning. In total, 8 foresters and 4 harvester drivers were involved in the experiment.

Our research questions are: What is the match in the tree selection between forester and harvester? Who has the better performance in identifying and removing damaged trees? Who removes more volume? Is there a difference in the stand stability immediately after the interventions by forester, harvester and random thinning? What is the stability of the stands after 50 years? Can we detect a difference concerning the productivity after 50 years? Are the results varying in stands with first and second thinning? Is random thinning a reasonable alternative?

Achievement of goals / Future practice

The match between forester and harvester selections amounts to 67%, which means that the harvester drivers, in their attempt to imitate the foresters, have a success rate of 67%. Out of all sampled trees 47% have stripping damage, 10% have one of the other above listed damages, 7% have both types of damages, that means that only 50% of the trees are without damage. Since almost half of the trees have a stripping damage, it is obvious that both of the protagonists, the foresters as well as the harvesters, in their selective process had to disregard this criterion in favour of other selection criteria. Therefore, the difference in the number of trees with stripping damage, that are still present in the stands after the selection by forester on the one hand and harvester on the other hand, is small. The harvester and the random thinning have the same result, and both leave 9% more stripping damages in the stands than the forester. Regarding the Other damages, the forester on average leaves 48, the harvester 69, and random thinning 108 damaged trees/ha in the stands. Thus in comparison with the forester the harvester leaves 44%, and random thinning leaves 125% more stems with Other damages in the stands. But in terms of absolute numbers the difference between forester and harvester is low, since it amounts to 21 stems. In view of the fact that the average stem number before thinning of all stands is 1307, we are talking only about a percentage of 1.6% of the stems.

In stands with first thinning as well as in stands with second thinning, the number of removed trees by forester, harvester and random is very balanced. Expressed in the mean diameter, in first thinning the harvesters remove the thinner trees (17.8 cm) than the foresters (19.1 cm), in second thinning harvesters remove the thicker trees (25.9 cm) than foresters (24.6 cm). In both of the cases, random thinning removes the thickest trees (21.1 cm in first thinning, 28.9 cm in second thinning). In total the mean diameter of removed trees by forester and harvester is equal (21.9 cm), whereas random removes the thicker trees (25 cm). As consequence, the removal of volume is constituted as it is depicted in Figure 20.



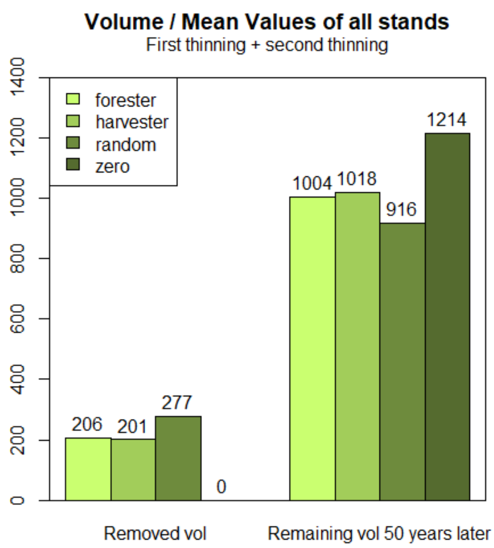


Figure 20. HD-values and stem volume of the stands after the 4 listed thinning variants, with view on stands with first thinning and stands with second thinning together. The numbers represent mean values of the 8 stands. Left hand: HD-values of the remaining trees immediately after the thinning, and after 50 years. Random and zero variant produce remarkably high HD-values after thinning, the zero variant leads to a much too high HD-value after 50 years. Right hand: Removed stem volume and remaining stem volume after 50 years. Random removes most volume, remaining volume after forester and harvester is balanced, zero variant leads to the highest volume.

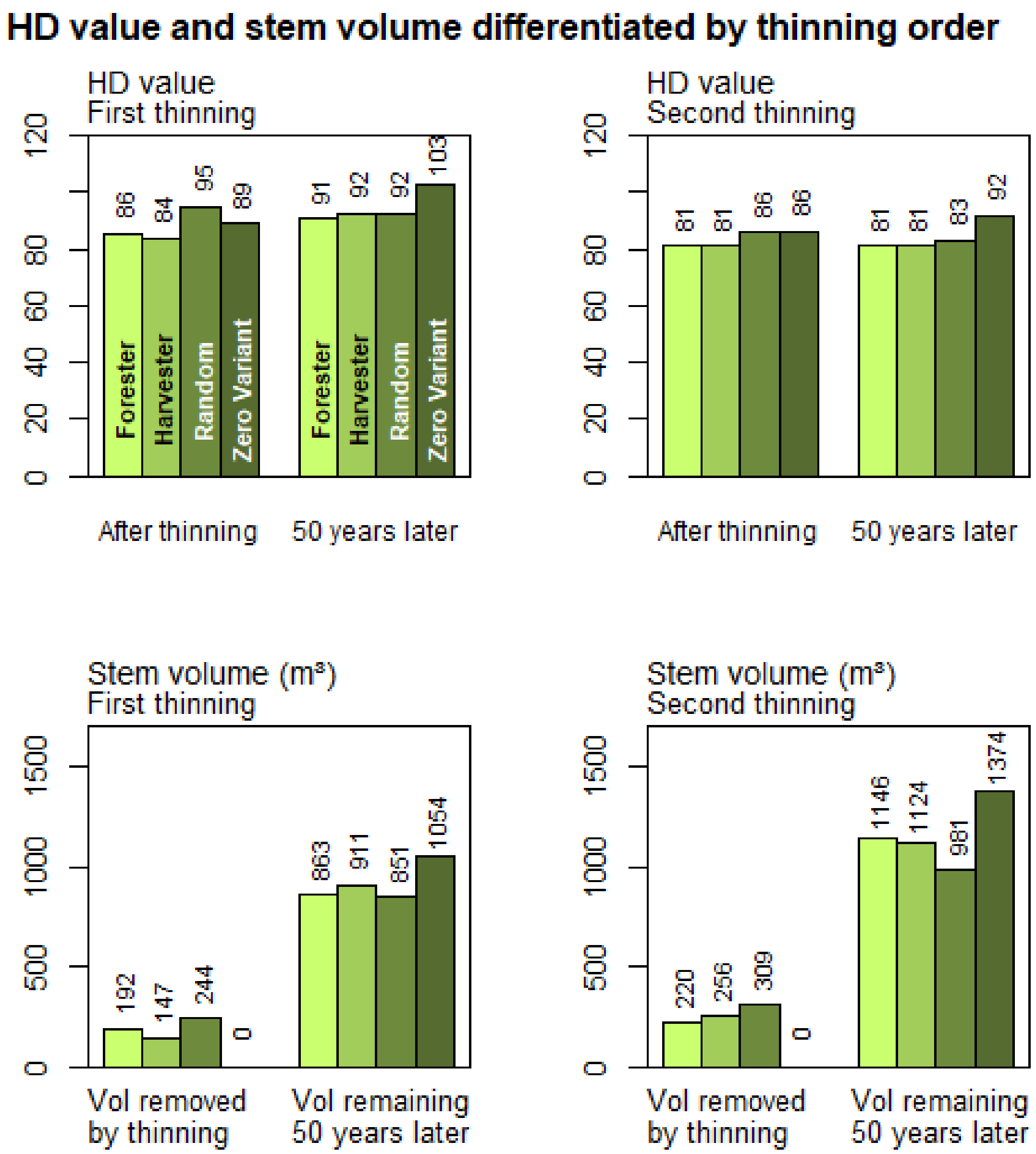


Figure 21. HD-values and stem volume of the stands after the 4 listed thinning variants, stands with first thinning and stands with second thinning considered separately. The numbers represent mean values of the 4 stands respectively. Top: HD-values after thinning and after 50 years, after first thinning (left) and after second thinning (right). Random and zero variant generate very instable stands, especially after thinning. In stands with second thinning forester as well as harvester produce stable stands. Bottom: Volume removed and volume 50 years later, after first thinning (left) and second thinning (right). Random thinning removes the most volume, but in the end, it is inferior to forester and harvester.

Considering stands with first thinning and second thinning together (Figure 20) the removal of forester (206 m^3) and harvester (201 m^3) is balanced, the volume removed by random thinning is higher (277 m^3). In context of first thinning (Figure 21) the harvester (147 m^3) removes less than the forester (192 m^3), in context of second thinning the harvester (256 m^3) removes slightly more than the forester (220 m^3). Again, the removal of random thinning is the highest in both cases (244 m^3 and 309 m^3 respectively). The result in productivity after 50 years (Figure 20) is also very balanced for forester (1004 m^3) and harvester (1018 m^3), the productivity after random thinning is clearly lower (916 m^3), the zero variant is far the most productive variant (1214 m^3). Considering the HD-ratio as a measure for the stability of a stand, the results for forester (83 after thinning and 86 at the end of the growth period) and harvester (83 after thinning and 87 at the end of the growth period) are balanced. Random thinning produces an HD-ratio of 90 immediately after thinning and 88 after 50 years, the values for the zero variant are 88 at the beginning of the growth period, and 97 at the end of the growth period. If we concentrate only on the stands where two thinnings had occurred (Figure 21, top right), the HD-values at the end of the growth period for forester as well as for harvester are 81, random thinning produces a final HD-value of 83, the zero variant leads to a HD of 92.

Impact on stand development, forest products, costs

In terms of the removal of damaged trees, the forester is superior to the harvester. Yet, since almost half of the trees have stripping damages, this selective criterion recedes into the background in favour of other aspects. The percentage of trees with some of the other damages is relatively low, so that the difference between the performance of the forester and the harvester – in context of this study – in effect is very small.

The selective behaviour between foresters and harvesters differs slightly, if we consider stands with one thinning and stands with two thinnings separately. In first thinning the harvesters tend to remove the thinner trees, in second thinning they tend to remove the thicker trees than the foresters.

Yet, the most significant result of the study in our opinion is a) that foresters and harvester drivers remove almost the same number of trees, and b) that within this similar quantity of removed trees the match of removed trees amounts to almost 70%. It is an obvious consequence that the stand characteristics – in terms of the HD-ratio as a measure for the stability, and the stem volume as a measure for the productivity – immediately after thinning as well as after a growth period of 50 years, are also very similar, as we could demonstrate above. Assuming, first that the harvester drivers have been trained by the foresters intensively, and second that their aim is to imitate the tree selection of the foresters, we can draw the conclusion that their performance is highly satisfactory, in both regards, the generation of stable as well as productive stands. The random thinning is principally reasonable only in second thinning, since the HD-value ranges within the comfort zone. In first thinning the random selection produces unstable stands, and therefore it should be avoided. However, in both cases the random thinning carries a loss of stem wood production. The zero variant in first thinning as well as in second thinning generates very high HD-values. Therefore, it is not a sensible alternative.

Hence, our recommendation is 1. to train the harvester drivers accurately by foresters, and 2. to enhance the thinning operations without previous tree marking wherever possible. In this way we adopt the principle of tree marking, that means implicitly by the harvester drivers. But at the same time, we avoid the costly first step, the tree marking by forest managers.

The cost benefits are as follows: The annual amount of stem volume to be processed in context of regular thinning is 7.7 million m³, as we mentioned above. The results of Task 2.3. (“Harvesting systems map for European forests”) suggest that approximately one third of the total growing stock in Austria could be harvested by a harvester-based fully mechanized harvesting system. That means that, out of the 7.7 million m³, approximately 2.6 million m³ could be processed by harvesters. As an outcome of this study, we can state that an experienced forester manages to tree mark about 150 m³ per day. Assuming that the salary is 17 €/hour, we arrive at 136 € per day. That means, by harvesting the 2.6 million m³ without previous tree marking, we save 17.300 workdays per year (2.6 million by 150), which corresponds to approximately 2.350.000 € per year (17.300 times 136 €).

Eberhard et al. Manuscript submitted to IJFE.

4.2.4. Case study Norway – Productivity of thinned and unthinned Norway spruce stands

Micky Allen and Rasmus Astrup

Current practice/Need for improvement

At present, relatively little thinning is performed in Norway and management guidelines are either outdated or lacking. Currently, thinning is initiated at the discretion of the landowner and is often applied late in the rotation in order to increase the profitability of the harvest. While potentially increasing short term financial gains, late thinning can result in poor canopy and root development reducing the stability of the forest. Additionally, the main type of thinning performed is the so called "free" thinning in which the harvester operator makes the decision on which trees to remove in thinning. This type of thinning is known to heavily favour the selection of faster growing better quality trees for removal which in turn diminishes the growth and quality of the residual stand. Collectively, the current thinning practices in Norway do not reflect the optimal management practices of Norway spruce in other regions and updated information and thinning guidelines are needed.

Goals

The purpose of this work was to evaluate the effects of thinning from below, at different stages in the rotation and different levels of thinning removals, on the growth of Norway spruce plantations. The main goal was to determine how increased levels of thinning may affect production of Norway spruce.

Achievement of Goals/Future Practice

The data used in this study come from a series of thinning trials consisting of 294 long-term permanent sample plots in thinned and unthinned Norway spruce plantations. These trials were established in the 1960's and 70's across all regions of Norway excluding the Northernmost area which contains little Norway spruce. Within these data are 311 growth observations in unthinned stands, 442 observations in once thinned stands, and 246 observations in twice thinned stands (Table 7). A description of these trials are provided in Braastad and Tveite (2001).

Table 7. Descriptive statistics of thinned and unthinned Norway spruce data.

Treatment	n		Age	SI	TPH	BA	V	BA_{TQ}	H_T
Unthinned	311	mean	41	16	2510	37.3	298		
		SD	13	3	860	15.3	196		
		min	18	11	777	6.1	21		
		max	92	21	5021	79.8	893		
1 Thinning	442	mean	45	15	1402	31.0	260	0.76	12.3
		SD	11	3	430	12.2	174	0.11	2.3
		min	25	11	600	6.3	26	0.47	8.5
		max	68	21	2640	67.4	917	0.92	21.7
2 Thinnings	246	mean	52	15	1067	33.9	309	0.76	15.9
		SD	9	2	228	9.3	147	0.11	1.8
		min	31	11	460	11.8	72	0.35	11.8
		max	68	20	1700	60.3	812	0.92	21.1

A = stand age from planting (years); SI = site index at base age 40 years; TPH = number of trees (ha^{-1}); BA = basal area (m^2 ha^{-1}); V = stand volume (m^3 ha^{-1}); BA_{tq} = basal area thinning quotient (BA after thinning divided by basal area before thinning); and H_T = dominant stand height (m) at thinning.

To understand the effects of thinning on volume production a system of equations was developed from the trial data in which different thinning scenarios could be examined. The first equation developed was for gross and net periodic annual volume increment (m^3 ha^{-1} yr^{-1}). Net volume is defined as the volume of all standing trees plus the volume of any tree removed in thinning. Gross volume increment is defined as the net volume plus the cumulative volume of all trees which have been lost to mortality. The best fit model has the form:

$$VPAI = (\alpha_0 + \alpha_{01}H + \alpha_{02}H_{PAI} + \alpha_{03}HH_{PAI})\, BA\, exp(-BA/\alpha_1) \quad (1)$$

where,

$VPAI$	=	gross or net volume periodic annual increment (m^3 ha^{-1} yr^{-1}),
H	=	dominant stand height (m),
H_{PAI}	=	dominant stand height increment (m yr^{-1}),
BA	=	stand basal area (m^2 ha^{-1})
exp	=	the base of the natural logarithm, and
α_i	=	parameters to be estimated.

Because the function for VPAI was dependent additionally on dominant stand height and basal area additional functions to describe the development of those variables were needed. For the purpose of the examining basal area development in unthinned stands, the model of Gizachew et al. (2012) was used. However, to examine basal area development in thinned stands a new model was needed. Using the model of Gizachew et al. (2012) as the base model the following model was developed:

$$BA = \beta_0 + \left(1 - exp\left(-\left(\beta_{11} + \beta_{12}BA_{TQ} + \beta_{13}H_T + \beta_{14}S\right) * yst + \beta_2\right)\right) \quad (2)$$

where,

β_0	=	$68.0752[1 - exp(-0.4831 * S)]^{11.715}$,
β_2	=	$log(1 - BA_{AT}/B_0)$,
β_{1i}	=	parameters to be estimated,
H_T	=	dominant stand height at thinning (m),
S	=	site index (m) at base age 40
BA_{TQ}	=	basal area after thinning / basal area before thinning
BA_{AT}	=	basal area after thinning (m^2 ha^{-1}), and
yst	=	years since thinning.

The asymptotic limit of basal area, parameter β_0, was developed by Gizachew et al. (2012) from Norwegian forest inventory data. Thinning response is incorporated into the rate parameter, β_1, as a linear function of basal area removal and site index. Parameter β_2 conditions the function such that the basal area at yst = 0 is equal to the basal area immediately after thinning.

For simulating volume growth in equation (2) an estimate of height and height increment is needed. Therefore, a height-age model was developed using the Chapman-Richards type function:

$$H_2 = H_1 * \left(\frac{1 - exp(-\theta_1 * A_2)}{1 - exp(-\theta_1 * A_1)}\right)^{\theta_2} \quad (3)$$

where,

H_1	=	current dominant stand height at age A_1,
H_2	=	future dominant stand height at age A_2, and
θ_1, θ_2	=	parameters to be estimated.

Monte Carlo simulation

For the comparison of different thinning scenarios a Monte Carlo simulation was performed using equations (1–3). Different site productivities were evaluated based on site index classes of 11, 14, 17, and 20 meters at a base age of 40 years, where age is defined as years since planting. A total of nine different thinning scenarios, including an unthinned control, were simulated in this work for these four site index classes (Table 8). Simulated thinnings were performed based on the representative thinnings in the data used for model fitting (Table 7) and can be categorized as either medium or heavy thinning, based on percentage basal area removal, and early or late thinning based on dominant stand height. The lengths of the simulations varied by site index class and were based on general rotation ages of even-aged Norway spruce stands. These ages were 120, 96, 81, and 77 years for site indices 11, 14, 17, and 20 meters, respectively, and come from analysis of the culmination of mean annual increment in Norway spruce stands (Søgaard et al. 2019).

Table 8. Description of thinning scenarios.

	1st thin			2nd thin	
ID	H_T	BA_{TQ}		H_T	BA_{TQ}
U			Unthinned		
T1.12.25	12	75			
T1.12.50	12	50			
T1.16.25	16	75			
T1.16.50	16	50			
T2.16.25	12	75		16	75
T2.16.50	12	50		16	50
T2.20.25	16	75		20	75
T2.20.50	16	50		20	50

ID = unique scenario identification, H_T = dominant stand height at thinning; and BA_{TQ} = basal area thinning quotient (basal area before thinning divided by basal area after thinning).

Based on this framework, a Monte Carlo analysis was performed using 10,000 simulations. From the parameter estimates and their variance-covariance matrix of equations (2–4), each simulation was initialized by randomly generating parameter values from a multivariate normal distribution accounting for the correlation between the parameters. After the simulations were completed, the gross and net volume increments were summed across the rotation period for each of the 10,000 simulations. Cumulative volumes for the nine treatments were then compared for significant differences.

Impact on stand development, products, costs

The results of this work indicate a strong pattern of volume production with stand density. Gross volume increment, which includes mortality, increases with increasing basal area, whereas, net volume increment was maximized at a basal area of 42 m^2 (Figure 22).

