Knowledge and Technologies for Effective Wood Procurement

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REPORT ON POTENTIAL FOR EFFICIENCY INCREASE IN SILVICULTURE

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1 Publishable summary

Silvicultural practices are applied to modify forest conditions and to meet the pre-defined goals of forest owners and/or other stakeholders. They have a strong regional focus driven by the species distribution, local forest management and forest-based industry tradition, policy constraints and forest ownership structure. The most productive silvicultural systems (eg. age class forest, continuous cover forest, shelterwood forest, coppice, coppice with standard, forest with exclusively commercial purposes ("short rotation" and "plantations")) have been identified and evaluated in this work. For these silvicultural systems, key regional management options have been selected for their potential to enhance the productivity of European forests.

In this report we describe 10 case studies in seven partner countries. The following groups were revealed:

1.) Mechanization in harvesting operations (three case studies),

2.) Tending and thinning practices (four case studies)

3.) More appropriate methods in early operations and stand establishment (three case studies).

In the course of our research, by examining increase potentials for European silviculture, we have identified two key themes: early operations (establishment methods, species mixes, stand densities, using improved regeneration material, fertilization) on the one hand, and tending/thinning on the other hand. Based on the case studies, we consider that one of the principal increase potentials for European forestry is to implement tending and thinning in conifer age-class forests more intensively, more properly and more cost-effectively. In addition, we have a second focus on early operations, in which context we have presented very innovative and versatile suggestions. One additional study on coppice, addressing an essential increase potential for forestry in the South-West European countries, completes the range of our investigations. Furthermore, the enhancement of mechanization in forestry in Europe has been seen as a necessary measure to improve the cost-efficiency and safety at work.

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2 Introduction

2.1 The role of task 2

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 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. 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 ten case studies in a total. In the course of the generation of the case studies three 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).

Two of the four 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 ten 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. The objective of Task 2.3 is to elaborate a method in order to assess the impact of the suggested measures on a larger scale. This way the results from the case studies, which have local validity, will be upscaled to European level.

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3 Results of case studies

3.1 Enhancing mechanization

3.1.1 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 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. 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 road sides. 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. The productivity, fuel consumption and quality of seedling stands after early pre-commercial thinning were measured.

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Figure 1 Motor-manual tending and mechanized tending 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 2). 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 amount 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, Sandtröm 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 PCT after uprooting is prevented.

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

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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.

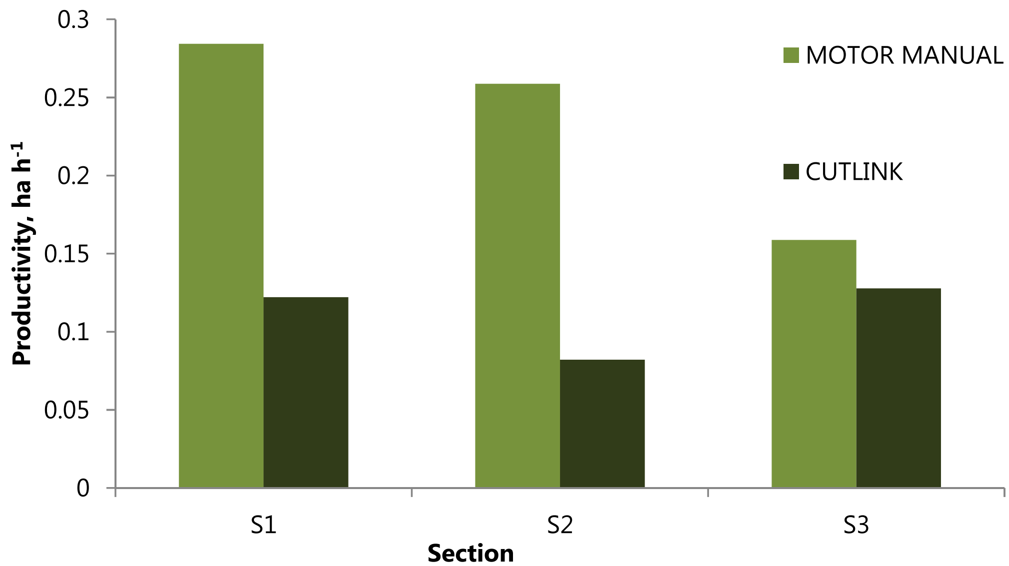

Figure 2 Productivity (ha h^{-1}) of motor-manual tending and Cutlink device in average of each section.