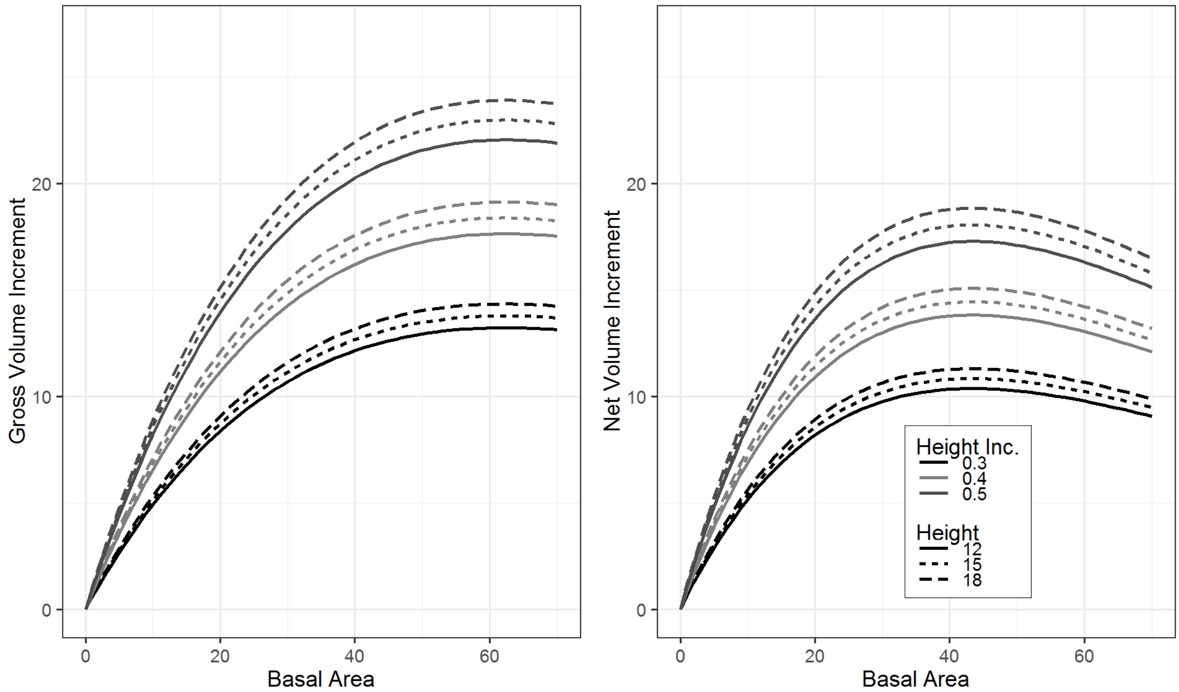


Figure 22. Implied relationship between gross or net volume periodic annual increment (m^3 ha^{-1} yr^{-1}) and basal area (m^2 ha^{-1}) based on equation (1) when stand height (m) and height increment (m yr^{-1}) are held constant.

The response of basal area development to thinning was highly dependent on site productivity (Figure 23). In the relatively lower site index classes the basal area of thinned scenarios remained well below the basal area of the unthinned scenarios. However, in the higher site index classes the basal area of the thinned scenarios returned to or surpassed the basal area of the unthinned scenario. Because the density effect on volume increment is large (e.g. Figure 22) the effects of thinning on basal area development can have a large effect on total volume production depending on the rotation length.

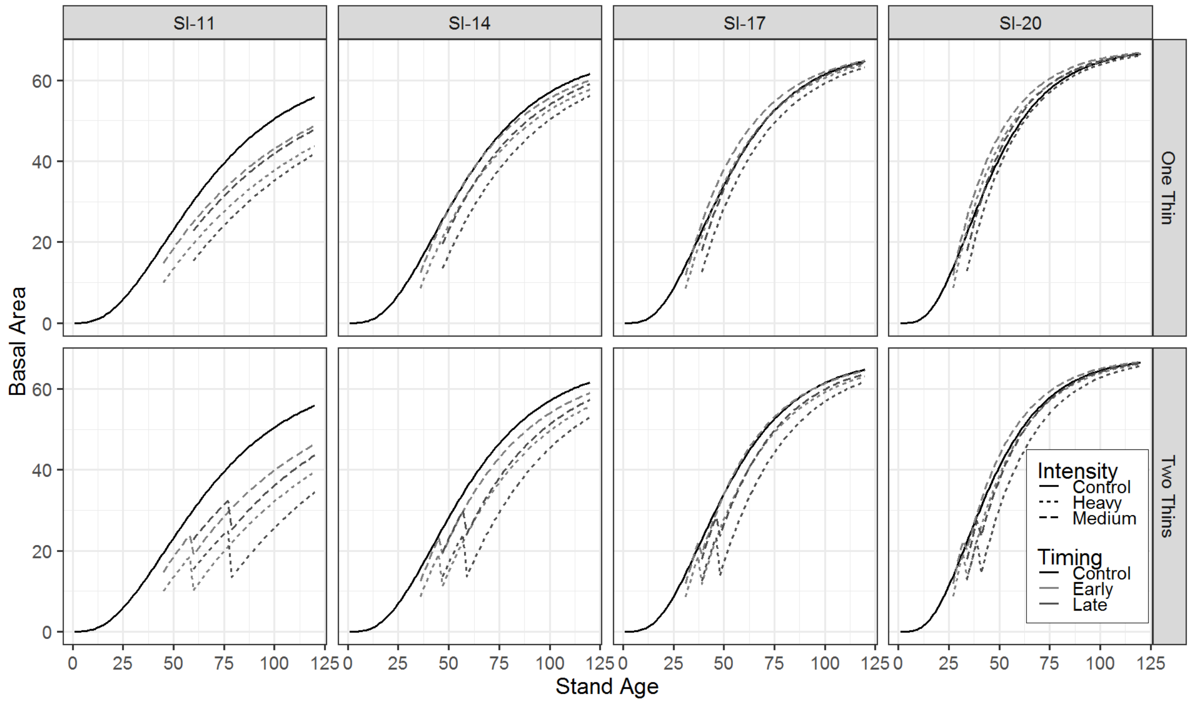


Figure 23. Basal area development of simulated unthinned and once or twice thinned stands. Thinning treatments are described with intensity as light (25% basal area reduction) or heavy (50% basal area reduction) and with timing as early (1st thin at 12m height) or late (1st thin at 16m height).

The effects of thinning on total volume production differed by thinning scenario. Based on the Monte Carlo simulations there were no significant differences in total net production between the nine management scenarios presented in Table 8, regardless of site index class (Figure 24). However, for total gross volume the only significant differences were between the unthinned scenario and the thinning scenarios which had two heavy thinnings (T2.16.50 and T2.20.50). Therefore, total harvestable volume was not different among thinned and unthinned stands but thinning was able to reduce losses in mortality when heavily thinned twice in a given rotation.

The results show that stand volume increment is highly dependent on the stand density. Gross volume increment increases with increasing basal area, whereas, net volume increment is maximized at a basal area of 42 m^2 ha^{-1}. Therefore, proper thinnings can decrease total gross production over ration and potentially increase total net production. However, the simulation results indicated no significant differences in total net production from all nine management scenarios examined. This indicates that increased thinning, within the thinning scenarios examined here, will not significantly reduce the total amount of volume harvested in a given rotation. Thus, while not increasing the total amount of volume produced, an increased amount of thinning in Norway spruce forests in Norway may be permitted without incurring a loss in total volume harvested.

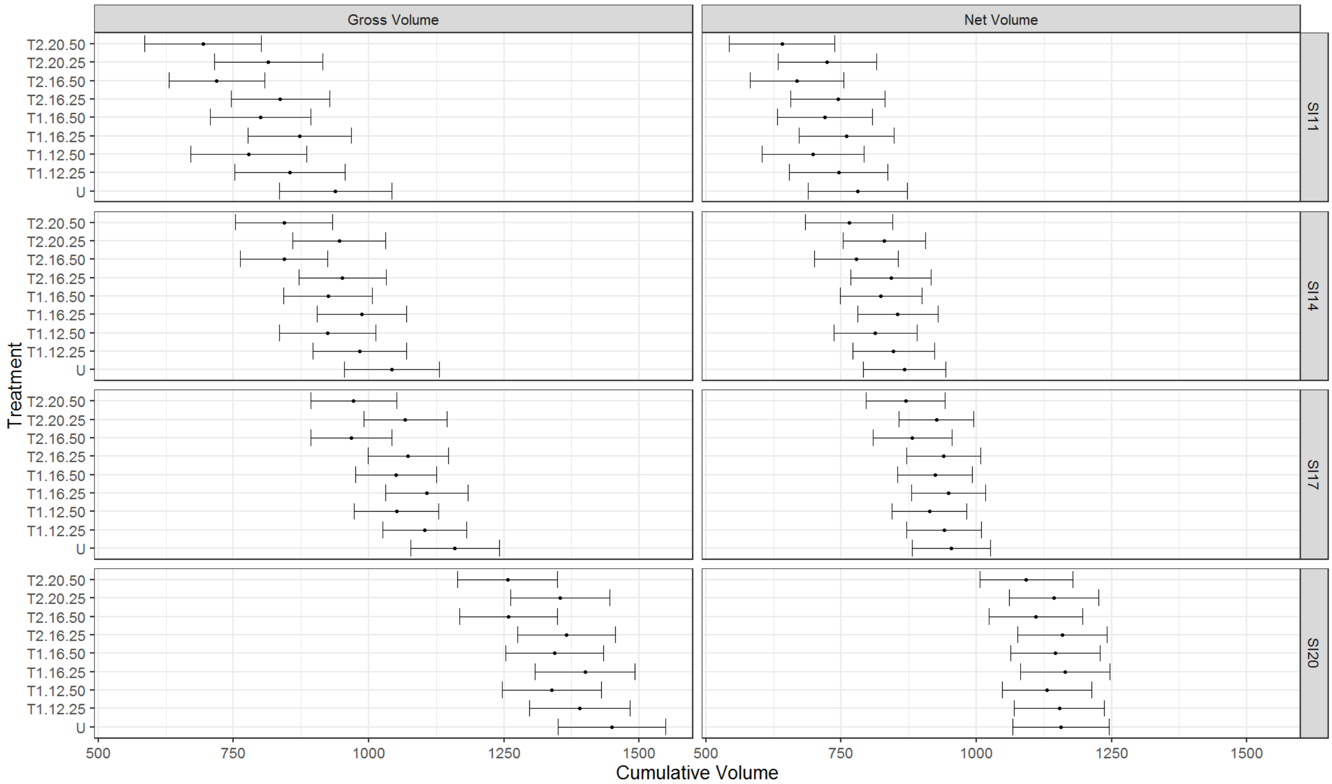


Figure 24. Means and 95% confidence intervals of cumulative gross and net volume over the simulated rotation period from a Monte-Carlo analysis of the nine thinning treatments presented in Table 38.

Micky Allen, Andreas Brunner, Clara Antón-Fernández and Rasmus Astrup. The relationship between volume increment and stand density in Norway spruce plantations. Forestry 2020; 00, 1–15, doi:10.1093/forestry/cpaa020.

4.3. Measures for early treatment and stand establishment

4.3.1. Case study Finland – Effects of improved regeneration material and fertilization on timber production

Johanna Routa, Antti Asikainen, Antti Kilpeläinen, Veli-Pekka Ikonen, Ari Venäläinen, Heli Peltola

Current practice / Need for improvement

Many previous experimental and simulation-based studies have shown that, by increasing the intensity of silvicultural activities, timber production and its economic profitability can be increased per unit land area in Nordic forests. Timber production per hectare can be increased on upland forest sites by use of appropriate site-specific regeneration methods and materials, tending of seedling stands, commercial thinnings, and nitrogen (N) fertilization over a rotation. In the long term, the use of improved regeneration materials could greatly increase timber production per unit land area in Nordic countries. This is because the volume growth of seed orchard (half-sib and full-sib families) stocks for Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies (L.) Karst.)* is 10–25% higher than that of unimproved stocks, based on experimental trials in Finland and Sweden The use of improved regeneration materials could gradually also provide significant economic benefits due to enhanced tree growth and earlier cuttings, despite the higher price of improved materials. On the other hand, the lack of regeneration materials with high breeding gain still currently constrains its use in Finland, and especially in Norway spruce. The use of clonal material with high breeding gain in conifers is also still limited in practical forestry due to the high cost and low availability of such seedlings.

In the short term, forest biomass production can be increased the most in Norway spruce and Scots pine stands by using N fertilization on upland forest sites, where the limited availability of N currently clearly limits growth more than the supply of water. A single application of 150 kg N ha^{-1} can increase the volume growth by about 10–20 m^3 ha^{-1} (up to 22–36% over a 10-year period) in middle-aged or older Norway spruce stands on mesic sites, and in Scots pine stands on subxeric sites, compared to non-fertilization. However, the growth response may vary, largely depending on the N dose, site fertility, climatic conditions and stand structure. Currently, about 150 kg N ha^{-1} is typically used in fertilization in Norway spruce and Scots pine on upland forest sites. For economic and operational reasons, it is recommended to use a relatively large N dose once, although the highest growth responses may be achieved by repeated N fertilization, using moderate amounts each time

From the viewpoint of the forest owner, the economic profitability of forestry is mainly determined by timber production (sawlogs and pulpwood), and especially by sawlog production. Fertilization can enhance the economic profitability of forest biomass production, by more rapid shifting of stems from pulpwood size to sawlog size. The combined use of N fertilization and improved regeneration materials on suitable upland forest sites may also enable earlier thinnings and the use of shorter rotation lengths than currently (e.g., less than 80 years). This, together with an increased timber yield over a rotation, could compensate for the costs of more intensive silvicultural actions.

The effects of the intensity of individual silvicultural treatments (e.g., use/no use of improved regeneration material, thinning, fertilization) on forest biomass production can be studied in field experiments. However, the use of a process-based forest ecosystem model based analysis would make it possible to analyze the sensitivity of forest biomass (e.g., timber) production, and its economic profitability, simultaneously with the varying intensity of different silvicultural treatments and environmental conditions. In this sense, such modelling can provide valuable support for defining optimal forest management strategies for practical forestry under changing climatic conditions. So far, this has been done mainly with statistical growth and yield models which have been developed to support decision-making in practical forestry.

Goals

The aim of this study was to examine how intensified silviculture affects timber production (sawlogs and pulpwood) and its economic profitability (net present value [NPV], with a 2% interest rate) based on process-based forest ecosystem model simulations. The study was conducted on Norway spruce and Scots pine stands on medium-fertile upland forest sites under middle boreal conditions in Finland, under current climate and minor climate change (the RCP2.6 forcing scenario). In intensified silviculture, improved regeneration materials were used, with assumption of 10–20% higher growth compared to unimproved regeneration materials (seedlings), and/or using N fertilization of 150 kg ha^{-1}, once or twice during a rotation of 50 to 70 years.

Achievement of goals / Future practice

Based on our simulations, the timber yield (only pulpwood) increased in the first commercial thinning by up to 7–9 % in Norway spruce and Scots pine stands compared to baseline management (i.e. management recommendations for Finnish forestry), when improved regeneration materials with 10 or 20% higher growth (without N fertilization) were used. Over the entire rotation, the corresponding increases were for a 50-, 60- and 70-year rotation lengths in Norway spruce stands 7–18, 12–22 and 5–15%, and in Scots pine stands 7–11, 9–18 and 9–16%, respectively.

In the case of N fertilization, we used 150 kg ha^{-1} once or twice during the rotation at the time of the first thinning and/or last thinning before the final cut. This kind of N addition is currently practiced in Norway spruce and Scots pine on upland boreal forest sites. In our study, compared to the baseline regime, the timber yield increased with fertilization of 150 kg N ha^{-1} once or twice during a rotation of 60 years (no breeding gain assumed) by up to 25 m^3 ha^{-1} in Norway spruce stands, and up to 11 m^3 ha^{-1} in Scots pine stands. This range is in agreement with previous experimental studies for these tree species in Nordic countries. On the other hand, higher increases in timber yield can also be achieved by using a higher dose and/or repeated fertilization over short intervals as has been shown in some previous studies.

As a result of the use of improved regeneration materials and/or N fertilization, the forest growth increased and thinnings were performed some years earlier, compared to the baseline management. The use of improved materials increased also the timber yield over a rotation in a relative sense more than did N fertilization alone, regardless of rotation length and tree species or climate applied. The use of improved seedlings and N fertilization together increased the timber yield the most, by up to 28% compared to the baseline management. Intensifying the management regime also clearly increased the amount and proportion of sawlogs (from total timber production), compared to the baseline management, and the most in a relative sense at shorter rotation lengths. The use of the most intensified management regime (two fertilizations and improved regeneration materials with 20% higher growth) increased the timber yield under the current climate by up to 90–98 m^3 ha^{-1} in Scots pine and Norway spruce stands, compared to the baseline management Correspondingly, under minor climate change, the increases were by up to 66 and 93 m^3 ha^{-1} (being larger in Scots pine).

In Norway spruce, the timber production was, on average, 3–4% lower under changing climate, whereas in Scots pine it was, on average, 9–13% higher. Similarly, based on previous experimental studies, warming climate favours the growth of Scots pine as opposed to Norway spruce, especially in southern boreal conditions on soils with low water-holding capacity. In the future, the expected higher summer temperatures and associated drought will most probably decrease the growth of Norway spruce under boreal conditions. On the other hand, drought episodes and severe climate warming may also decrease the growth even in Scots pine.

Impact on stand development, forest products and costs

In general, intensive management (thinning, fertilization and breeding gain) results in increased growth rate and may thus decrease thinning interval and rotation length (in years). This would be the case if the timing and intensity of thinnings are driven by the development of dominant height and stand basal area, and if the timing of final felling is defined based on mean diameter (basal area weighted) of trees in a stand, which are the current forest management practices in Finland. In our study, the timing and intensity of thinnings were driven by the development of dominant height and stand basal area. However, the timing of final felling was defined based on rotation length instead of mean diameter. On the other hand, the mean diameter of trees in a stand at the time of final felling was in different simulations in our study in the range of recommended mean diameter in practical forestry in Finland. The use of longer rotation length may decrease the NPV, and especially if the increase in saw log amount does not compensate the longer time needed for incomes and/or if higher interest rate is used in economic calculations. Based on this, the profitability of management regime including N fertilization and the use of improved regeneration material may be greater than that reported in this study.

Our findings, that the use of better-growing seedlings and N fertilization were profitable investments for forest owners, with a 2% interest rate, are in line with the findings of previous studies, which suggested that tree improvement and N fertilization are financially justifiable. Hynynen et al. (2015) and Heinonen et al. (2018) also stated that, by intensifying forest management and using a combination of different methods (fertilization, improved regeneration materials, ditch network maintenance) at suitable sites, forest growth and timber supply could be increased in a resource-efficient way in different boreal regions, and without decreasing current forest resources at the national level. According to Hynynen at al. (2015), intensive management could be interpreted as a clear economic incentive to make long-term investments in forest management and forestry.

By intensifying forest management, we could increase forest growth and timber production per unit land area in a resource-efficient way. From the forest owner's perspective, the use of improved regeneration materials and N fertilization, both alone and especially together, in Norway spruce and Scots pine stands on medium-fertile upland forest sites, appear to be profitable investments under middle boreal conditions, both under the current and minor climate change. However, especially more severe climate change than assumed in this work could reduce largely the growth, timber yield and consequently also the economic profitability of forestry in Norway spruce, also under middle boreal conditions. On the other hand, more intensive management may at least partially compensate for the productivity losses expected otherwise for forest owners. In future studies, the increasing risks to forests from various abiotic and biotic forest damage should also be considered.