Routa, J., Nuutinen, Y. and Asikainen, A. 2019. Productivity of mechanizing early tending in spruce seedling stand. CROJFE, doi: https://doi.org/10.5552/crojfe.2020.619.

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3.1.2 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 3 An overview of the study area.

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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 4 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 by a factor 4, 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 3Mi 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!

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

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3.1.3 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 uncluding: stand structure (e.g. age, species structure and site tipes defined in the Table 1), 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 1. 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 exception of larch (2 stands only), manual harvesting dominates (Figure 6). Moreover, the largest share (nearly 25%) of mechanized harvesting, has been recorded for Scots pine. Interestingly, deciduous tree species (birch, beech) were

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in some cases also felled with harvesters. The share of mechanized harvesting for these tree species was about 7%

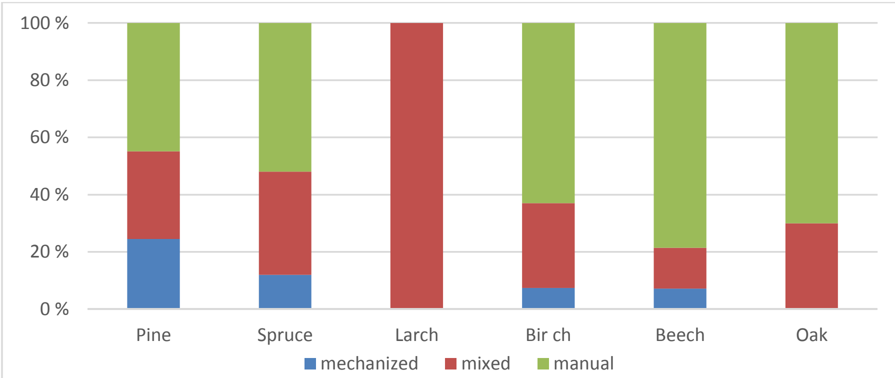

Figure 6 Share of analysed harvesting methods in relations to tree species.

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 7).

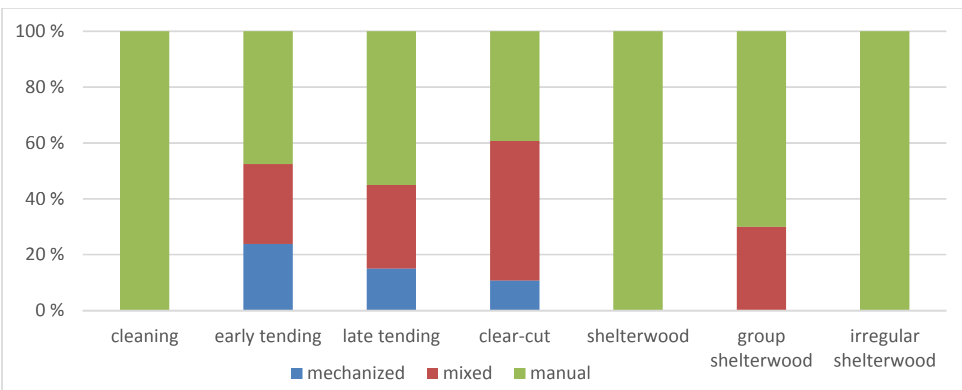

Figure 7 Share (%) of all types of harvesting achieved in 2018 according to analysed types of fellings.

Considering all analysed felling methods from the site type point of view, manual harvesting is present in all site types (Figure 8). 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).

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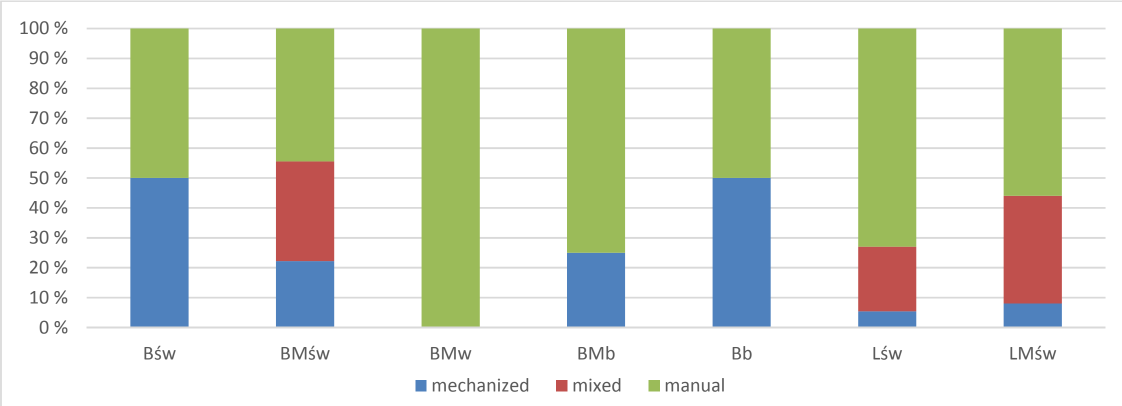

Figure 8 Types of felling according to site types.

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/1m^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.

3.1.3.1 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.

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The last question concerned factors limiting mechanized harvesting. The respondents indicated seven factors of different origin (Figure 9). 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%).

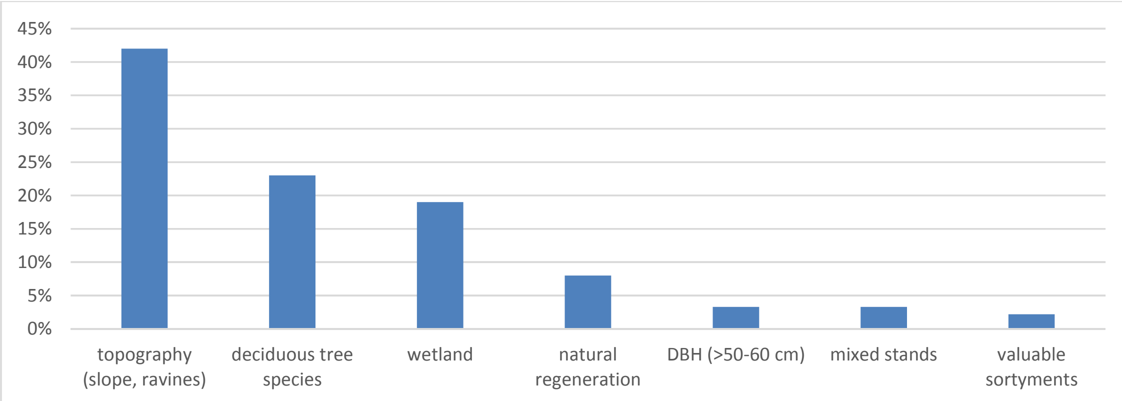

Figure 9 Factors limiting mechanised harvesting

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.

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3.2 Intensifying tending and thinning practices

3.2.1 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.