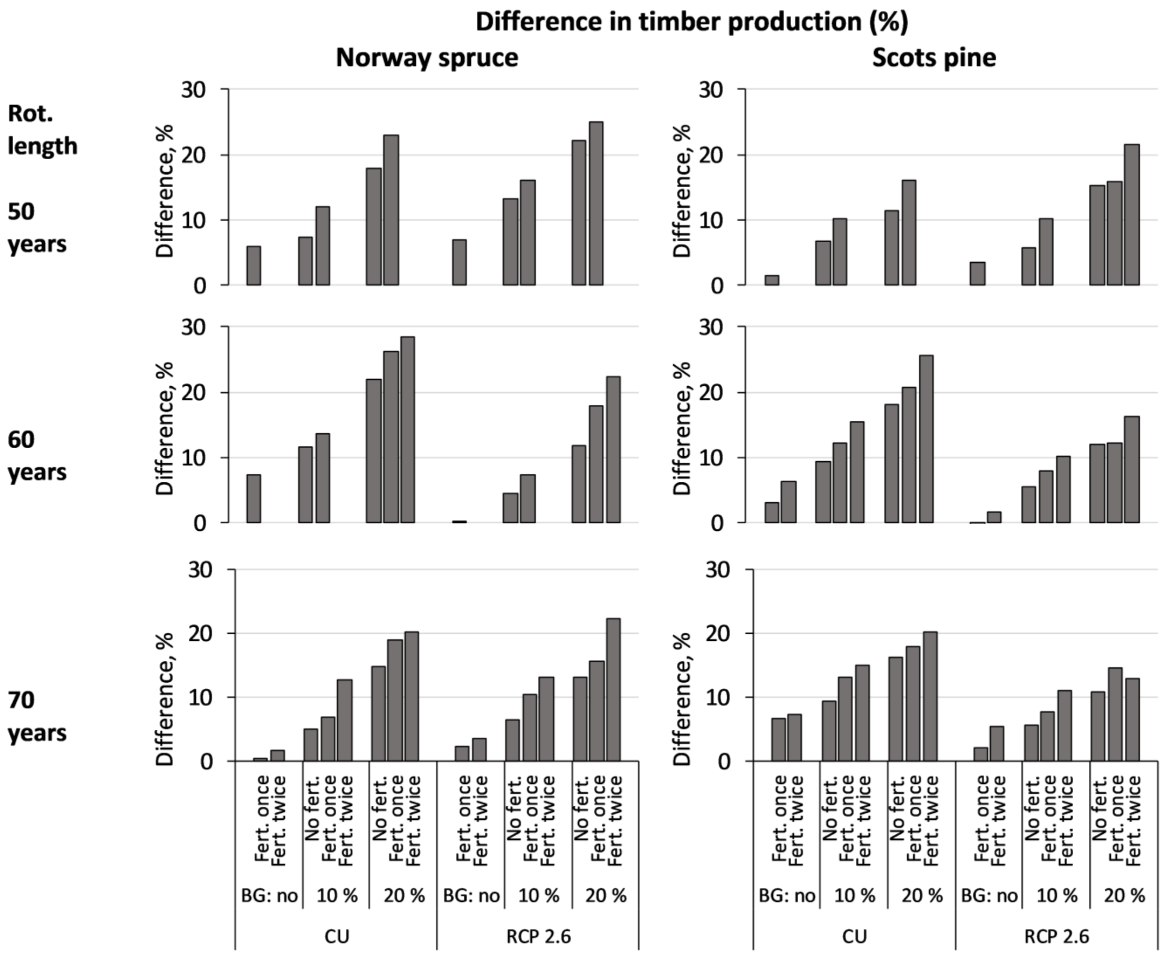


Figure 25. Effects of fertilization and improved regeneration materials on annual timber production (m3 ha^{-1} a^{-1}) as a difference (%) from baseline management, with rotation lengths of 50, 60 and 70 years under the current (CU) and changing (RPC2.6) climate in Norway spruce and Scots pine.

Routa, J., Kilpeläinen, A., Ikonen, V-P., Asikainen, A., Venäläinen, A. and Peltola, H. 2019. Effects of intensified silviculture on timber production and its economic profitability in boreal Norway spruce and Scots pine stands under changing climatic conditions. Forestry 92, 648–658.

4.3.2. Case study Denmark – Power cultures; fast growing species on skid roads

Niels Strange and Karsten Raae

The term `power cultures' reflects the implementation of regeneration systems which make use of fast growing species mixed into in stands mend for quality production of timber or logs. It is the idea that the fast growing species both supports the main species in the stand during the first years and after 10-25 years of growth delivers a first and profitable output in terms of biomass (Fig. 24). We have chosen production of quality timber of Norway spruce and use hybrid larch as the fast growing supportive species planted on future skidding roads.

Current practice / Need for improvememt

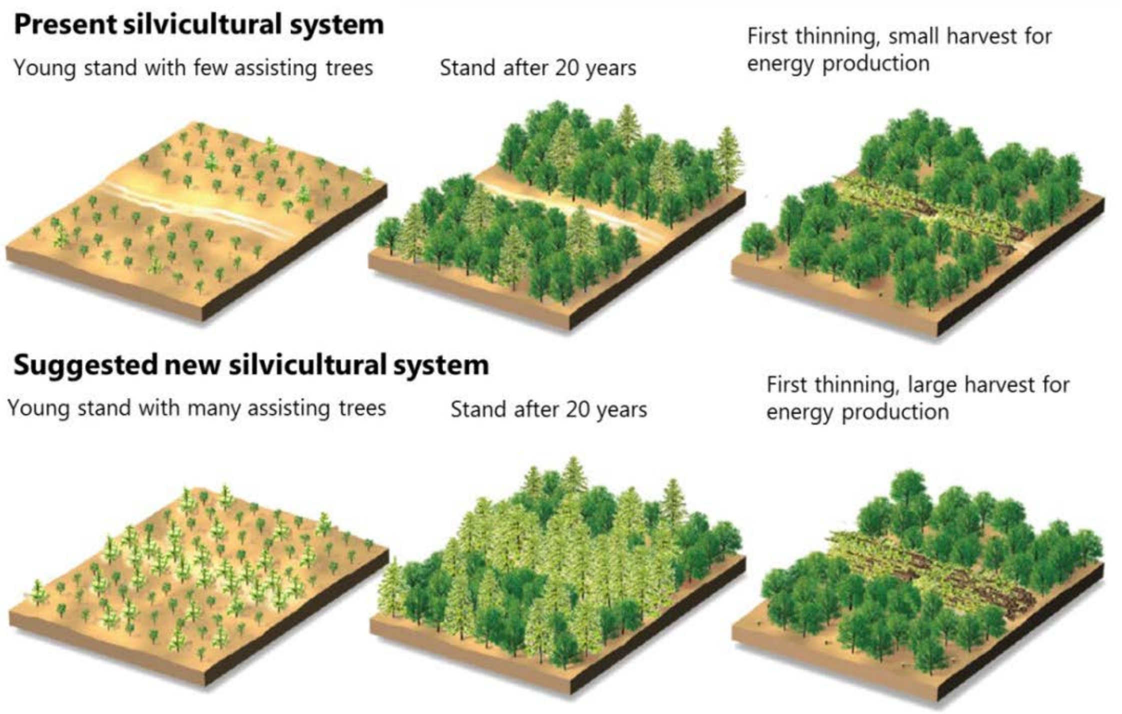


Figure 26. Presentation of the suggested new silvicultural system (so-called power cultures) and a silvicultural system with prepared skidding roads.

Three scenarios to be compared

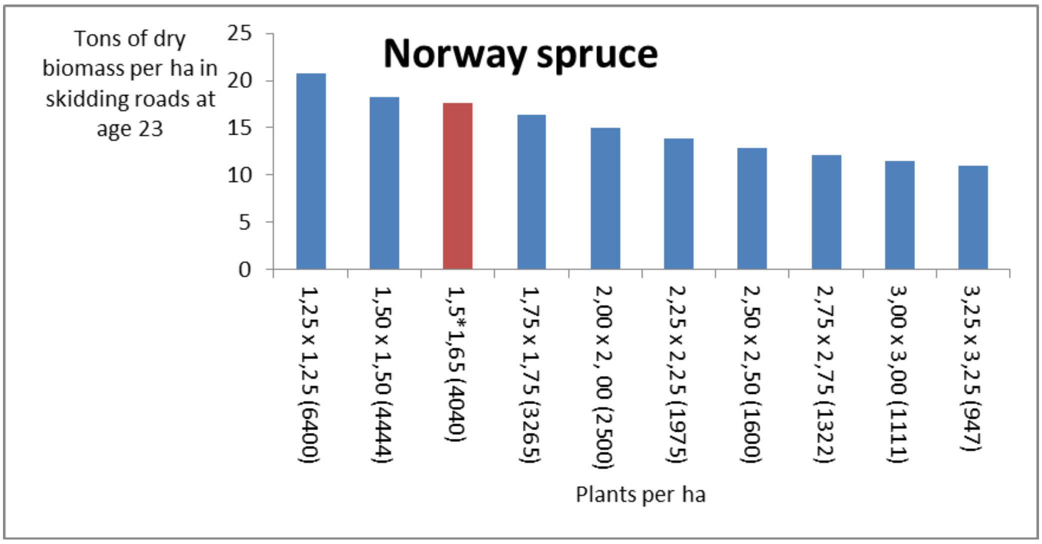
The first scenario is Norway spruce planted in the whole area of a hectare except where skidding roads are planned to be. We assume skidding roads will take up 20% of the area. Spacing is 1.5m x 1.65m ~ 3,200 seedlings per hectare.

The second scenario is Norway spruce planted over the whole area of a hectare. Spacing is 1.5m x 1.65m ~ 4,000 seedlings per hectare.

The third scenario is Norway spruce planted over the whole area of a hectare except where skidding roads are planned to be. Hybrid larch is planted in the skidding roads. Spacing is 1.5m x 1.65m ~ 3,200 Norway spruce and 220 Hybrid larch seedlings per hectare (spacing 3m x 3m). After the first ordinary thinning year 23, in scenario 2 and 3, that is establishment of skidding roads, in scenario 1 ordinary selective thinning, all three scenarios / stands are envisaged to be managed the same way and develop along the same pattern. The planting distances presented above are based on current pract

Achievement of goals / Future practice

A.



B.

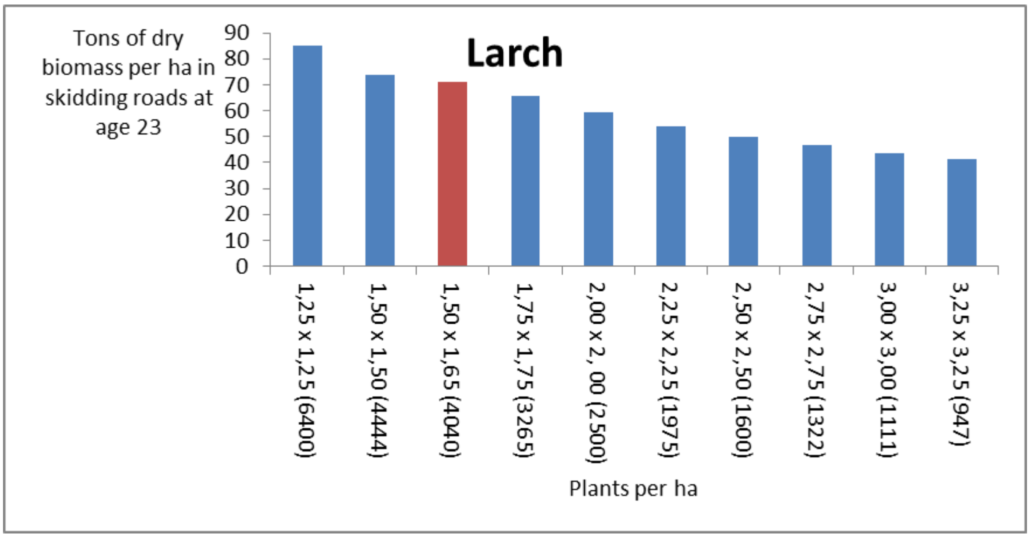


Figure 27. The biomass production of Norway spruce (A) and Hybrid Larch (b) in skidding roads covering 20% of the area. First axis shows the number of plants per ha and in parentheses the number of plants per ha skidding roads. The assumed reference for spacing distances in current practice is marked with red columns.

Goals: Comparison of biomass production

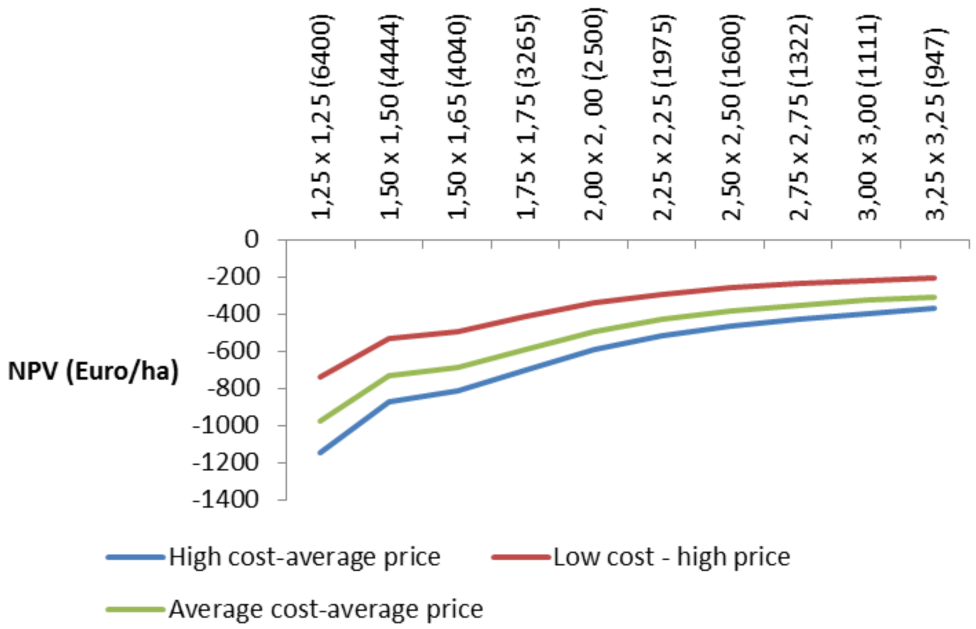
We applied biomass functions from Nord-Larsen et al. (2017) and data on diameter and height from growth and yield tables for comparing the biomass production from the three distinct systems. However, scenario 1 we refer to as a reference scenario (pre-planned skidding roads), and estimated the additional biomass production delivered by scenario 2 and 3. Fig. 27. presents the total biomass production in skidding roads covering 20% of the area. It is noted that the biomass production of hybrid larch is approximately four times higher than Norway spruce assuming similar planting distances. The biomass production of hybrid larch in skidding roads is very sensitive to planting distances.

Planting skidding roads revealed that biomass production could increase by approximately 18 tons of dry biomass per ha if regenerated with Norway spruce (1.5m x 1.65m planting distance) and for hybrid larch approximately 44 tons per ha at 3.0m x 3.0m planting distance and approximately 71 tons per ha at 1,5m x 1,65m planting distance.

We applied data from SKOVDYRKERNE on assumed upper and lower ranges of i) energy prices, ii) harvest and chipping costs, iii) transportation costs, iv) planting costs, v) and cleaning costs. We converted into loose cubic metres by multiplying tons of dry biomass by 5,89. We estimated the net present value (NPV) of the two scenarios assuming that the NPV of the 20 % pre-planned skidding roads in scenario 1 (no planting in skidding roads) is zero.

We estimated the net present value of planting Norway spruce respectively hybrid larch in the skidding trails assuming a 2 per cent discount rate at three cost and price scenarios (Figure 28). The net present value at various planting densities is negative for all price scenarios, except for hybrid larch assuming a low cost – high price scenario. Note that the maximum planting density for hybrid larch is achieved at a planting distance of 1.75m x 1.75m. However, it appears that the net present value is less sensitive to planting distance at higher planting distances.

A



B

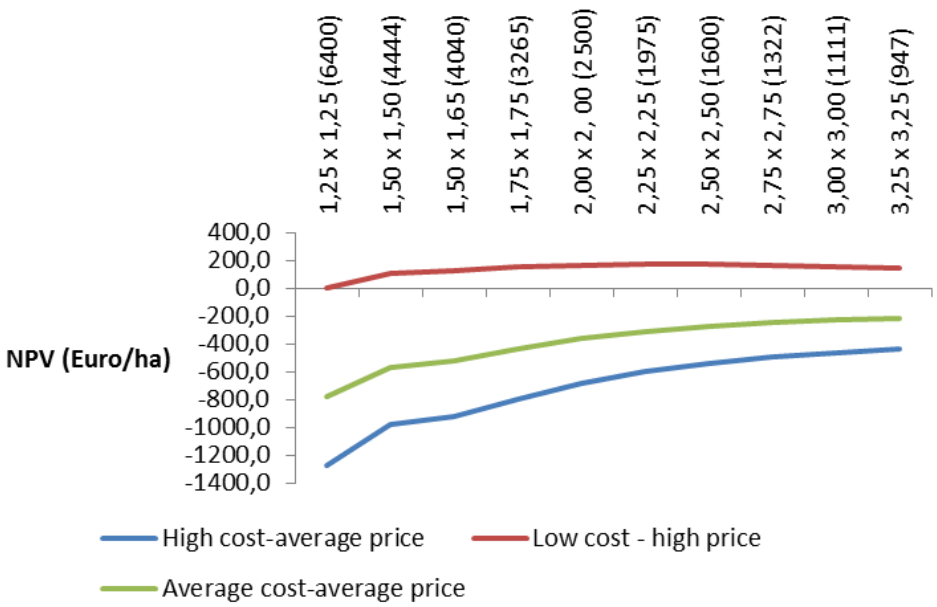


Figure 28. Net present value at various planting densities and cost and price scenarios for Norway spruce (A) and hybrid larch (B) assuming a 2 per cent discount rate.

We estimated the net present value of planting Norway spruce respectively hybrid larch in the skidding trails at a range of discount rates (Figure 29). Interestingly the net present value increases with increasing discount rate if we assume the high cost –average price scenario. The reason is that the gross margin of the felling at age 23 is negative, and therefore the net present value contribution decreases with increasing discount rates.

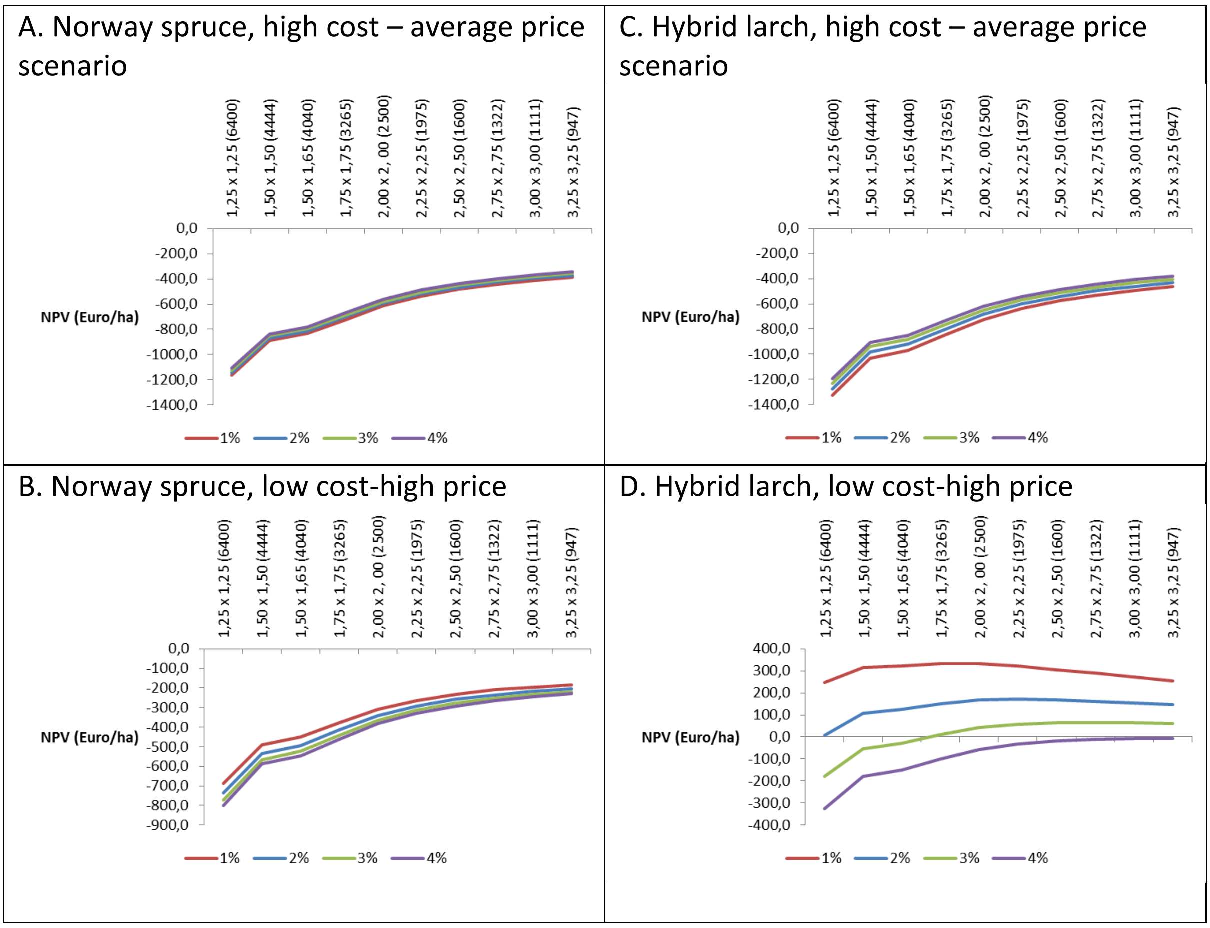


Figure 29. Net present value at various planting densities and cost and price scenarios for Norway spruce (A+B) and hybrid larch (C+D). We assumed high cost – average price scenario in A and C, and a low cost-high price scenario in B and D.