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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 10):

- 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 sylvesteris L.), age 24 years, with little undergrowth

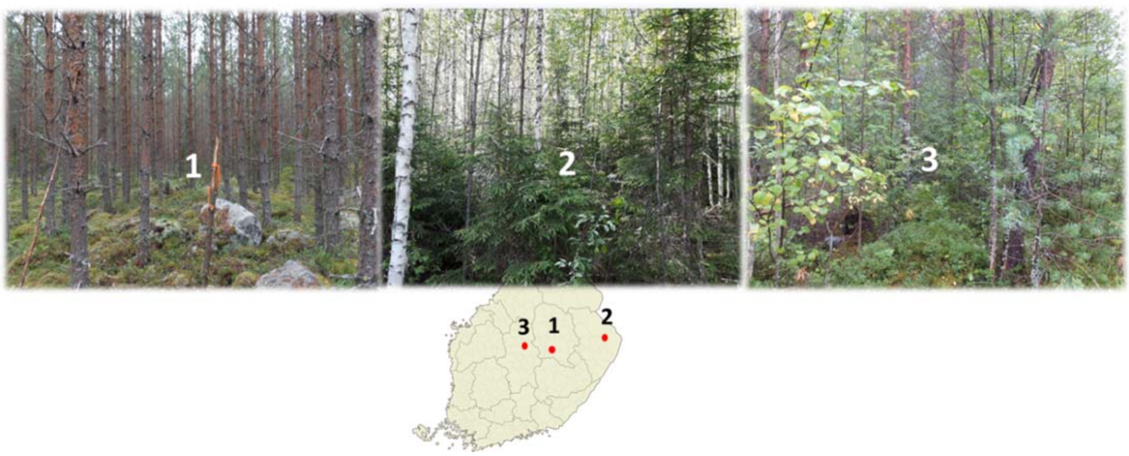

Figure 10 Study stands.

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 11). 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).

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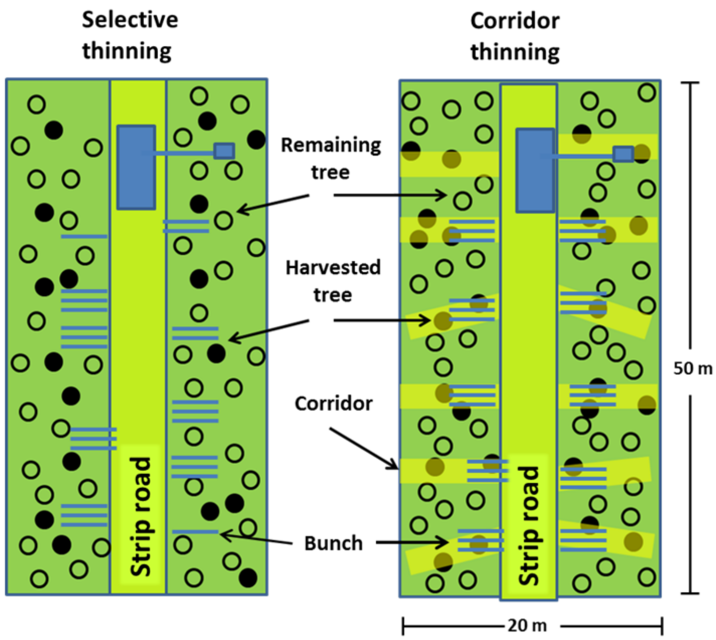

Figure 11 Schematic description of the plot of operator-based corridor thinning and selective thinning methods used in the treatment plots.

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 respectively 7% higher in stand 3 % 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 12).