The negative net present values reflects that although planting skidding roads may increase the biomass production considerably (41–85 tons/ha for hybrid larch and 10–20 tons/ha for Norway spruce), it may come as a cost to the forest owner. However, not planting the skidding roads may still imply a cleaning cost of 1800 DKK/ha and a lower quality of the trees next to the skidding road. This may further reduce the investment cost in increasing the biomass production from intensifying production from skidding roads.

Figure 29 also demonstrates that the optimal spacing of plants depends on discount rates as well as the costs and prices. Assuming low cost – high prices the net present value is positive for hybrid larch at all spacing distances if the discount rate is lower than 2 per cent.

We compared the difference in net present value of planting hybrid larch and Norway spruce in the skidding roads at different planting distances (Figure 30) assuming a 2% discount rate and the low cost – high price scenario. It is illustrated that replacing Norway spruce with hybrid larch in the skidding roads may be a good investment.

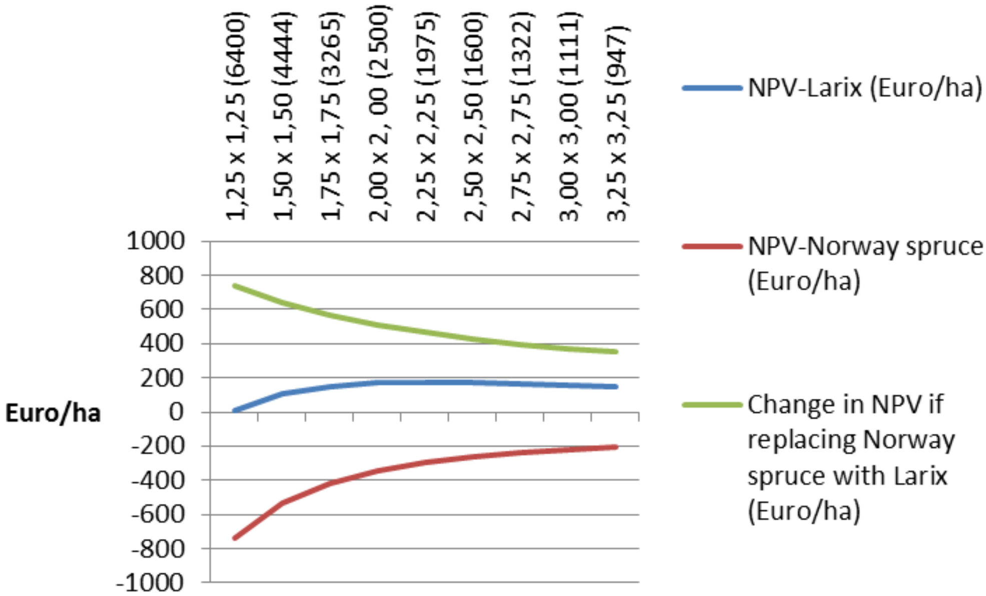


Figure 30. The estimated change in net present value (NPV) and production of dry biomass by replacing Norway spruce with hybrid larch in the skidding roads. Assuming low cost- high price scenario and a discount rate at 2 per cent. The difference decreases with increasing discount rates.

The results are sensitive to all assumptions made: Growth, cost, prices, etc. These examples also demonstrate the gains in biomass production could be higher if power culture principles are applied in slow growing broadleaf stands.

Impact on stand development, forest products, costs

The idea of `power cultures', rests mixing in fast growing species intended for intermediaere products in planted forest stands aiming for high quality production of timber or logs. We believe this silvicultural measure is valid for most of the European forestry, and our findings should be transferable to other silvicultural contexts.

The simulations demonstrated that biomass production can be increased significantly. We found, applying current price and cost data, that the net present value of production in skidding roads is negative, although assuming lower discount rates (e.g. 1 per cent) and low cost-high price scenarios, the net present value could be positive. However, quality effects on trees next to the skidding roads were not included, and similar cleaning costs would still be present in stands where no trees have been planted in skidding roads. We also found that the optimal planting distance is sensitive to the discount rate. The higher discount rate the higher spacing distance is optimal.

The economic output and the efficiency of the manpower and machines used are sensitive to a number of factors including e.g. the design of the stand, timing of thinning operations, logistics of operations, changing climatic conditions, market prices and costs.

4.3.3. Case study France – Stump removal in maritime pine plantations

Hernán Serrano-León and Christophe Orazio

Current practice / Need for improvement

One of the productive forest areas in Europe, where the processing capacity is high compared with the available resource, is the Landes of Gascogne forest in the Nouvelle-Aquitaine region of France. The Landes Massif is the largest planted and privately owned (92 %) forest in Europe, with a total forest area of approximately 1 million ha, mostly dominated by maritime pine stands and intensively managed (Mora et al., 2014). This forest produces 7.6 million m^3 harvested annually, representing 24% of the national wood harvest (MAAF-IGN, 2016). Despite the large area and productivity, the available resource supply is under high pressure as a result of the large catastrophic windthrows from the storms "Martin" in 1999 and "Klaus" in 2009. Such extreme climatic events have increased the phytosanitary risk, for which monoculture stands can be especially sensitive (Jactel et al., 2009). A major phytosanitary risk is root rot diseases caused by *Heterobasidion annosum* and *Armillaria ostoyae*. These rot fungus inoculate roots and stumps after final felling and cause decay, growth reduction and tree mortality while spreading by root contact. It can remain viable for decades, placing coniferous stands at an increased health risk in subsequent rotations (Cleary et al., 2013; Woodward et al., 1998). Another particular risk in coniferous plantations is the large pine weevil (*Hylobius abietis*), a major pest for conifer seedlings whose larvae develops in the on the large roots of freshly cut stumps before feeding on the bark of the young plants (Jactel et al., 2009; Långström and Day, 2002).

While site preparation techniques are commonly conducted in intensive forestry to improve the conditions for afforestation and growth, soil preparation before planting can also have a significant effect on health risk during stand development (Jactel et al., 2009). Phytosanitary risks can be responsible of major dieback in the Landes forests if no risk handling measures are taken during stand preparation, especially as phytosanitary threats are likely to increase with climate change (Canteloup and Castro, 2012; GIS GPMF, 2013; Piou and Jactel, 2010). Conventional practices after clearcut in maritime pine stand in the Landes consist on leaving the stand for a fallow period of 2–3 years between final harvesting and reforestation, aiming to reduce the pest and pathogens risk by taking advantage of progressive decomposition of the stump substrate (Brunette and Caurla, 2016; Jactel et al., 2009). However, fallow period delays the reforestation actions. Alternative risk prevention measures have been considered in the last decades (stump chemical treatment, soil cleaning, stump burying), especially after the damage caused by the storms Martin (1999) and Klaus (2009) required massive savage cuttings and reforestation efforts (Brunette and Caurla, 2016; Merzeau and Maris, 2001).

A promising techniques for effective risk prevention consist on the extraction of the stumps and coarse roots from the clearcut within 1 year after final felling (Augusto et al., 2018; Landmann and Nivet, 2014). Stumps are uprooted from the clearcut ground using specific hydraulic grippers and stump shears adapted to mechanical excavators (Fraysse, 2007; Merzeau and Maris, 2001). Stump removal has been used as an effective phytosanitary control method against *Hylobius* and root rot diseases in other parts of Europe and North America. (Heritage and Moore, 2001). (Cleary et al., 2013; Vasaitis et al., 2008).

In addition to its application as a management tool for health risk control, the main benefits for the forest owners from an economical perspective is the use of the stump biomass as a new resource for the production of woodfuel, providing an additional income that compensates the cost of the stump extraction (Colin et al., 2009; Walmsley and Godbold, 2010). Stump extraction in the Landes has been particularly favored from the post-storm socioeconomic context of the last decades: pressure on the wood resource with limited production, increasing local demand of wood biomass for energy, and public subsidies or investment from the wood energy sector allowing forest owners to extract stumps wihtout cost (Banos and Dehez, 2017). (Brahic and Deuffic, 2017; Emeyriat, 2016; Landmann and Nivet, 2014).

Nevertheless, despite its large potential and availability, stump biomass is currently underexploited in the region. Surveys carried out between forest owners in the Landes showed that, even though the majority (70%) deem stump wood energy as an opportunity to value forest by-products and obtain additional income, only a low proportion of owners (17%) has already extracted stumps for wood biomass (Brahic and Deuffic, 2017). Forest owners are therefore eager to have a better understanding of the economic profitability of stump removal to amortize their investments. Given that the emerging favorable conditions for widespread exploitation of stumps put forest owners in an unprecedented situation of choice, there is a need to evaluate the economic and financial performance of the stump removal practice as a combined measure for combined health risk control and bioenergy recovery in the Landes.

Goals

This case study aims to analyze the micro-economic and financial effects at stand level of stump removal for combined risk control and bioenergy recovery, in comparison with the conventional stand preparation practice after clearcut. The study area is focused on private plantations of maritime pine in the Landes Massif (region Nouvelle-Aquitaine, France).

Stand-level development was modelled using the forest growth model PP3 integrated in the simulation platform CAPSIS (Lemoine, 1991; Meredieu, 2002). Growth simulations were conducted for an average fertility stand (dry mesophilic, site index 23.5m at 40 years) regenerated by seedling planting. The standard silvicultural itinerary was simulated according to the recommended site-specific management guidelines (Sardin and Canteloup, 2003). Standard silviculture consist on a planting density of 1250 seedlings/ha and four thinning operations from above leading the stand to a final density of 300 trees/ha for final harvest at 45 years. Total stump biomass was calculated from stand characteristics at rotation age using the allometric relationships estimated by Bert and Danjon (2006). Mobilisable stump biomass was assumed as 60% of available underground biomass (Colin et al., 2009). Two site preparation practices for health risk control were considered: a standard fallow period of 2 years between final harvesting and reforestation, and the stump removal for bioenergy recovery following clearcut. Both measures were considered to have comparable control effectivity against Heterobasidion annosum and Hylobes risk, assuming no damage levels or mortality due to future infestation during the rotation.

The financial performance of the different scenarios was assessed in terms of net present value (NPV, €/ha) and soil expectation value (SEV, €/ha) by applying the formula of the Faustmann model (Klemperer, 1996). We analysed the financial performance applying a discount rate of 3%, as conventionally used in forest management in France and Europe (Rakotoarison et al., 2015; Terreaux, 1989). The costs of the silvicultural regime are based on the average baseline prices of the technical itineraries for silvicultural operations proposed by ONF (2013). For the scenarios with total stump harvest, the subsequent facilitation of soil preparation operations was considered as a reduction of 5% of ploughing costs corresponding to the efficiency gains estimations (GIS GPMF, 2013). The costs of the harvest operations were included on the stumpage price for wood and stump, as stem harvest and extraction operations costs are usually covered by the wood contractor after negotiation with the forest owner.

In order to determine the conditions within which stump extraction is an economically viable operation, five scenarios for extraction costs of stumps as co-products of forest exploitation were assessed, representing different monetary transactions between forest owners and industry consumers:

1) *Scen1 – Fallow*: Standard fallow period of 2 years, no stump extraction.

2) *Scen2 – Stump costs*: Stump extraction costs covered by the forest owner without income nor compensation from stump biomass, assuming no market for stump biomass. The total stump removal costs is estimated at 690 €/ha (Brunette and Caurla, 2016).

3) *Scen3 – Stump 0€/t*: Stump extraction free of charge, assuming a post-storm reforestation context where the extraction costs of non-market stump wood are compensated with the subsidies for cleaning work, or covered by the energy wood industry as a transaction between the cleaning service provided and the stump biomass – *stump market indexed to its production costs* (Banos and Dehez, 2017).

4) *Scen4 – Stump 2€/t*: Stump extraction provides an additional income of 2 € / t of stump biomass, considering a symbolic transaction price for the stump extraction that compensate the owner keeping the purchased lot on his land until its transport (Banos and Dehez, 2017).

5) *Scen5 – Stump 10€/t*: Stump extraction provides an additional income of 10 € / t of stump biomass, assuming a high price for stump biomass market indexed for the substitution effect of fossil fuels (Banos and Dehez, 2017).

Finally, a sensitivity analysis for stumpage price was conducted to take into account the effect of different timber prices on the financial performance of the stand management. Three wood price scenarios were considered, corresponding respectively to the years with lower, medium and higher price curves for the period 2013–2017 from the regional timber sales statistics (CRPF Nouvelle-Aquitaine, 2017).

Achievement of goals / Future practice

The figure 31 presents the financial performance in SEV (€/ha) resulting from the different stump extraction and fallow scenarios for the three stumpage timber price scenarios. Regardless of the stumpage price scenarios, the fallow period (*Scen1 – Fallow*) was only economically preferable if stump extraction costs are covered by the forest owner without income nor compensation from stump biomass (*Scen2 – Stump costs*). The extra costs of the stump extraction operation were not compensated by the reduction of site preparation costs without stumps and the shortening of the silvicultural regime from earlier plantations. Compared with the SEV of the *Scen1–Fallow*, the losses in SEV of *Scen2–Stump costs* where higher for the lower stumpage price scenario (-656 €/ha, -58%) than for the average (-483 €/ha, -15%) and higher stumpage price scenarios (-383 €/ha, -9%).

Nevertheless, when the extraction costs are not assumed by the forest owner, the stump extraction operation combined with bioenergy recovery was always financially preferable than the fallow period.

For the *Scen3 – Stump 0€/t* in which the stump extraction is free of charge or extra income, the gains in SEV compared to the fallow scenario ranged from +282 €/ha (+25%) for the lower price scenario up to +555 €/ha (+13%) for the high price scenario, with a gain of +455 €/ha (+14%) for the average price scenario. For the *Scen4 – Stump 2€/t* in which the stump extraction transaction provides an additional income of 2 €/t to the forest owner, the SEV gains with respect to the fallow scenario increased considerably: +359 €/ha (+31%) for the lower price scenario, +532 €/ha (+16%) for the average price scenario, and +631 €/ha (+14%) for the high price scenario. Finally, the resulting SEV gains from the most favorable *Scen5 – Stump 10€/t* can reach up to +665 €/ha (+58%) for the lower price scenario, +838 €/ha (+26%) for the average price scenario, and +937 €/ha (+21%) for the high price scenario.

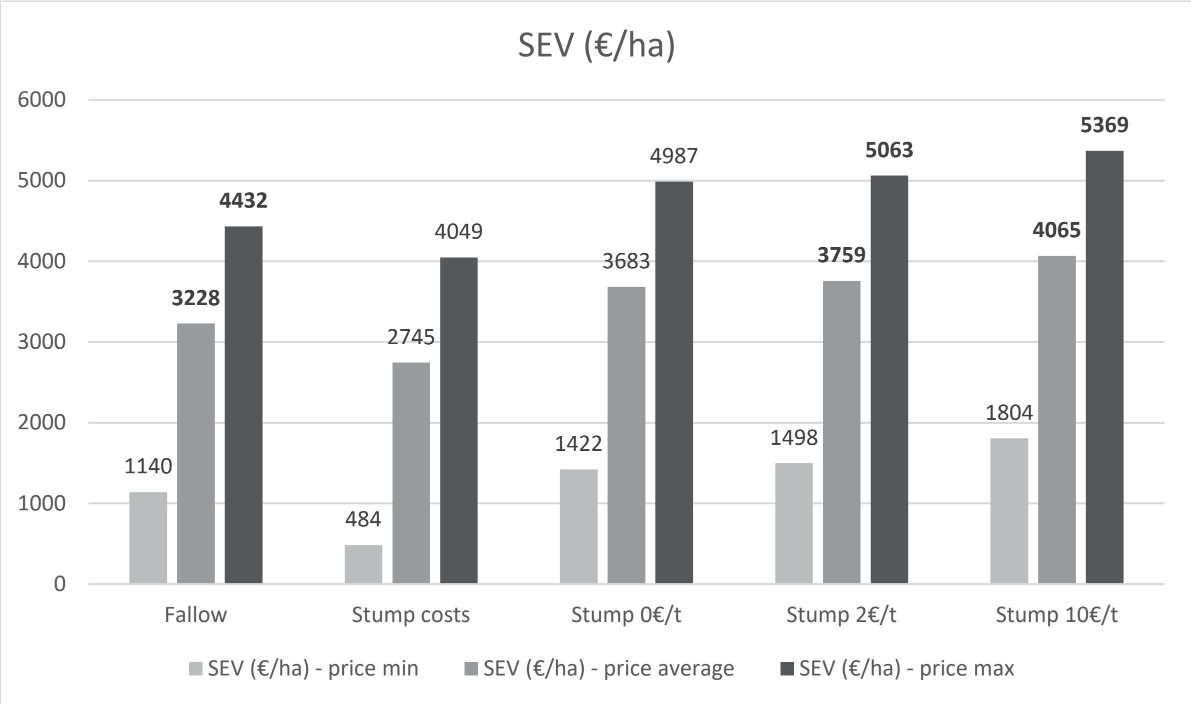


Figure 31. Sensitivity analysis of financial performance in terms of SEV (€/ha, discount rate 3%) from different economic scenarios of stump extraction of a maritime pine stand in the French Landes, compared with the conventional stand preparation practice of fallow period after clearcut.

The results of the financial analysis shows the economic conditions for which stump extraction is a financially viable strategy in comparison with the conventional stand preparation practice of fallow period after clearcut. Our study is in line with previous economic studies that showed that risk handling measures are effective economic strategies if compared with the losses from the absence of risk handling measures. Given a certain risk of contamination, the economic value loss of the contaminated trees in addition to the reduction of the overall stand density result in a non-proportional economic decrease in SEV over time (Bogdanski et al., 2018; Brunette and Caurla, 2016). However, a comprehensive assessment of the economic rationale for stump harvesting in the Landes considering the potential additional income from stump biomass was absent.

In this sense, our results provide a better understanding of the economic profitability of stump removal as a measure for combined health risk control and bioenergy recovery. The profitability of stump harvesting when stump biomass is valued as a bioenergy resource allows for forest managers to consider stump removal as a routine operation in the region in a context of favourable conditions. Colin et al. (2009) estimated that 60% of private forest properties in the Landes could be potentially harvested, considering several technical-economic thresholds for stump harvesting (mobilisable stump biomass per hectare, aggregated stand area, skidding and transport distance). Assuming that 60% of available underground biomass can be mobilisable for stump biomass, the potential stumps biomass that could be mobilized annually in the Landes massif was estimated at around 360,000 tons/year (calculated at 50% moisture of biomass). The potential harvest in the Landes region alone would represent 50% of the stump biomass availability for entire France. Stump harvesting in France is currently just limited to sandy soils of the Landes region, given its context of intensive forestry in large-scale planted forests with favorable conditions for stump extraction (flat terrain and sandy soils that limit the risk of erosion) (Landmann and Nivet, 2014).

Nevertheless, the profitability of this practice depends on the compromise between forest owners and the extracting contractors consuming the stump resource, which in turn depend on the energy market and the technical-economic thresholds for stump harvesting. Moreover, the widespread exploitation of stumps in the Landes should be subject to the development of best practice guidelines that minimize the potential negative impacts in order to ensure a sustainable use of this technique. Considering the different technical, economic, and environmental factors beyond the specificities of this case study, the methodology used in this economic assessment could be used in further analysis to estimate the extrapolation potential at regional level of the potential of different stump removal scenarios to the entire Landes Massif.

Impact on stand development, forest products, costs

The main benefit for the forest owners from an economical perspective is the use of the stump biomass as a new resource for the production of bioenergy for fossil fuel substitution, providing an additional income that compensates the cost of the stump extraction while contributing to the transition from a fossil- to a bio-based economy (Colin et al., 2009; Walmsley and Godbold, 2010)**.** contribution to the transition from a fossil- to a bio-based economy with the production of bioenergy from stump biomass. However, the net effect on climate change mitigation from the substitution effect of fossil fuels depends on the trade-off with the reduction of the carbon storage in the soil from the removal of soil organic matter and the increased carbon emissions from the soil caused by the up-rooting (Melin, 2014; Melin et al., 2010). Given the lack of similar studies in the case of the Landes region, the short- and long-term consequences of this practice of stump harvesting on the carbon storage and emissions are still uncertain.

In addition to its application as a combined management tool for health risk control and bioenergy recovery, stump extraction has further technical-economic benefits in terms of forest management. The immediate effect is that stump removal allows faster reforestation after clearcut compared with the conventional health prevention practice, as no fallow period of several years is required. Moreover, stump extraction can reduce the reforestation cost due to work productivity improvement and efficiency gains in site preparation operations, as remaining stumps after clearcut create obstacles for the soil preparation equipment (GIS GPMF, 2013; Saarinen, 2006).

Stump removal can have different potential effects on tree growth and consider the potential additional income from stump biomass depending on the species and site (Bogdanski et al., 2018; Cleary et al., 2013; Vasaitis et al., 2008, Walmsley and Godbold, 2010). In the Landes region, several long term experimental sites has recently been established within the Sylvogène project (Chantre et al, 2008) to analyze the impact of stump harvesting as a curative control measure against *Heterobasidion* root rot, as well as to measure the impact in soil fertility from different modalities of biomass export. The first growth measures in young maritime pines at age 5 years did not show any significant effect of the biomass export modality (stump, branches, stump and branches) compared with the conventional stem harvest (GIS GPMF, unpublished).

Nevertheless, as stump harvesting represents an intensification of forest management activities, increasing stump harvesting is not absent of raising concerns about its sustainable management (Walmsley and Godbold, 2010). While increased ground disturbance as soil erosion and compaction might be limited in the favorable flat terrain and sandy soils of the Landes regions, the extraction of stump biomass will result in additional exports of mineral mass out of the ecosystem that can have potential negative impact on soil nutrition. Nevertheless, recent studies in maritime pine stands in the Landes show that this risk can be limited by harvesting only the coarser root elements, which are less rich in assimilable organic elements than fine roots (Augusto et al., 2015, 2014). In this sense, harvesting stumps without lateral roots could be a relatively sustainable alternative of bioenergy harvest from a nutrient balance perspective, especially when compared to other sources of biomass such as logging residues or whole tree harvest (Persson, 2013).

Regarding biodiversity, a direct impact from stump removal is the reduction of habitat for saproxylic species that depend on this coarse woody debris as their key substrate (Brin et al., 2013). However, there is a limited knowledge about the effect of different thresholds of stump and slash removal on the biodiversity in temperate zones. On the lack of available information to define removal thresholds in order to minimize the impact on biodiversity, some good practices can be proposed related to the zoning of extractions (i.e. target the stump extraction in stands with presence or risk of pathogenic fungi) and the storage of slash before export (i.e. maintaining in the stand part of the unharvest or extracted stumps, maintaining a diversity of wood sizes and stages of decomposition) (Landmann and Nivet, 2014).

Further research is therefore needed to quantify the productivity and environmental effects of stump harvest in maritime pine systems in the Landes of Gascogne forest. Further analysis should be based on established long-term experiments (i.e. SYLVOGENE project) and sustainable impact assessments in order to determine the overall costs and benefits from stump harvesting. This will allow the development of best practice guidelines to minimize the potential negative impacts in order to ensure a sustainable use and promotion of this technique.

4.4. Business tools for improved stand treatment and wood mobilization services

Robert Prinz, Dag Fjeld, Øivind Østby-Berntsen, Niels Strange, Karsten Raae, Johanna Routa

4.4.1. IT solutions in selected countries

In a first step, a particular focus was on IT-tools, internet-based applications and other interfaces that enable both the requisition and marketing of silvicultural and harvesting services in three Nordic countries, Denmark, Finland and Norway. The main IT solutions in the selected countries were mapped.

4.4.2. Business process mapping (BPM) of selected cases

In a second step, the main focus was on the description of results of the business process mapping (BPM) of selected cases in Finland and Norway. Mapping the business processes required in procuring services or forest-based products enabled them to be systematically analysed – within their respective operation environment described in more detail below.

Case Finland

In Finnish conditions, the focus was on selected tools and a general level covering the principle of tools (e.g. IT markets) conducting a simplified comparison between “Online IT platform” vs. “traditional offer inquiry”.

The assessment focused thereby on the match making between the forest owner and the need for a forest service with a service provider. The produced simplified process maps give an indication of the steps from a forest owner perspective when using an online IT platform. The process maps show the beginning of the activity when joining starting with the registration at the IT service until the a service announcement has been sent to a service provider and from the beginning of the match making with the sending of the service announcement until then end of the activity through the financial accounting or payment of the utilized service.

The utilization of available online market places by forest owners builds on publically available services including their (open source) data and information, therefore their principle functioning is slightly different.

The traditional direct offer inquiry assumed a direct contact between the forest owner and a service provider without intermediate actors (Figure 32).

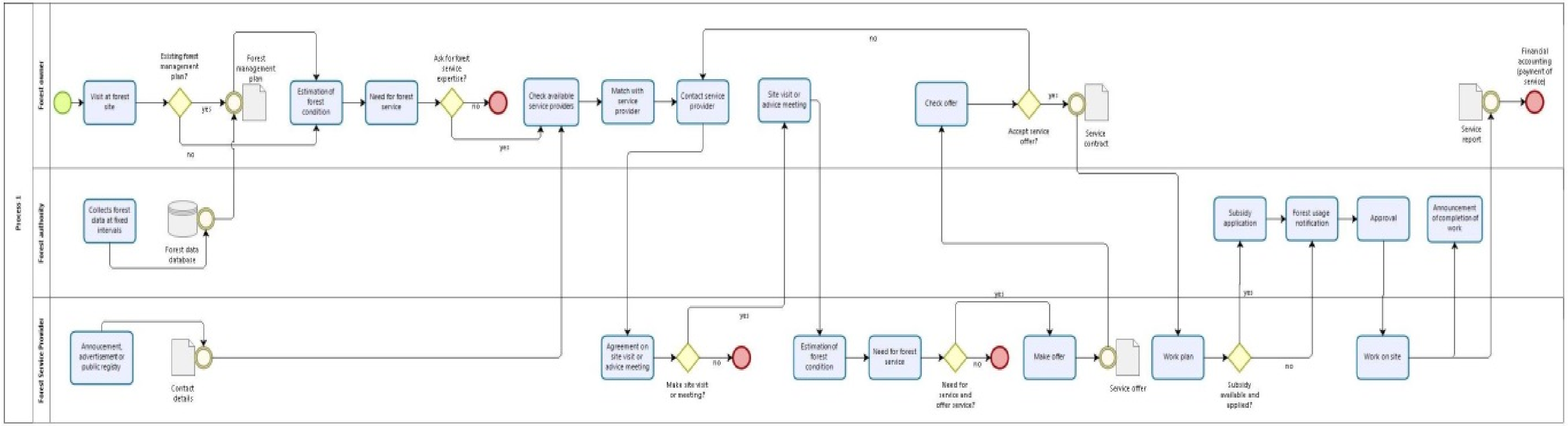


Figure 32. Simplified example process map showing the entire chain of a traditional service purchasing process from a forest owner perspective using traditional direct contact to a forest service provider.

Using the number of interactions as an indicator of process efficiency of the alternative business models, the simplified process of the "traditional direct offer inquiry" showed three main actors and numerous data exchange processes between the actors, depending on the availability of subsidies and assuming the contact to one main service provider (Figure 33).

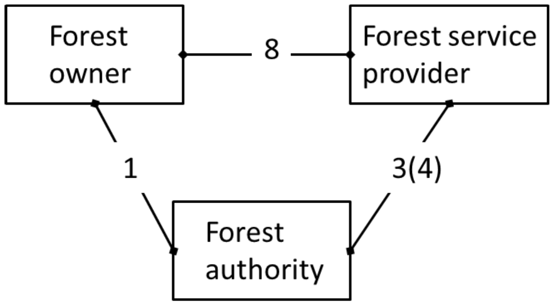


Figure 33. Example of process map for a traditional service purchasing process from a forest owner perspective using traditional direct contact to a forest service provider with 3 main actors and numerous data exchange processes. The number of data exchange processes between the forest service provider and the forest authority depends on the availability of subsidies assuming that the service provider takes care of the announcement.

The case “Online IT platform” focused on a simplified general level covering the principle of tool “Online IT platform” based on the available service Metsään.fi from a forest owner´s perspective (Figure 34).

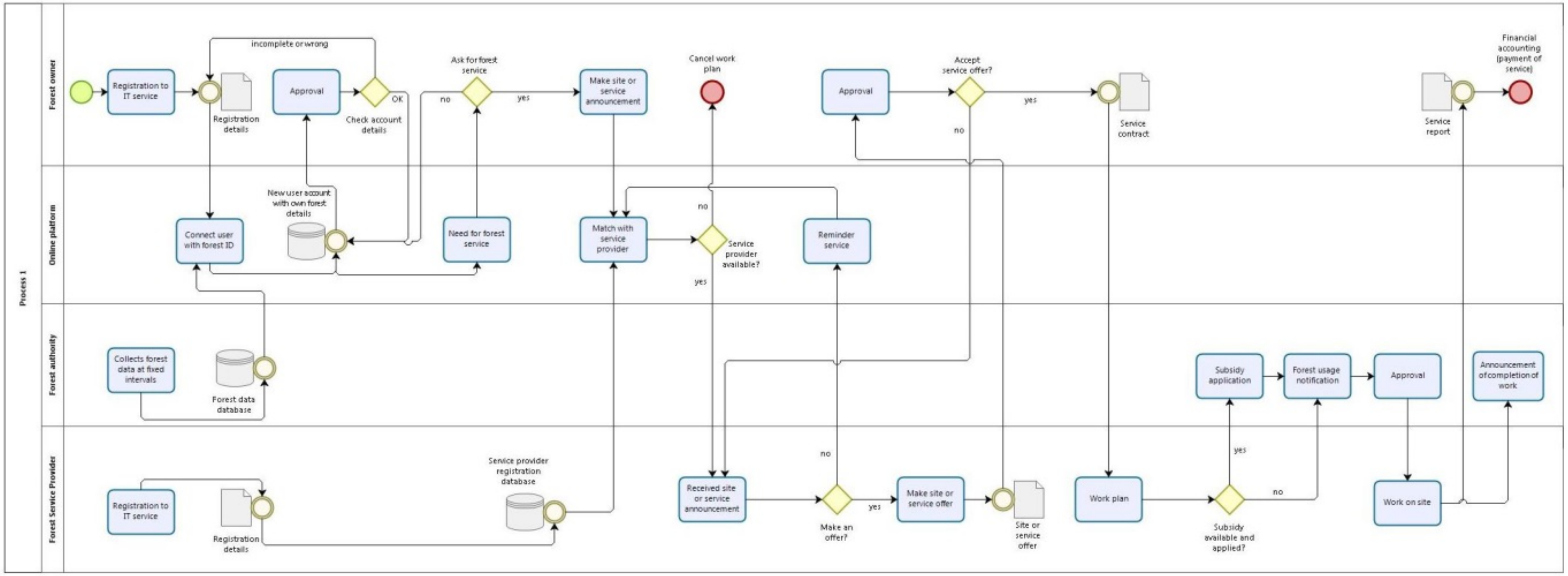


Figure 34. Simplified example process map showing the entire chain of a service purchasing process from a forest owner perspective using online IT platform.

The number of interactions (as an indicator of process efficiency) in the simplified process of the "online IT platform" showed four main actors and numerous data exchange processes between the actors, depending on the availability of subsidies and registration situation of actors and without a reminder function (Figure 35).

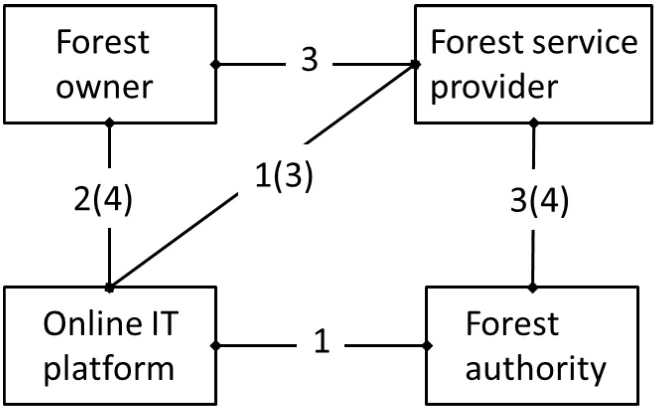


Figure 35. Example of process map for a service purchasing process from a forest owner perspective using an IT service platform with 4 main actors and numerous data exchange processes. The number of data exchange processes between the forest service provider and the forest authority depends on the availability of subsidies assuming that the service provider takes care of the announcement, the number of data exchange processes between the forest service provider and the Online IT platform depends if the service provider is already registered to the platform, the number of data exchange processes between the forest owner and the Online IT platform depends if the forest owner is already registered to the platform.

In addition to the reduced amount of data exchange processes for the forest owner, the processing time of data exchanges is being reduced. This is the case as the online IT platform performs its process basically almost instantly and without major delay. Nevertheless, the entire reaction and handling time in both cases still depends on individual persons involved.

Case Norway

Industrial wood supply in Norway is managed primarily via regional forest owner associations (FOAs). The mill customers establish supply contracts with the FOAs, who in turn contract wood with their members. Each association offers harvesting and silviculture services to their members via their own contractors. In general, business services for wood supply are well established in Norwegian Forestry. Most farm forests have forestry plans and the supply chain processes though purchase, harvesting, delivery and payment are supported by a sector-wide IT-infrastructure.

Nationally, the annual harvest (10–12 million m^3) is under half of the annual increment (25 million m3). In southeast Norway, forestry conditions are more similar to the other Nordic countries, and harvesting levels near annual increment. In these areas there is still a clear pattern of seasonal variation in harvesting with the consequence of uneven capacity utilization and high costs. The current wood supply situation can be characterized as a hot market with consequently short planning horizons for purchase and harvesting.

The overall goal of the case study was to examine the wood mobilization processes in Norwegian forestry, in terms of potential improvements and future services. The first sub-goal was therefore to provide a general business process mapping of wood purchase and production for Norwegian forest owner associations. The second sub-goal was to provide an initial test of one selected service improvement, long-term management agreements.

A simple quantitative model was used to map the effects of the increased planning horizon on key performance indicators (KPIs) for the production phase. For all 27 simulations, the distributions of monthly KPIs are shown below in figure 36. The distributions can be compared between panels from the smallest contract bank (1 quarter) to the largest (3 quarters). In this case the cover time is expressed as the number of quarters of production time which the contract bank corresponds to. For each KPI (deviation from production goals, machine hours, distance between sites) the distribution narrows as the contract bank cover time increases.

Figure 36. Distribution of monthly production KPIs for three sizes of contract bank (panel variable: 1–3 quarters). Deviations from monthly production goals (above), machine utilization (middle), and distance between harvesting sites (below).

Between the 27 simulations, there exists considerable variation in the solutions as a result of the varying levels of production bonus (1, 5, 10 NOK/m^3). Figure 37 shows the combinations (trade-off) of relative deviations in monthly production (from defined goals) and machine utilization (from defined hours). An insignificant bonus (1 NOK/m^3) maintained small deviations in machine utilization (< 10 % on the x-axis), but allowed extreme variations in production (up to 70 % on the y-axis). A significant bonus (10 NOK/m^3) maintained minor deviations in production (< 25 % on the y-axis) while allowing greater deviations in machine utilization (up to 20 % on the x-axis).

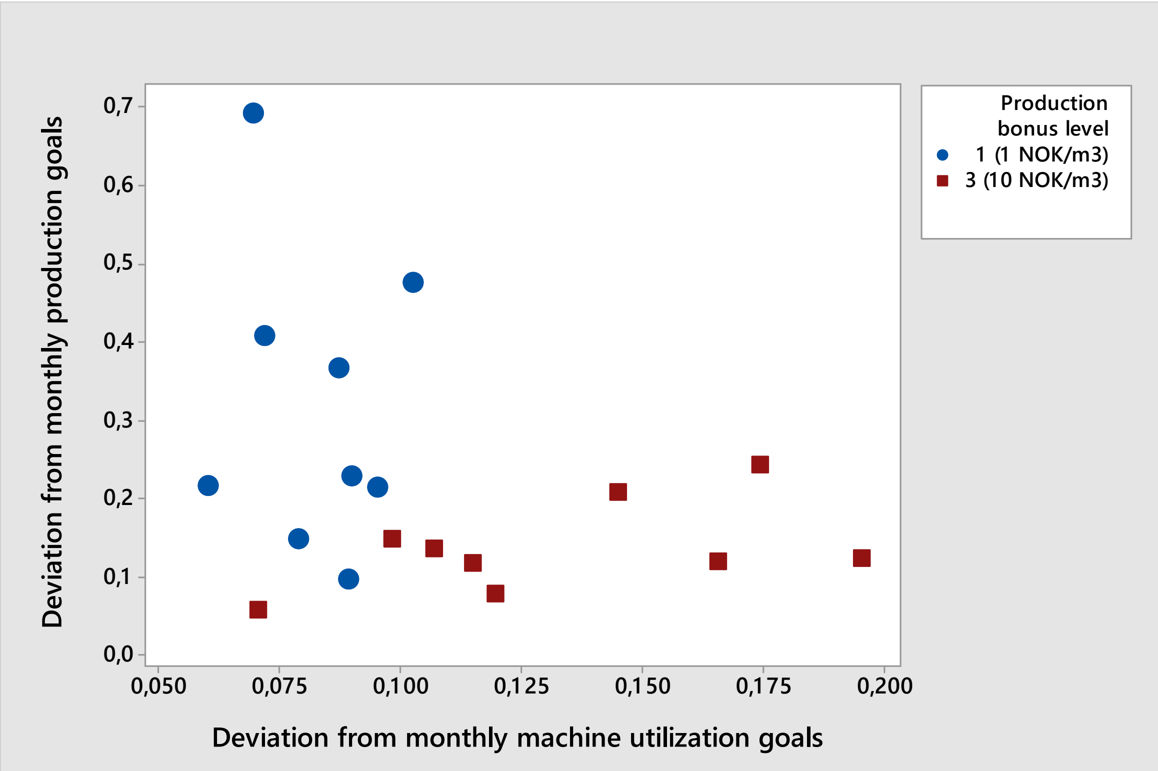


Figure 37. The relationship between monthly deviations from goals for production (y-axis) and machine utilization (x-axis) with two different levels of production bonus (1 and 10 NOK/m^3).

Given the original 3 levels of contract bank cover times (3, 6, 9 months) it is also possible to track how the KPIs vary in relation to the remaining cover time as the simulation passed from March (winter) to April (spring thaw) and May (early summer).

With an insignificant bonus for meeting production goals (1: 1 NOK/m^3) production deviations increased steeply with the increased cover time (Figure 38, left) while utilization deviations decreased slightly from an already low levels of approx. 10% (Figure 38, right). With a high production bonus (3: 10 NOK/m^3) production deviations maintained low levels (10–20%), while utilization deviations started high (15–20%), decreasing with increasing cover times.