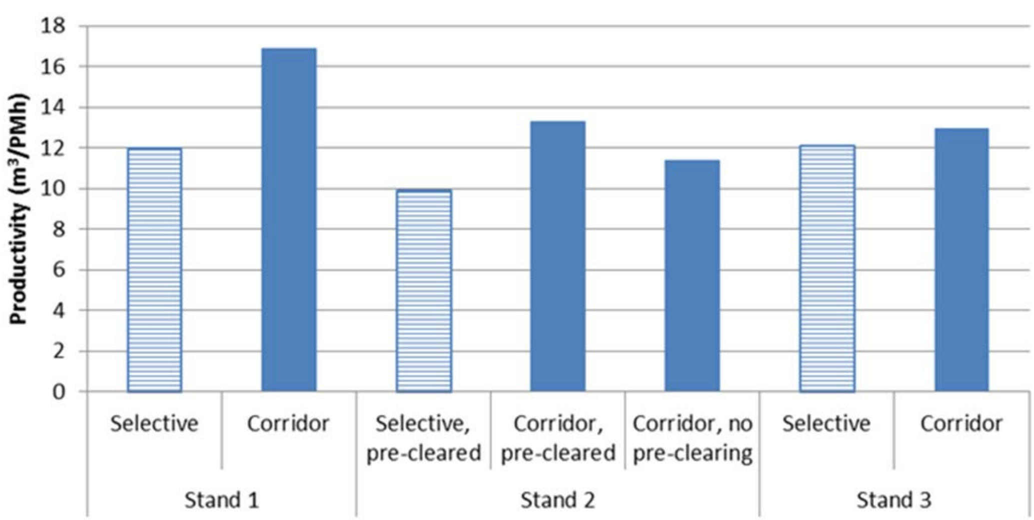

Figure 12 Productivity of thinning treatments in the three different study stands.

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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 13).

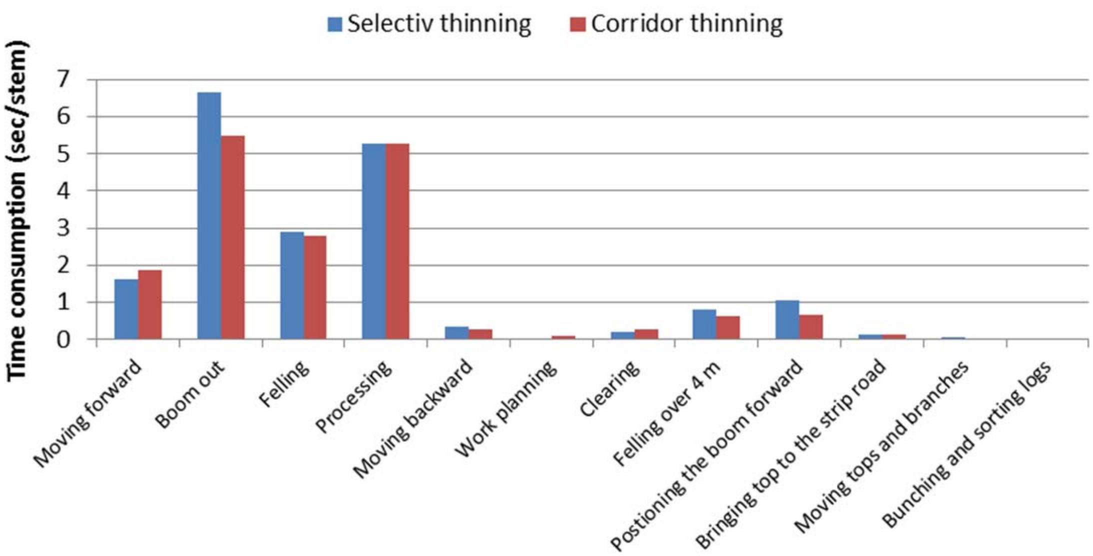

Figure 13 Average time consumption structure of work elements of effective work time (E_0h) in stand 1.

In Figure 14, 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%).