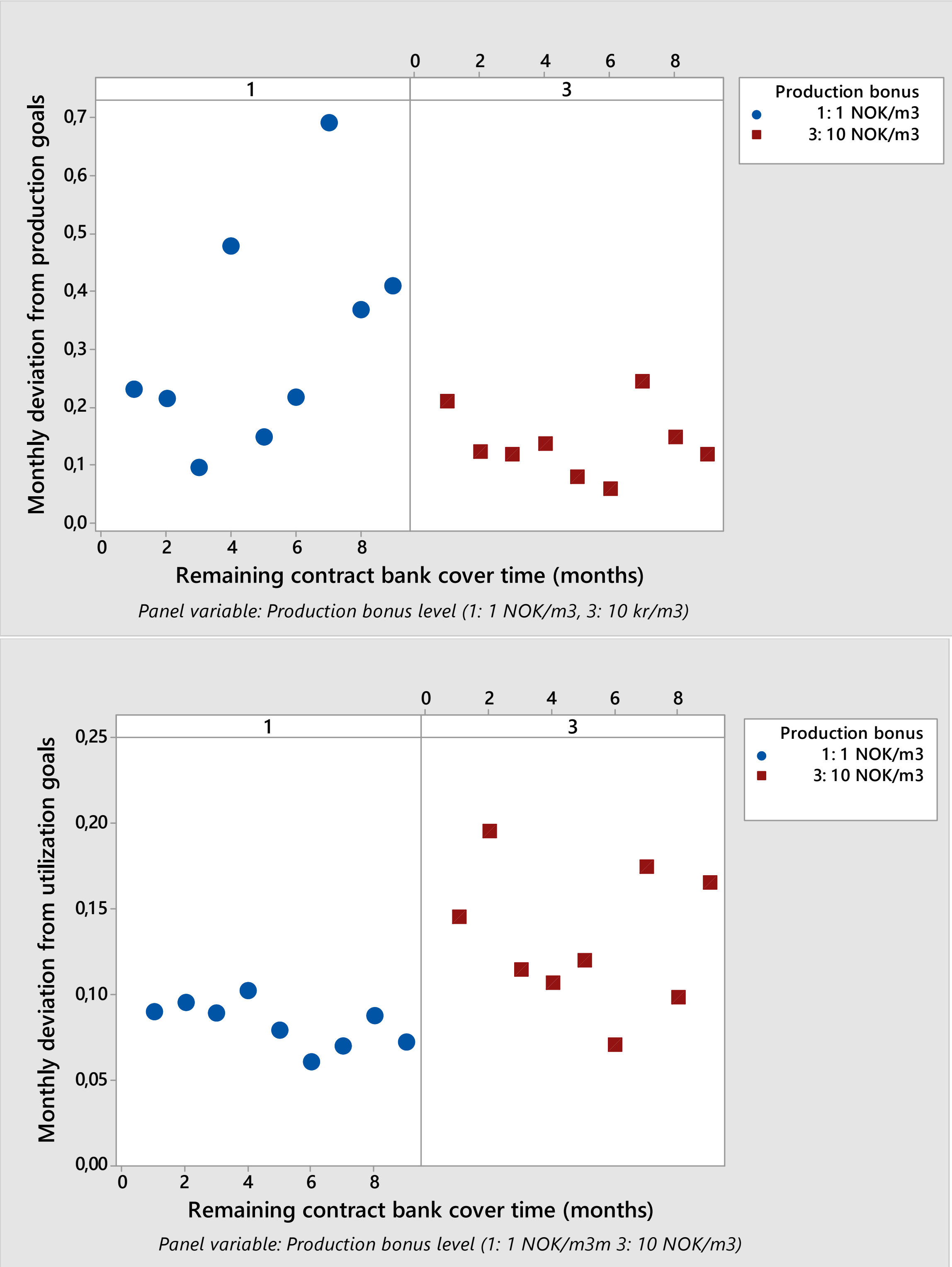


Figure 38. Deviations from production (left y-axis) and machine utilization (right y-axis) goals with increasing contract bank cover time (months on both x-axis) with two different levels of production bonus (blue: 1 and red: 10 NOK/m^3).

5. Harvesting Systems Map for Europe

In this chapter we develop a tool with the aim of upscaling the suggested measures for efficiency increase, described in the previous chapter. This tool is a harvesting systems map that evaluates the areas where pre-defined harvesting systems can be applied. Since the intensification of mechanized silvicultural operations is our task, we asses the upmost mechanized harvesting variant for each given point of the map. The map builds upon a set of subtools that are required for our upscaling purposes.

The essential factors for the suitability of a harvesting system for a particular site are: slope and ruggedness of the terrain, tree species composition and tree dimensions, trafficability of the forest soil and accessibility of the forest site. Within this study we assess these limiting factors at the European level. For this task pan-European datasets containing information about forest structure and tree species composition, land cover, conservation areas, topography, soil and road network are combined. The outcome is a map that at 500 m resolution shows the highest mechanized harvesting system that can potentially be operated at any location in European forests.

Highly mechanized harvesting systems improve the safety at work and reduce the physical stress of the workers. If operated correctly, cut-to-length harvesting, done by higher mechanized harvesting systems like harvester and forwarder, also lead to lower stand damage compared to motor-manual felling and forwarding in whole tree methods (Camp, 2002; Koşir, 2008; Kühmaier, 2011; Limbeck-Lilienau, 2003). The reason is that higher mechanized systems allow a more controlled tree handling, which is important for stand damage reduction (Magagnotti et al., 2012; Spinelli et al., 2014). However, soil compaction resulting from the ground load caused by the machines can have a long-term negative impact on the environment. The planning of forest operations including the most favourable season for harvesting operation is important in this context. Fuel consumption by heavier machines also needs to be considered. We do not explicitly address environmental factors in our analysis, but implicitly, by excluding some soil types as not being trafficable by heavier machines. Other soils may be trafficable only during favourable times as mentioned above. The map is not giving recommendations which harvesting system should be used at a given site, nor does it replacea site inspection. What our map shows is the share of possible areas of application for each harvesting systems at the large scale.

Data and data preparation

We utilize forest structure (forest type, tree species, diameter at breast height, standing volume), terrain (slope and soil), infrastructure (road network) and legal (conservation areas) information to create a pan-European map of harvesting systems at 500 m resolution. All datasets are either available or are projected to ETRS89-LAEA (European Terrestrial Reference System 89-Lambert Azimuthal Equal-Area) projection. Datasets that are not available at 500 m resolution are either aggregated or disaggregated to the required resolution. The forest structure gridded dataset is used as reference layer, all other data layers are aligned to this reference layer.

Forest Structure

Information about forest structure is extracted from a pan-European, gridded dataset (Moreno et al., 2017). The updated forest structure dataset used in this study contains harmonized national forest inventory (NFI) data from 14 European countries. This NFI plot level data is aggregated to 8 km grid-cell size using ETRS89-LAEA projection. A gap-filling algorithm is used to expand this aggregated NFI data to areas where no NFI data are available.

Tree Species

Information about tree species comes from a Tree Species Map for European forests based on NFI data and a multinomial logistic regression model using various abiotic factors as predictors to fill areas without NFI data (Brus et al., 2012). Percentage share for 20 tree species and the dominant tree species per cell are provided. The data is available at 1 km resolution and ETRS89-LAEA projection.

Land cover

Land cover information is provided by satellite driven data (MODIS), which is available at 500 m resolution (Friedl and Sulla-Menashe, 2015). The map we used represent conditionsin the year 2016 and we use the University of Maryland (UMD) classification.

Conservation Areas

The Common Database on Designated Areas provided by the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) in community with the European Environment Agency (EEA) gives information about officially designated protected areas such as national parks or nature reserves in Europe.

Digital Elevation Model (DEM)

Our digital elevation model (DEM), coming from the Copernicus Land Monitoring Service, is provided at 25 m resolution, the overall vertical accuracy (RMSE) is 2.9 meters.

Soil data

Soil information comes from the European Soil Database (ESDB) of the European Soil Data Centre (ESDAC). One has to note that the variables for soil properties are often not measured on local soil samples but estimated over large areas by expert judgment resulting from synthesis and generalisation of national or regional maps (Panagos, 2006).

Road Network

Open Street Map (OSM) provides freely available geodata which can be used for the creation of maps. OSM data as shapefiles for each country is provided by Geofabrik (www.geofabrik.de) and was obtained between January and April 2019. Roads are available as line shapefile features and key-value pairs can be used to extract certain road types.

5.1.1. Methods

Definition of harvesting systems

A harvesting system is constituted by the components felling, processing and extracting. For our purposes we define nine harvesting systems and their technical limitations (Table 9). As technical limitations we take into account extraction distance, slope, trafficability of the soil, tree dimensions (diameter) and tree species composition. Extraction distance is only a limiting factor for the extraction with winch assisted machines (harvester or forwarder) and cable yarder (cable length). The tree species composition as limiting factor refers to the question, if broadleaves are available or not. This is of relevance since the handling of broadleaves for harvesters is much more difficult than of conifers. For Skidder, Harvester and Forwarder on flat terrain extraction distance is not considered to be a limiting factor. Slope and soil limit the general trafficability for heavy machinery.

Data utilization

We calculate the road density within a certain radius as a proxy for extraction distance based on the OSM road network data. First, we use the highway key to extract forest roads Road density then is calculated using the line density tool in the ArcGIS toolbox. Line density is calculated for each 500 m cell using radii of 300 and 600 m. If a road density of 1 m/ha is calculated for a pixel, we assume that the minimum extraction distance from the centre of the cell is 300 or 600 m, respectively. These distances correspond to the technical limitations of 400 and 800 m set for winch-assisted machines and cable-yarding systems (Tab. 9).

Ground-based harvesting systems are often limited by the slope. Based on the digital elevation model we calculate the slope for each 500 m grid cell, by using three slope classes: 1) up to 30 %, 2) between 30 and 60 %, 3) higher than 60 %.

Table 9. The nine harvesting systems and their technical limitations as used in the harvesting systems classification.

Harvesting System	Level of mechanization	Technical Limitations				
		Extraction Distance	Slope	DBH	Tree Species	Soil
Not Accessible or Helicopter	Partially	-	-	-	-	-
Chainsaw and Skidder	Partially		< 30 %	-	-	-
Chainsaw and Forwarder	Partially		< 30 %	-	-	limited
Harvester and Forwarder	Fully		< 30 %	tree spec. specific	limited	limited
Chainsaw and Cable Yarder	Highly	≤ 800 m	< 100 %	-	-	-
Chainsaw and Cable Yarder Processor	Highly	≤ 800 m	< 100 %	< 60 cm	-	-
Chainsaw and Winch-assisted Forwarder	Partially	≤ 400 m	< 60 %	-	-	limited
Steep Terrain Harvester and Cable Yarder	Fully	≤ 800 m	< 60 %	tree spec. specific	limited	limited
Steep Terrain Harvester and Winch-assisted Forwarder	Fully	≤ 400 m	< 60 %	tree spec. specific	limited	limited

Apart from slope and roughness of the terrain, trafficability is affected by soil type and texture, altogether determining the soil bearing capacity. In general, higher soil moisture leads to lower bearing capacity. Therefore, the use of heavy machinery on wet soils either is not possible or limited to specific times during the year when the soil is frozen or very dry. We use the attributes provided by the ESDB to define soil types affected by groundwater and use these soils as a limiting factor for the application of heavy machinery. This is a simplification as the soil moisture or water content is not only influenced by the soil type but also its texture as well as the prevailing weather conditions.

Furthermore, the operation of harvester/processor systems for felling and processing is limited by a tree species specific maximum diameter at breast height (DBH). We choose rather small tree species-specific diameter limits for the use of a harvester as we take into account not only the felling but also the subsequent processing of the tree by the harvester head (Tab. 10).

Table 10. Tree specific diameter at breast height (DBH) limits for felling and processing with harvester head. Tree species and ID as in the EU Tree Species Map (Brus et al., 2012).

ID	Tree Species	DBH limit (cm)
1	Abies spp	40
2	Alnus spp	40
3	Betula spp	40
4	Carpinus spp	25
5	Castanea spp	25
6	Eucalyptus spp	40
7	Fagus spp	25
8	Fraxinus spp	25
9	Larix spp	40
10	Broadleaved misc	25
11	Conifers misc	40
12	Pinus misc	40
13	Quercus misc	25
14	Picea spp	40
15	Pinus pinaster	40
16	Pinus sylvestris	40
17	Populus spp	unsuitable
18	Pseudotsuga menziesii	40
19	Quercus robur/petraea	25
20	Robinia spp	25

Calculation of Harvesting Systems

The use of the before mentioned limitation criteria to determine the potential harvesting system for a forested cell can be illustrated by a decision tree (Fig. 32).

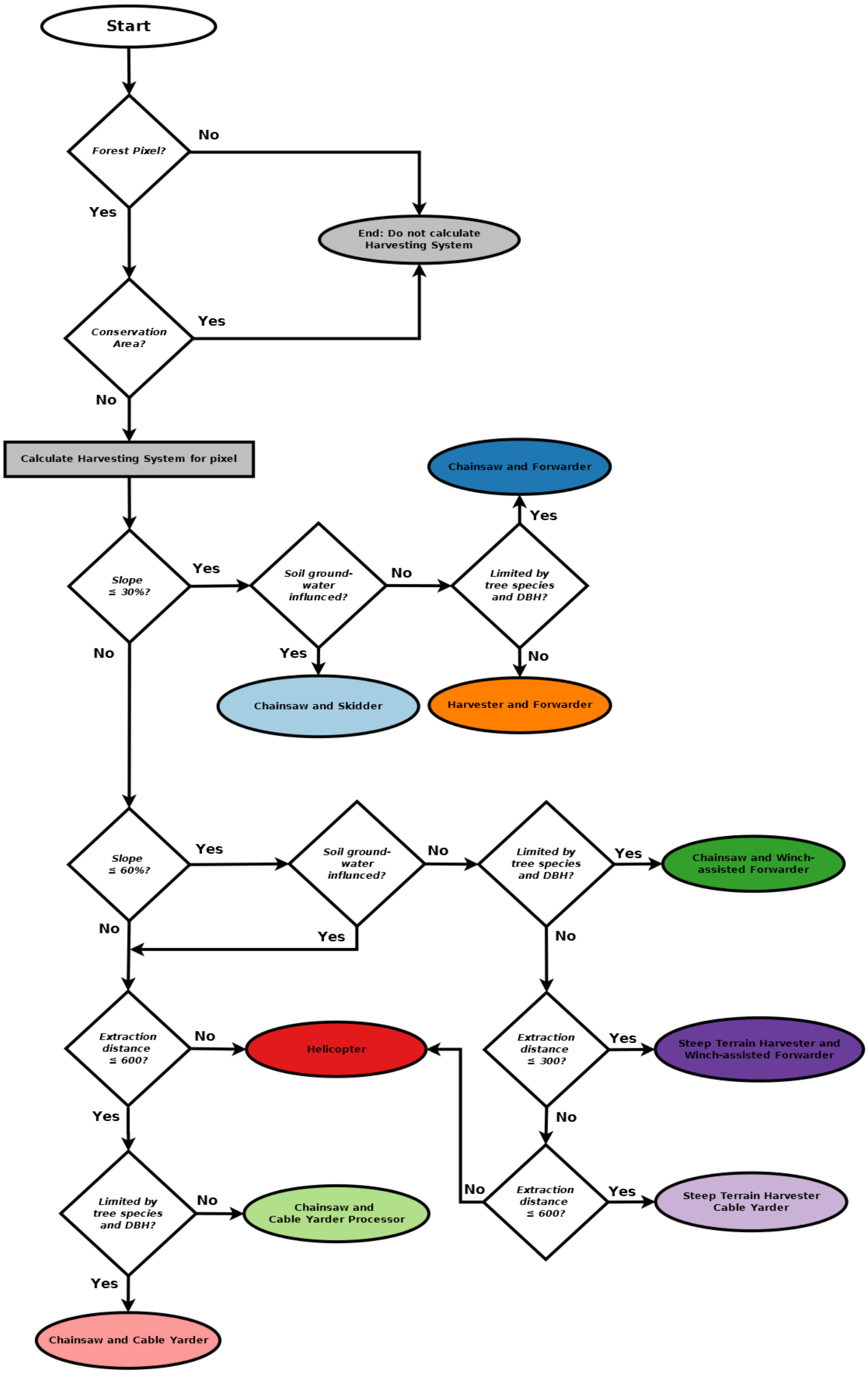


Figure 39. Decision tree showing how the potential most suitable harvesting system is found for each cell. The decision tree prefers more mechanized harvesting systems over lesser mechanized systems.

The potential harvesting system is calculated for all forested grid cells except for conservation areas where timber harvesting is prohibited. A 500 m grid cell is determined to be forested if it has one of the following land cover types: evergreen needleleaf forests (ENF), evergreen broadleaf forests (EBF), deciduous needleleaf forests (DNF), deciduous broadleaf forests (DBF), mixed forests (MF) and woody savannas (WS). Using the conservation area data we determine grid cells falling into the IUCN categories Ia (Strict Nature Reserve), Ib (Wilderness Area) and II (National Park) as areas where harvesting activities are prohibited. If more than one harvesting system are applicable for a given grid cell the decision tree prefers more mechanized harvesting systems, e.g. preferring the 'Harvester and Forwarder' over the 'Chainsaw and Forwarder' system. Therefore exactly one harvesting system is assigned to each grid cell.

Calculating forest area and standing volume

To estimate the amount of wood resources which can be accessed by the different harvesting systems, we calculate standing volume for every forested grid cell. Within the UMD land cover classification forest types (ENF, EBF, DNF, DBF and MF) by definition have a tree cover over 60 %. In our calculations each forest type cell contributes 25 ha (500 m times 500 m). Woody savannas (WS) are defined by tree cover between 30 and 60 % and canopy height greater than 2 m and therefore we define a factor of 0.45 when calculating forested area for a WS cell so that each cell contributes 11.25 ha of forest area. This forest area is multiplied with the volume per hectare to obtain the standing volume for each 500 m grid cell. Figure 33 shows the standing timber volume in Europe.

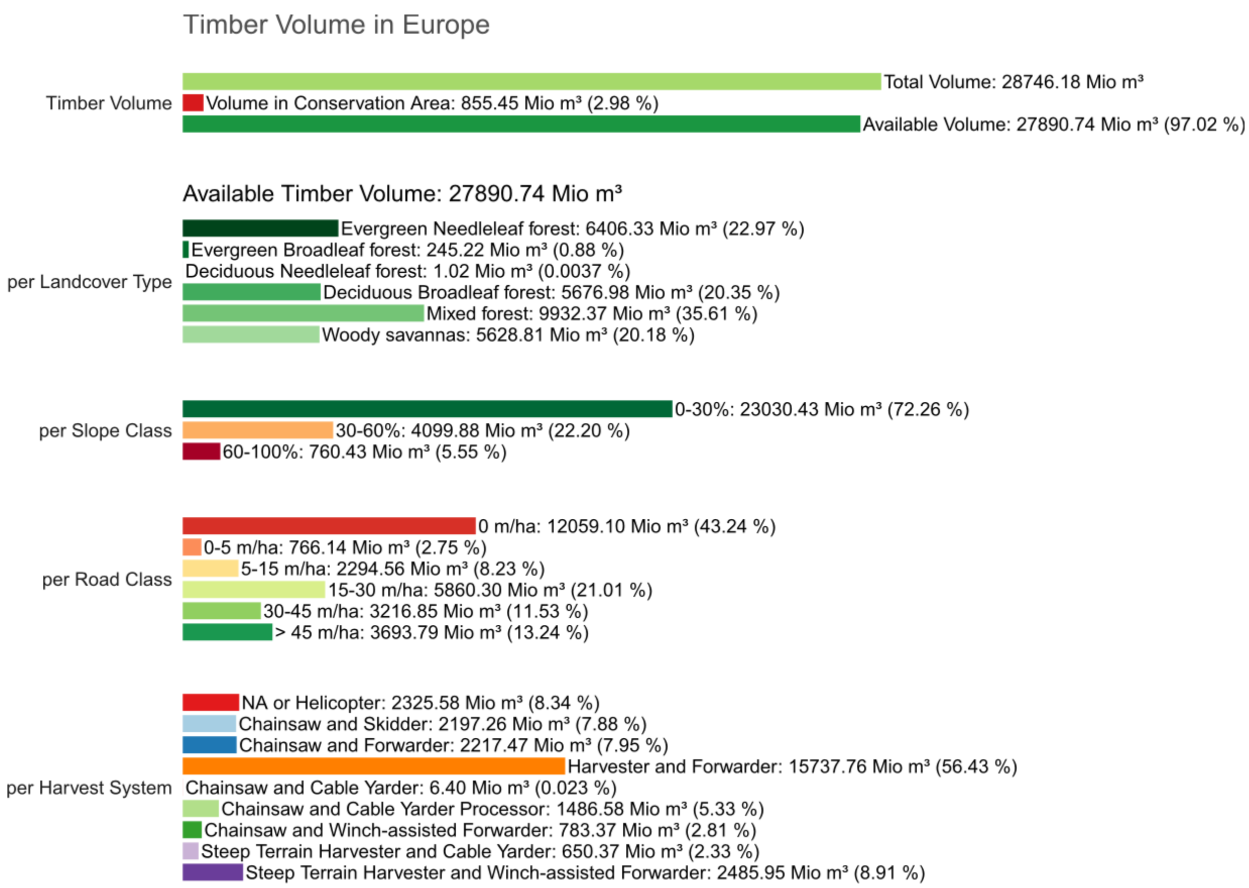


Figure 40. Distribution of European forest resources regarding landcover type, slope and road class and harvesting systems.