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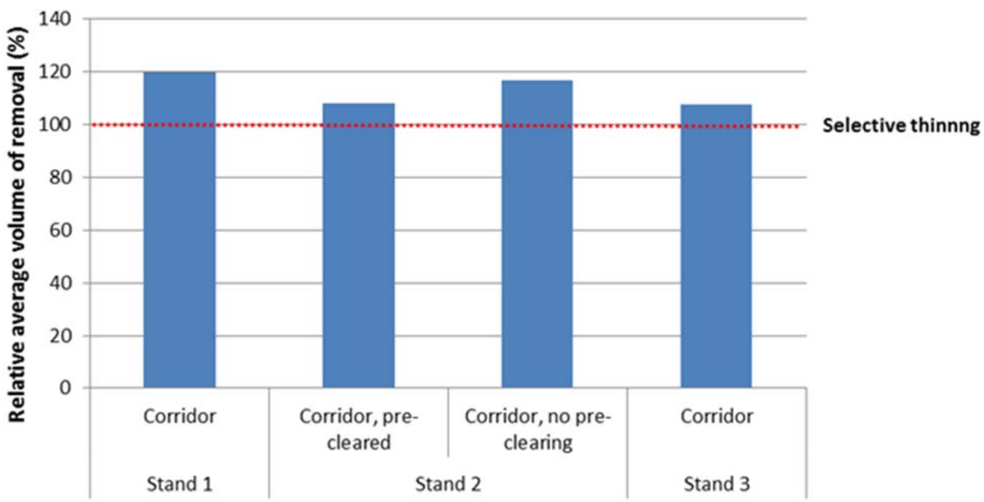

Figure 14 Relative volumes of harvested trees per treatments in stand 1, 2, and 3.

In our study, the CT method was developed in three different working environments: no under growth, 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.

Nuutinen ,Y, Miina, J., Saksa, T. , Bergström, D. and Routa, J. Comparing the characteristics of boom-corridor and selective thinned stands of Scots pine and birch. Manuscript.

Bergström, D. Nuutinen ,Y and Routa, J. Time study, productivity, cost in conifer stands incl. forwarding Manuscript.

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3.2.2 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 15). 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 16). 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.

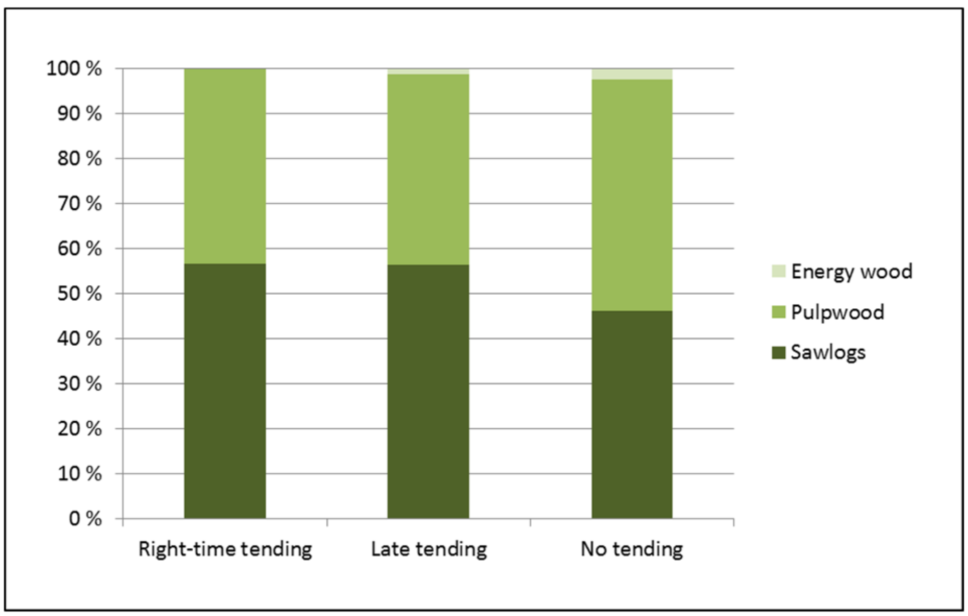

Figure 15 Structure of harvesting removals (%) in different 100-year scenarios.

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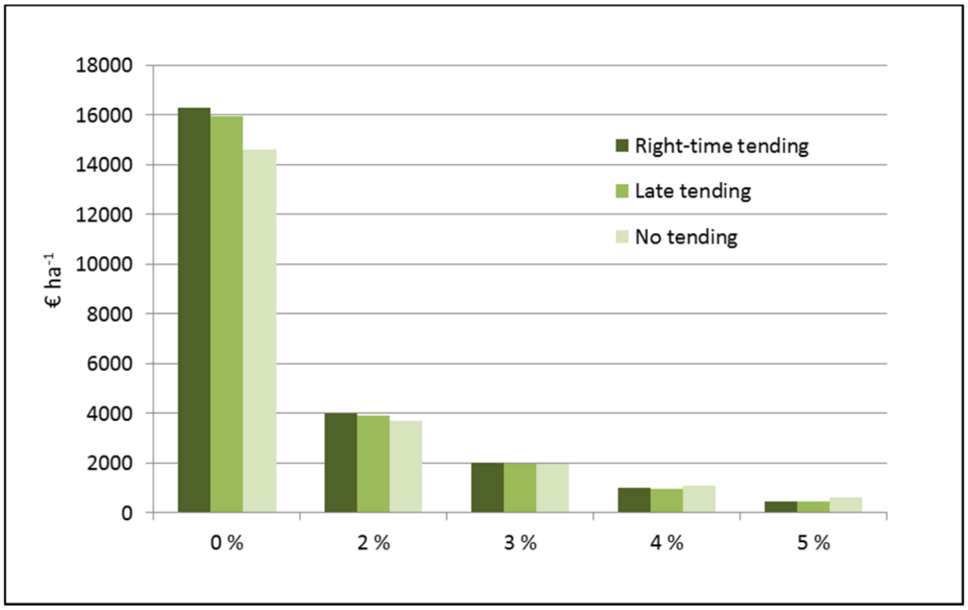

Figure 16 Average net present value (€ ha^{-1}) from 100 year period in different scenarios.

Kojola, S., Routa, J., Huuskonen, S., Hynynen, J. Effects of tending to forest total production. Manuscript.

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3.2.3 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).

Therefore, 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 17).

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Figure 17 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.

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 m^3. 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.

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 results 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?

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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 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, they 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 18.

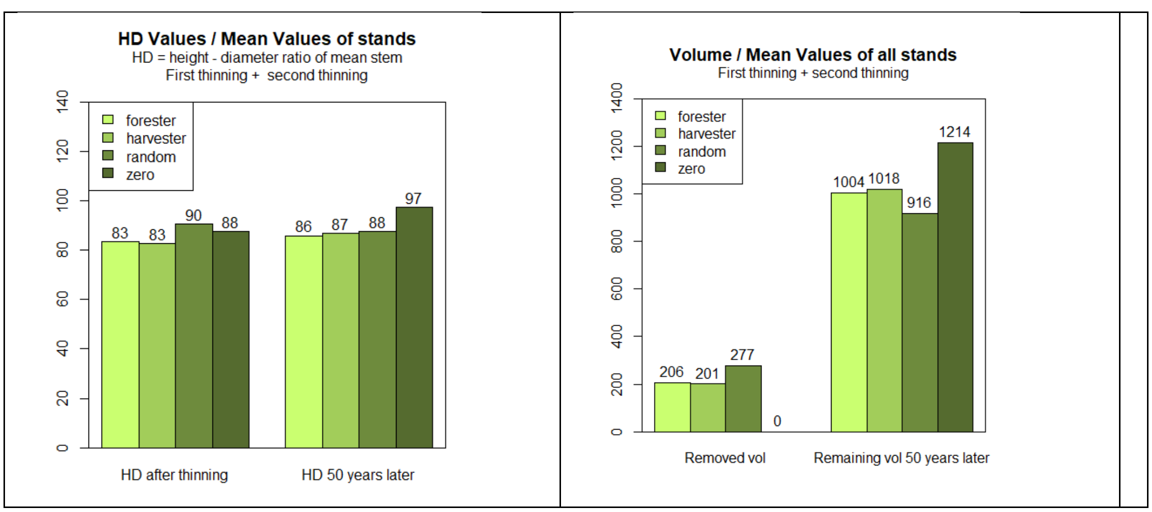

Figure 18 HD-values and stem volume of the stands after the 4 listed thinning variants, with view on stands with first thinning and stands with second thinning together. The numbers represent mean values of the 8 stands. Left hand: HD-values of the remaining trees immediately after the thinning, and 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

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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.