5.1.2. Results and analysis

According to our analysis, around three percent of Europe's timber volume ranges within IUCN categories Ia (Strict Nature Reserve), Ib (Wilderness Area) or II (National Park) protected areas and are not available for timber harvesting (Fig. 33). We consider the remaining volume of around 27 891 million m³ as being available, although timber harvesting may also be limited in forests with other than commercial main purposes, likeprotective or recreational purposes. But these factors are not included in our analysis.

Flat areas and a high share of needleleaf or mixed forests favour the use of mechanized harvesting systems. Over half of European forests is suited for the harvester and forwarder system (Fig. 34). It is the dominant harvesting system in the Scandinavian countries. As expected, it is also quite common in the flat areas like in Central and Southern Europe. Although we do not consider general accessibility of a harvesting site as a limiting factor for ground-based heavy machines such as harvester and forwarder, their efficiency may be limited by a poor road network. Over 40 % of harvestable timber is located in areas where no road suitable for harvesting operations is present within a search radius of 282 m (representing an area of around 25 ha) in our data. However, this value probably is too high as roads are missing in the Open Street Map (OSM) data. In general, mountainous regions (e.g. Carpathians, Dinarides, Alps, Pyrenees, Scandinavian Mountains) show a poor road network according to the OSM data (Fig. 35). This may reflect the actual situation in these regions as well as the factor that OSM data in these areas might be incomplete. As OSM depends on an active community it is likely that remote areas are not as well surveyed as populated areas. of the OSM data due to active communities.

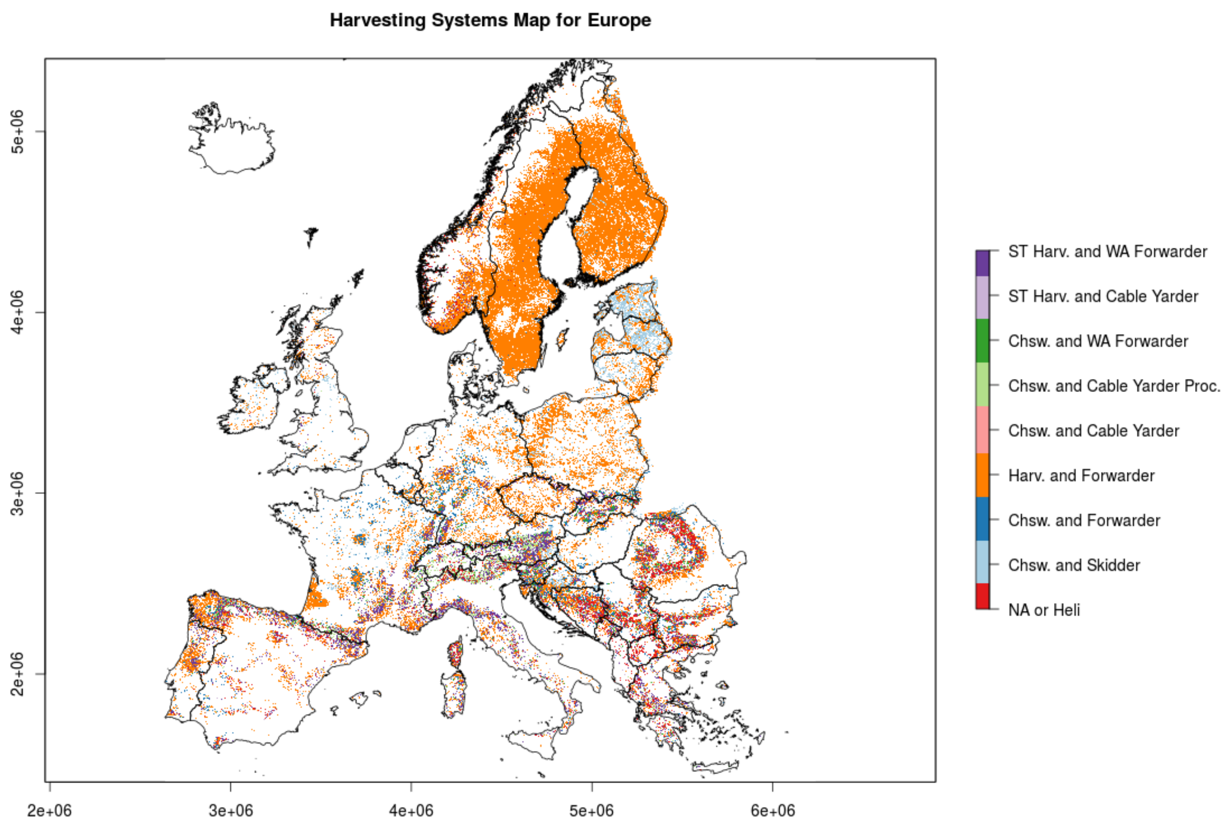


Figure 41. Harvesting Systems Map for Europe. The cell resolution is 500 m.

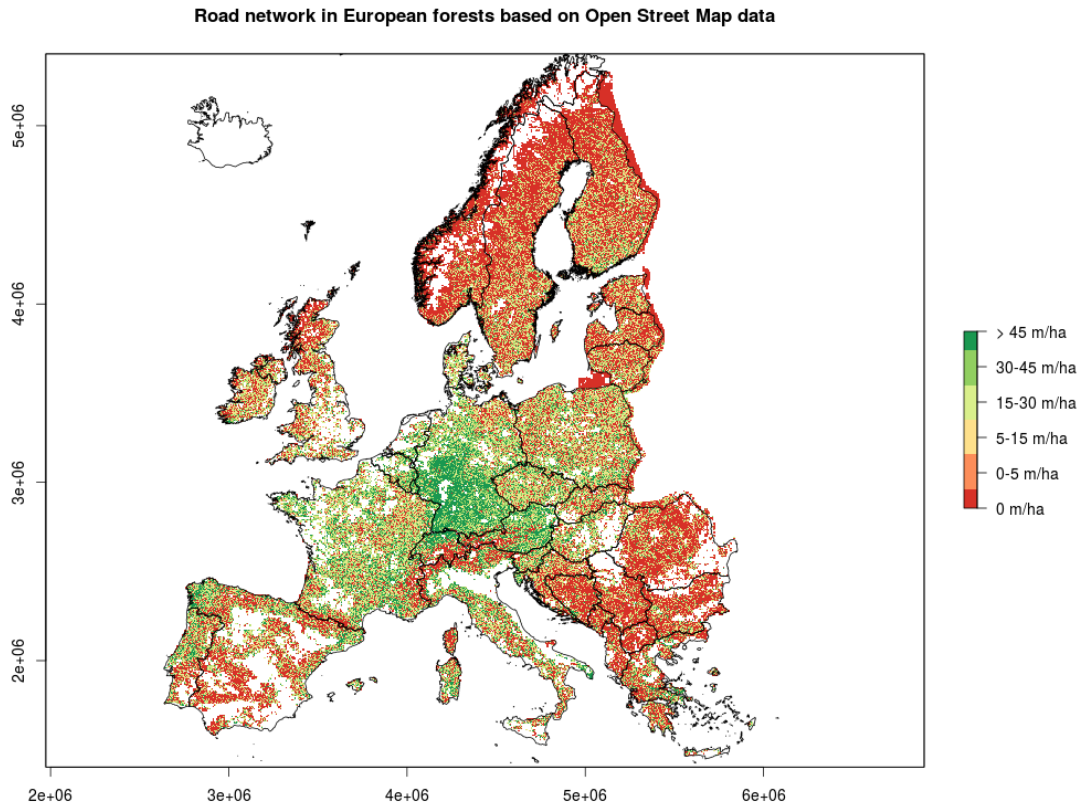


Figure 42. Road network in European based on Open Street Map data.

According to our calculations (only in steep terrain the extractiondistance is a limiting factor) around 8.3 % of timber is located in areas where no road is present at a distance suitable for operating winch-assisted or cable-yarding systems. These areas are not accessible or accessible only by helicopter. Great shares of these areas are located in the Carpathians and Dinarides (Fig. 34). Around 8 % of Europe's timber in flat terrain cannot be harvested by a harvester due to diameter limitations. Most of these areas lie in Northern France, Germany and South- and Central-East Europe (Fig. 34). Only 0.02 % of timber cannot be processed by the cable-yarder processor due to diameter limitations.

Around 8 % of the timber volume is stocking on flat sites where the soil limits the use of heavy machines. A great share of these areas can be found in the Baltic countries which are rich in wetlands. In Finland also wetlands can also be found, but they are extensively drained and in general they do not limit the use of heavier machines. Other areas of this type can be found on the British Isles, in Poland, Northern France, Croatia, southern Austria and the Benelux countries (Fig. 34). Under such conditions, the chainsaw and skidder system is an alternative. It should be noted that during very favourable seasons when the soil is very dry or frozen, forest operations using heavy machines might still be possible in these areas.

Validation

Validation was done at different scales. Six validation sites in four countries were used to compare the calculated results with the actual situation at the grid cell level. At coarser level (e.g. country-level) the results were validated by expert judgment on the plausibility of the results. First validation results showe that the share of winch-assisted or cable-yarding systems in steep terrain was underestimated. Based on these results the classification was updated to better reflect the actual situation. In general the validation results suggest that the calculations at the grid cell level show sufficient congruence with the actual situation.

There are, however, limitations, as could have been expected. In general, these limitations can be attributed to two factors: The resolution of the input data is too coarse for depicting particular features, or there is a lack of quality in the input data. For instance, the use of the harvester and forwarder system is often limited by obstacles like erosion channels, trenches and boulders, or by the slope and the ruggedness of the terrain. These features are either not present in the original digital elevation model, as their dimensions are below the 25 m resolution, or information is lost by aggregating to the 500 m grid cell size. Regarding soil information the accuracy of the European Soil Database in general is poor. Furthermore, the classification of soils as not being suited for the operation of heavy machinery used in this study is based mainly on the soil type, while other factors like soil texture may be the deciding factor at a given site. In addition, on some of the validation sites for which the map excludes the use of a harvester due to tree species specific DBH limits, actually a harvester is in use. This may be due to several reasons. As explained, we choose low tree specific DBH limits because we prefer to underestimate rather than to overestimate the felling and processing capacity of a harvester. And finally, for some cells detailed information on the involved tree species is lacking. If these cells are classified as a broadleaf forest we assume a tree species with strict diameter limitations, although in reality it could eventually be birch , which is a broadleaf type that is rather easier to handle.

Table 11. Forest Area per harvesting system in 1000 ha and %; HS1 = NA or Helicopter, HS2 = Chainsaw and Skidder, HS3 = Chainsaw and Forwarder, HS4 = Harvester and Forwarder, HS5 = Chainsaw and Cable Yarder, HS6 = Chainsaw and Cable Yarder Processor, HS7 = Chainsaw and Winch-assisted Forwarder, HS8 = Steep Terrain Harvester and Cable Yarder, HS9 = Steep Terrain Harvester and Winch-assisted Forwarder

	Available	HS1	%	HS2	%	HS3	%	HS4	%	HS5	%	HS6	%	HS7	%	HS8	%	HS9	%
Austria	3732.5	132.0	3.54	252.3	6.76	104.6	2.80	731.3	19.59	5.9	0.16	999.0	26.76	125.3	3.36	67.3	1.80	1314.9	35.23
Belgium	531.4	0.3	0.05	50.8	9.56	152.3	28.67	304.6	57.32	0.0	0.00	1.1	0.20	8.5	1.60	0.4	0.07	13.5	2.53
Bulgaria	3079.4	829.3	26.93	149.1	4.84	357.2	11.60	898.1	29.16	0.0	0.00	199.8	6.49	138.2	4.49	199.3	6.47	308.4	10.01
Croatia	2022.6	107.7	5.33	361.4	17.87	366.4	18.11	822.9	40.69	0.0	0.00	66.7	3.30	83.4	4.13	66.5	3.29	147.6	7.30
Czech Rep.	2440.0	5.7	0.23	29.3	1.20	94.3	3.86	1955.2	80.13	0.0	0.00	10.8	0.44	19.7	0.81	32.1	1.31	292.9	12.00
Denmark	207.6	0.0	0.00	12.1	5.83	32.1	15.48	163.3	78.68	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Estonia	2182.8	0.0	0.00	1516.7	69.48	0.0	0.00	666.1	30.51	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Finland	16394.1	2.4	0.01	212.4	1.30	113.6	0.69	16063.9	97.99	0.0	0.00	0.0	0.00	0.0	0.00	0.9	0.01	1.0	0.01
France	10101.8	443.3	4.39	720.2	7.13	1325.2	13.12	4690.6	46.43	4.8	0.05	687.0	6.80	268.9	2.66	369.1	3.65	1592.7	15.77
Germany	9036.1	28.1	0.31	734.0	8.12	1470.1	16.27	5459.4	60.42	0.1	0.00	156.9	1.74	326.9	3.62	19.1	0.21	841.5	9.31
Greece	2323.8	503.2	21.65	2.3	0.10	70.3	3.02	562.9	24.22	0.5	0.02	227.2	9.78	63.2	2.72	258.9	11.14	635.4	27.34
Hungary	1120.6	2.5	0.23	190.3	16.98	110.9	9.89	717.1	64.00	0.0	0.00	11.5	1.03	16.3	1.45	9.6	0.85	62.4	5.57
Ireland	609.0	10.2	1.67	225.3	36.99	15.0	2.46	327.1	53.71	0.0	0.00	4.0	0.65	1.1	0.18	7.4	1.22	19.0	3.12
Italy	5953.4	729.5	12.25	39.1	0.66	128.7	2.16	1250.7	21.01	3.0	0.05	1302.4	21.88	151.3	2.54	476.8	8.01	1871.8	31.44
Latvia	2974.1	0.0	0.00	1730.5	58.19	0.9	0.03	1242.7	41.78	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Lithuania	1806.0	0.0	0.00	645.0	35.71	18.1	1.00	1142.9	63.28	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Luxembourg	53.3	0.0	0.05	2.1	3.89	10.6	19.79	33.2	62.34	0.0	0.02	0.2	0.34	3.3	6.27	0.0	0.09	3.8	7.21
Montenegro	376.8	116.7	30.99	5.4	1.44	11.9	3.15	85.4	22.68	0.3	0.09	42.0	11.15	20.5	5.43	36.5	9.68	58.0	15.40
Netherlands	171.6	0.0	0.00	90.2	52.58	0.1	0.06	81.3	47.35	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
N. Macedonia	570.9	332.1	58.18	0.1	0.02	48.0	8.41	61.9	10.84	0.0	0.00	37.9	6.64	24.1	4.21	30.0	5.26	36.7	6.43
Norway	6906.7	830.9	12.03	231.4	3.35	5.5	0.08	4894.8	70.87	0.0	0.00	179.3	2.60	0.7	0.01	316.3	4.58	447.9	6.48
Poland	8356.3	44.7	0.54	995.3	11.91	341.9	4.09	6661.6	79.72	0.0	0.00	34.4	0.41	72.0	0.86	45.0	0.54	161.4	1.93
Portugal	1367.2	40.3	2.95	17.2	1.26	55.0	4.02	865.0	63.27	0.4	0.03	15.1	1.10	11.5	0.84	66.4	4.86	296.3	21.68
Romania	6582.1	2039.1	30.98	203.5	3.09	620.5	9.43	2043.2	31.04	0.0	0.00	476.4	7.24	299.7	4.55	384.3	5.84	515.4	7.83
Serbia	2171.2	797.7	36.74	72.0	3.32	321.0	14.79	445.9	20.54	0.0	0.00	142.5	6.56	125.3	5.77	115.0	5.30	151.8	6.99
Slovakia	1949.2	101.7	5.22	66.1	3.39	281.1	14.42	583.2	29.92	0.0	0.00	98.5	5.05	202.3	10.38	127.5	6.54	488.7	25.07
Slovenia	1132.8	43.3	3.82	39.2	3.46	182.4	16.10	313.4	27.67	0.0	0.00	144.8	12.78	111.2	9.82	44.7	3.95	253.7	22.40
Spain	6030.0	720.9	11.96	14.4	0.24	268.8	4.46	2493.2	41.35	5.5	0.09	407.0	6.75	160.2	2.66	491.9	8.16	1468.2	24.35
Sweden	21581.6	67.3	0.31	58.3	0.27	61.3	0.28	21333.3	98.85	0.0	0.00	0.4	0.00	0.0	0.00	32.7	0.15	28.2	0.13
Switzerland	1010.3	112.0	11.08	28.8	2.85	40.1	3.97	159.9	15.83	2.0	0.19	359.1	35.55	65.9	6.53	17.3	1.71	225.2	22.29
UK	1565.4	54.6	3.49	354.9	22.67	99.1	6.33	873.0	55.77	0.2	0.01	32.1	2.05	9.2	0.59	39.4	2.52	102.9	6.57

Table 12. Volume per Harvesting System in 10^6 m^3 and %;HS1 = NA or Helicopter, HS2 = Chainsaw and Skidder, HS3 = Chainsaw and Forwarder, HS4 = Harvester and Forwarder, HS5 = Chainsaw and Cable Yarder, HS6 = Chainsaw and Cable Yarder Processor, HS7 = Chainsaw and Winch-assisted Forwarder, HS8 = Steep Terrain Harvester and Cable Yarder, HS9 = Steep Terrain Harvester and Winch-assisted Forwarder

	Available	HS1	%	HS2	%	HS3	%	HS4	%	HS5	%	HS6	%	HS7	%	HS8	%	HS9	%
Austria	1187.9	40.6	3.42	83.6	7.04	33.6	2.83	229.9	19.35	2.9	0.24	321.6	27.07	41.3	3.47	20.9	1.76	413.6	34.82
Belgium	135.7	0.0	0.03	11.4	8.38	44.0	32.40	74.7	55.07	0.0	0.00	0.3	0.23	2.1	1.52	0.1	0.06	3.1	2.32
Bulgaria	970.1	271.7	28.00	42.1	4.34	143.5	14.80	237.7	24.50	0.0	0.00	72.6	7.48	59.0	6.08	56.3	5.81	87.2	8.98
Croatia	615.3	31.3	5.09	104.2	16.93	149.5	24.29	212.4	34.52	0.0	0.00	25.1	4.07	36.4	5.92	17.2	2.80	39.2	6.38
Czech Rep.	1230.3	3.1	0.26	13.4	1.09	50.2	4.08	981.7	79.80	0.0	0.00	5.1	0.42	10.3	0.84	16.9	1.38	149.4	12.14
Denmark	49.2	0.0	0.00	3.2	6.43	9.5	19.38	36.5	74.19	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Estonia	479.8	0.0	0.00	335.8	69.98	0.0	0.00	144.0	30.02	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Finland	2529.8	0.3	0.01	32.0	1.26	19.1	0.76	2478.2	97.96	0.0	0.00	0.0	0.00	0.0	0.00	0.1	0.00	0.1	0.01
France	1393.9	61.7	4.42	99.1	7.11	182.4	13.09	649.3	46.58	1.0	0.07	93.9	6.73	37.5	2.69	50.5	3.62	218.5	15.68
Germany	3079.8	10.0	0.33	220.8	7.17	516.1	16.76	1824.6	59.24	0.0	0.00	62.3	2.02	116.1	3.77	7.6	0.25	322.2	10.46
Greece	226.6	48.2	21.25	0.1	0.06	6.5	2.86	49.4	21.81	0.0	0.01	24.2	10.67	8.7	3.84	24.9	10.97	64.6	28.52
Hungary	354.7	0.8	0.23	57.7	16.28	40.5	11.41	221.8	62.53	0.0	0.00	3.9	1.11	6.0	1.69	3.1	0.87	20.9	5.88
Ireland	124.8	1.6	1.31	49.8	39.89	4.0	3.17	63.9	51.22	0.0	0.00	0.8	0.67	0.3	0.20	1.2	0.99	3.2	2.54
Italy	1015.8	135.1	13.30	6.5	0.64	28.1	2.77	152.1	14.97	1.0	0.10	285.5	28.11	37.5	3.69	68.8	6.78	301.2	29.65
Latvia	590.6	0.0	0.00	338.5	57.32	0.3	0.05	251.8	42.63	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Lithuania	378.6	0.0	0.00	138.6	36.61	3.6	0.94	236.5	62.46	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Luxembourg	18.0	0.0	0.05	0.5	2.58	4.3	23.97	10.4	57.54	0.0	0.03	0.1	0.50	1.5	8.44	0.0	0.12	1.2	6.76
Montenegro	95.0	31.7	33.33	0.3	0.34	3.5	3.72	18.1	19.04	0.1	0.12	12.2	12.82	7.5	7.87	8.3	8.71	13.3	14.05
Netherlands	34.9	0.0	0.00	17.9	51.39	0.0	0.09	16.9	48.53	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
N. Macedonia	164.0	96.6	58.93	0.0	0.02	18.4	11.24	12.8	7.83	0.0	0.00	11.9	7.27	9.1	5.58	6.8	4.14	8.2	5.00
Norway	800.3	79.9	9.99	28.8	3.60	1.4	0.17	585.8	73.19	0.0	0.00	19.4	2.42	0.2	0.02	34.0	4.25	50.9	6.35
Poland	2237.8	14.2	0.63	252.5	11.28	116.8	5.22	1752.3	78.30	0.0	0.00	11.6	0.52	24.6	1.10	13.8	0.62	52.0	2.32
Portugal	119.7	3.3	2.75	0.8	0.68	2.7	2.29	75.2	62.86	0.0	0.01	1.4	1.17	1.0	0.85	6.2	5.17	29.0	24.20
Romania	2261.3	778.9	34.44	57.2	2.53	260.7	11.53	560.3	24.78	0.0	0.00	193.3	8.55	130.4	5.77	120.5	5.33	160.0	7.08
Serbia	720.0	274.6	38.15	18.6	2.59	132.1	18.35	114.8	15.95	0.0	0.00	55.6	7.73	52.2	7.25	30.9	4.29	41.0	5.70
Slovakia	564.0	29.9	5.30	21.8	3.86	83.9	14.88	162.4	28.80	0.0	0.00	29.4	5.21	67.5	11.97	36.1	6.41	133.0	23.58
Slovenia	399.2	15.7	3.92	13.1	3.28	81.4	20.38	92.7	23.23	0.0	0.00	54.7	13.70	49.1	12.29	13.5	3.39	79.1	19.81
Spain	565.5	58.7	10.38	1.4	0.24	18.9	3.35	221.9	39.24	0.6	0.10	45.2	8.00	20.0	3.54	45.8	8.10	153.0	27.06
Sweden	3422.7	8.4	0.25	10.1	0.30	18.7	0.55	3376.7	98.66	0.0	0.00	0.1	0.00	0.0	0.00	4.6	0.14	4.1	0.12
Switzerland	240.3	28.8	12.00	6.3	2.61	10.6	4.42	35.4	14.71	0.8	0.34	86.0	35.80	18.6	7.72	4.0	1.67	49.8	20.71
UK	307.7	10.6	3.45	69.7	22.67	20.1	6.52	172.0	55.88	0.0	0.01	6.5	2.12	2.0	0.65	7.7	2.50	19.1	6.20

5.2. Up-scaling of Case Studies

5.2.1. Up-scaling

The developed harvesting systems map provides us with two informations that are essential for the upscaling of the case study results; the country-wise annual harvestable volume, and the regions where fully mechanized harvesting systems are applicable. The principle of how we do the upscaling is the following: For example, a case study has demonstrated an innovative practice in the context of the wood harvest, so first we quantify the benefits of new system in Euro/ha.Then we asess the timber volume that can be processed by the suggested technique, based on informations on the country-wise growing stock on the one hand, and the evaluation of the area where the suggested measure can be applied, on the other hand. Thus, by multiplying the savings per cubicmeter by the amount of removable volume, we calculate the total savings within a particular country and on European level.

The calculations are based upon the following assumptions, taken from Eurostat for the 28 EU countries during the years 2000 to 2010, and findings of this study: a) The percentage of the annual sustainable use of timber is 3% of growing stock b) the volume harvested in context of thinning amounts to one third of the total felling, and c) the volume removed in first thinning results to one third of total thinning.

Case studies involving harvesting systems

Five of the twelve case studies involve mechanised harvesting systems with harvester or forwarder. Finland´s case studies include two studies on the enhancement of mechanization, the Corridor Thinning and tending with Cutlink. Based on our map, almost all of Finland's forested area can be accessed by harvester and/or forwarder (Tab. 11). As a result of this study, in Finland around 16 million ha and 2 475 million m³ of timber can be accessed by a harvester (Tab. 11 and 12). This amounts to 98 % of forest area as well as timber volume. The annual harvestable volume amounts to 74 million m³ for forest areas accessible by harvester and forwarder system and to 75.9 million m³ in total. This is in line with the fellings reported by State of European Forests for the year 2010. The estimations of the Finnish National Forest Inventory (NFI 12 2014-2018, Forest resources statistics) for the maximum sustainable cut for the period 2015-2024 are slightly higher (84.28 million m³/year).

Corridor Thinning is limited to first thinning. Thus, according to the before mentioned assumptions in Finland the harvestable volume in 1st thinning amounts to 8 million m³ per year. Depending on the undergrowth in a forest stand Corridor Thinning leads to savings between 0.5 and 3 € per m³. Assuming a mean saving of 1.5 €/m³, this results in savings of around 12 million € per year. If this analysis is extended to all North European countries the annual harvestable volume in 1st thinning is 75 million m³. Assuming a mean saving of 1 €/m³ we arrive at savings of 75 million € per year.

The benefit of planting fast growing species on skid roads to increase the income of first thinnings was analysed by the Danish case study. In Denmark, around 163 thousand hectares and 36.5 million m³ of forests can be accessed by harvester and forwarder (Tab. 11). Around 123 thousand hectares of this forest area is dominated by Norway spruce. The study showed that, depending on the planting distance, biomass production can be increased by 60 tons per ha if hybrid larch is used for the skidding roads. This results in a biomass increase of 7.38 million tons for the Danish forests. Even if in Finland, Norway and Sweden the growth conditions are not suitable for hybrid larch, the case study also concluded that additional 18 tons of biomass production per ha can be achieved if Norway spruce is planted on skidding roads instead of leaving them empty. Using fast growing species suitable for the respective growing conditions the biomass increase would be even higher. However, it has to be noted that in the analysed scenarios, the higher productivity could not compensate for the additional costs.

In Central European countries tree marking by forester prior to thinning operations is a common practice. The Austrian case study showed that when harvester drivers have previously been trained in silvicultural practice, either explicitly or implicitly by executing the instructions of foresters over the years, the tree marking can be omitted. For Austria the National Forest Inventory recommends an annual use of 7.7 million m³ stem volume in context of thinning, which corresponds to 37 % of the total felling. Around one fifth of Austrian´s forest area can be accessed by a harvester. This means that out of the 7.7 million m³ approximately 1.5 million m³ could be thinned by harvesters. Assuming a high training level for all harvester drivers, tree marking can be omitted for these areas. Under the further assumption that experienced foresters on average are able to do tree marking for 150 m³ of stem volume per day, 10 000 workdays could be saved per year. With a salary of 136 € per day (17 €/hour) approximately 1.36 million € could be saved annually. Further 40 % of forest area in Austria can be accessed by steep terrain harvester. Tree selection in these areas can also be done by the harvester driver which leads to further potential savings. Yet, we have to keep in mind that many forests in steep terrain have protective purposes where commercial use is restricted.

Tree marking is practiced also in Poland as demonstrated by the questionnaire presented in Task 2.2. Around 6.66 million ha of forest and 1750 million m³ of timber in Poland can be accessed by harvester (Tab. 12). Again, assuming a 3 % portion for sustainable use, the annual total felling amounts to 52.5 million m³. Considering that one third of total felling should come from thinning, 17.5 million m³ in forests accessible by harvester need to be thinned annually. According to the assumptions in the Austrian case study, an experienced forest manager is able to tree mark 150 m³ per day, and therefore 116 000 days are needed. With a salary of 64 € per day in Poland (8 €/hour or 34 PLN/hour) 7.4 million € could be saved in case of omitting tree marking before thinning operation. This, however, assumes already trained harvester drivers. Thus, some of the savings may be in invested in educational programs for machine operators as established in Finland.

Case studies focussing on silvicultural practices regardless of harvesting system

A case study from Finland demonstrated that right-time tending generates a higher sawlog-yield and, depending on the assumed interest rate, a higher net present value. The share of sawlogs on the total harvesting is 56 % in case of right time tending, and 46 % if no tending is practiced. As mentioned above, according to the harvesting systems map the harvestable volume in Finland is 75.9 million m³ per year. This implies in theory a plus of 7.59 million m³ of sawlogs if right-time tending done.

A further case study from Finland was concerned with the effect of improved regeneration material and fertilization on medium-fertile upland forest sites for Norway spruce and Scots pine. According to NFI 12, 13 million hectares of the forests in Finland are dominated by Scots pine, with a growing stock of 1244 million m³, and 5 million hectares are dominated by Norway spruce, with a growing stock of 740 million m³. Likewise, the NFI 12 tells us that 40 % of Finland’s forests are located on medium fertile soils, which is 5.2 million hectares with a volume of 498 million m³ for Scots pine, and 2 million hectares with a volume of 296 million m³ for Scots pine. According to the findings of the case study improved regeneration material leads to a volume increase of 11.5 % for Scots pine and 13 % for Norway spruce. Hence the the added benefit is 57 million m³ and 38 million m³, respectively. By using N fertilization, the productivity can be further increased, up to 11 m³/ha for Scots pine and 25 m³/ha for Norway spruce. This results to an additional annual yield of 57.2 million m³ for Scots pine and 50 million m³ for Norway spruce.

6. Conclusions

The aim of the here presented research was to increase the access to wood resources in European forests, by concentrating on two aspects, i) the efficiency increase of silviculture and silvicultural operations, and ii) the development of business tools for an optimized interaction between the protagonists of forestry, the forest owners, the service providers for the wood production, and the customers. The method of fulfilling this aim in both regards consisted in a two-step approach, first the assessment of increase potentials, and second the evaluation of selected improvement options in the form of case studies. It was an additional task to upscale the suggested findings from regional to European-wide level, wherever possible.

For the identification of *increase potentials in silviculture* we started from collecting the current practices in European forestry by using a questionnaire survey. According to the questionnaire results, European forestry can be characterized by 6 key silvicultural systems: Age class forest, shelterwood, continuous cover forest, coppice, coppice with standard and short rotation forestry. These systems are implemented by 4 principal management systems: Clear cut, gap removal, single tree removal and shelterwood cuttings. The basic method for stand rejuvenation is the natural regeneration. Artificial regeneration in terms of plantation and seed dispersal is intended for completing the natural regeneration on the one hand and doing afforestation after clear cut on the other hand. The principal harvesting systems, including felling and yarding (and eventually processing the logs), are represented by harvester and forwarder, chainsaw and skidder/forwarder, chainsaw and cable yarder.

For the purpose of making transparent the differences in European forestry we used a very rough classification of European growth regions in terms of North, Central/Central East, West, South. This structure all in all corresponds to the classification given by *boreal, subcontinental/continental/alpine, atlantic, mediterranean* (Geiger, R. 1954: Klassifikation der Klimate nach W. Köppen. In: Landolt-Börnstein Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, Band 3, Berlin.)

As a pattern in European forestry, the answers collected by the questionnaire suggest that there is a gradient from North via Central/Central East and West to South, apparently constituted by the available tree species in each of these regions. In the North the number of tree species is limited, with a dominance of conifers (Norway spruce, pine). The prevalent silvicultural system is age class forest with clear cut, regeneration to large extent is established by planting, the harvesting is mostly done by fully mechanized harvester – forwarder technique. Rotation periods are short, and thinnings are rare. Along the delineated gradient the number of tree species increases, both in terms of conifers (Norway spruce, pine, fir, larch…), as well as broadleaves (beech, oak, hornbeam, chestnut…), silvicultural systems and management strategies in use are numerous, rejuvenation shifts from artificial to natural, in age class forest, continuous cover forest and shelterwood the rotation periods are extended and thinnings are a business as usual. The prevalent harvesting systems are chainsaw with skidder/forwarder and chainsaw with cable yarder. To some extent, silviculture in North is less complicated, but the mechanization of harvesting operations is highly developed. Along the described gradient, the silviculture becomes more complicated, but the degree of mechanization is reduced. In the latter context, the challenge for an intensification of fully mechanized harvesting systems (harvester – forwarder technique) is twofold, first resulting from the fact that several broadleaves are included, and second from the steepness in the montaineous territories, especially the alpine region.

Based on this interpretation of the questionnaire feedback and very generally speaking, two main increase potentials for European forestry were identified: A promotion of thinning, with a focus on the growth region North, and an enhancement of mechanization, with focus on Central East, the alpine region and South. As a third increase potential relevant for all the growth regions, early stand management operations were identified. In a next step, the following case studies for the elaboration of improvement options were carried out: *Promotion of thinning:* The first study investigated the effect of thinning on the volume production of stands. It showed that the zero variant (no thinning) only at low yield classes is clearly superior to all the tested thinning variants. At increasing yield-class the superiority of the zero variant decreases, and on very productive sites, thinned stands become more productive than un-thinned stands. A further study emphasised the importance of the timing of cleaning and tending in seedling stands. Time of intervention controls diameter growth and therefore has a noticeable impact on both, the development and the profitability of a stand. A delay of only few years might cause considerable losses in both regards. Further two studies dealt with the adjustment of thinning methods, by taking in account the previous measures taken in a particular stand. In stands with rich undergrowth and high stand density, selective thinning is cost- and time intensive.Under such conditions boom corridor thinning (BCT) is a reasonable alternative, as an accomplished case study demonstrated. A a significant advantage of BCT is the reduction of boom movements compared with selective thinning. Therefore, BCT makes the thinning in young dense stands more profitable. A further advantage is that a great part of the undergrowth remains in the stand and thereby vertical complexity and biodiversity are higher than after selective thinning. In stands that have been prepared sufficiently, whether in the form of wider spacing at stand establishment, or in the form of intensive tending, selective thinning is more advisable. A study related to this topic demonstrated that there are savings potentials for thinnings consisting in two work steps, the treemarking by forest manager and the harvester operation. The study demonstrated that well trained and experienced harvester drivers achieve a high compliance with the forest managers prescriptions concerning tree selection, so that the tree marking as extra workstep can be omitted.

Enhancement of mechanization: A first study in this context aimed at intensifying the tending activities by adopting the Cutlink device, which is a fully mechanized system for tending. The study demonstrated that on a technical level the device already runs very smoothly. A further argument that favours this technique over the motor manual tending is the possible labour shortage during high season for silvicultural work. A further study strived for enhancing the mechanization of final harvest in coppice management. This is a highly relevant topic for European forestry, since coppice comprises 16% of the European forested land. The benefits of the mechanization in this context are: Reduction of the fatalities by factor 4, reduction of harvesting costs, increase of wood supply, reduction of wildfire risks, and last but not least beneficial consequences for environmental and cultural values. Another study aimed at discovering the limiting factors for the application of harvesters in thinning operations. As an essential obstacle the study identified some organizational background. It is a traditional contract system, established and continued by a powerful market participant such as state forests, which offers no incentives for the private entrepreneurs to rationalise their work.

Early operations: The fundamental question for the first here conducted research was, what is the effect of the use of improved regeneration material in combination with N- fertilization, respecting different environmental conditions and assuming various climate change scenarios? Results of process-based forest ecosystem simulations suggested that, in the context Norway spruce and Scots pine on mesic upland forest sites under middle boreal conditions, such a combination leads to an increase of total forest yield (up to 28%) of the proportion of saw logs, to earlier commercial thinning and a shortening of the rotation length. A second study evaluated the idea of the so-called power cultures, where a fast-growing tree species such as Hybrid larch, is planted on future skidding trails in a stand established for the production of quality timber, such as Norway spruce. The net present as key indicator for the meaningfulness of this method appears to be ambivalent, since it highly depends on the assumptions for discount rate, costs and prizes. Still this measure is promising, if the savings for clearing on the one hand, and the positive effects on the quality of the remaining trees on the other hand, are taken in account. A final study was carried out in the context of Maritime pine monoculture plantations, evaluating the financial effects of the stump removal as a measure to prevent phytosanitary uncertainties due to *Heterobasidion annosum* and *Hylobius abietis* after clear-cut. Beside the reduction of phytosanitary threats, according to the study this method delivers the benefits of an additional wood biomass supply, a reduction of the subsequent site preparation costs, and a shortening of the rotation length. Yet, it is recognized that environmental impacts of this procedure still remain to be researched in long-term investigations.

For the upscaling of the findings as to silvicultural innovations and mechanization of silvicultural operations, a harvestings systems map for Europe was generated, including information on the extension of forested area, not accessible conservation areas, tree species distribution, stocking volume, steepness of terrain, soil qualities, and forest road net. The up-scaling is a theoretical exercise which is based on our available data and includes the uncertainty of the data, limitations and simplifications. The reported savings and earnings or areas of application have thus to be interpreted with care. Nevertheless, it is clear that by implementing the measurements suggested in the realized case studies, there is high potential for promoting the full mechanization of harvesting operations and thus for making forest operations more efficient and profitable. For silvicultural treatments where appropriate mechanized tools are yet to evolve, as is the case for the mechanized tending device, the potential area of application should encourage further development.

For the purpose of *developing business tools* for an optimized interaction between the protagonists of the forestry work chain, two case studies were conducted. The Finnish case study compared between the case “Online IT platform” and the case “traditional direct offer inquiry”. The key finding of this study is that the presented simplified model applying an online IT platform required less process interactions than the traditional direct inquiry alternative. The current design of the Finnish tool can be considered as an optimal design of a service tool when compared to a common traditional offer inquiry. By adapting technology and service according to their own needs, other regions could benefit from this role model. The Norwegian case study provided generalized business process maps for purchase and production planning in a Norwegian farm forestry context, with special focus on long-term forest management agreements. The key finding is that such agreements ultimately provide the potential to stabilize wood purchase in a hot domestic market, to increase the planning horizons and to reduce purchase lead times for initial contact with the forest owner. This can be particularly useful in a context of periodic deviations in demand, production or operating conditions.

To sum up, in eight out of twelve case studies in the context of silvicultural improvement options, Norway spruce is the main tree species, and age class forest is the practised management form. In addition, six studies are concerned with tending and thinning. Hence, we consider that a central message of our research consists in doing tending and thinning in Norway spruce age class forests more intensively, more properly and more cost-effectively. Furthermore, it is highly advisable to use online business tools for the interaction between forest owners and providers of forest management services. This might be an effective way for the wood mobilization in the forests of small-scale forest owners all over Europe.

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