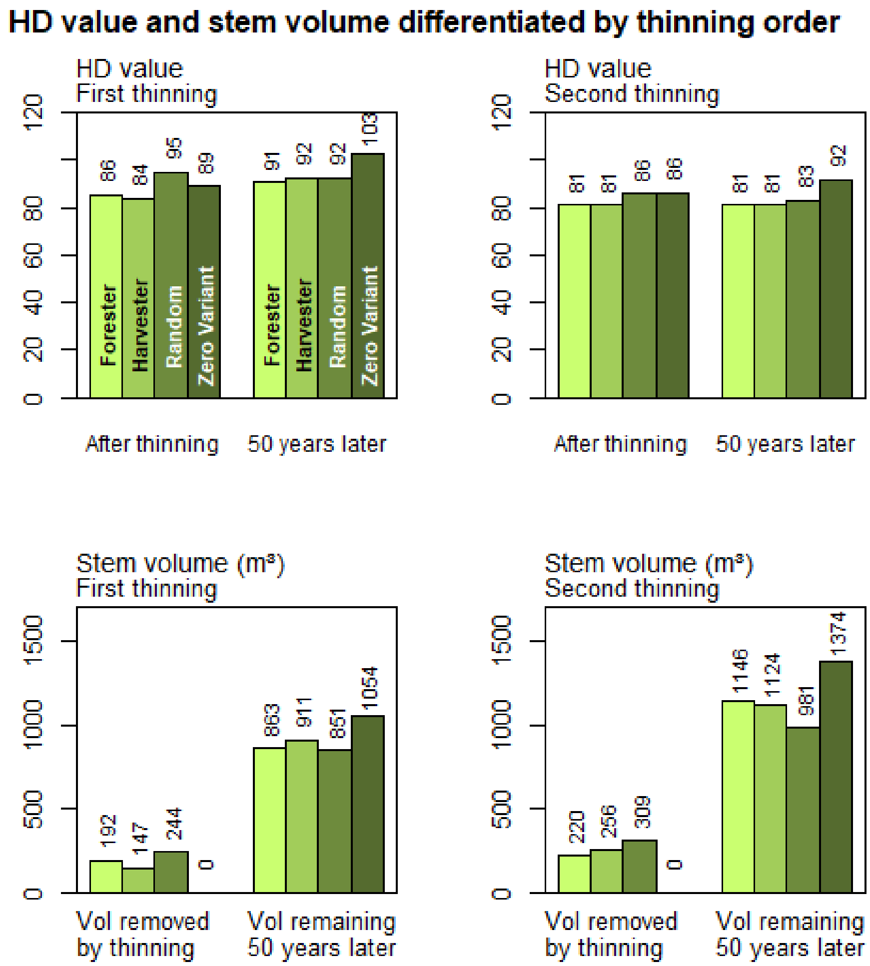

Figure 19 HD-values and stem volume of the stands after the 4 listed thinning variants, stands with first thinning and stands with second thinning considered separately. The numbers represent mean values of the 4 stands respectively. Top: HD-values after thinning and after 50 years, after first thinning (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 18) 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 19) 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

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forester (220 m³). Again, the removal of random thinning is the highest in both cases (244 m³ and 309 m³ respectively). The result in productivity after 50 years (Figure 18 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.

) is also very balanced for forester (1004 m³) and harvester (1018 m³), the productivity after random thinning is clearly lower (916 m³), the zero variant is far the most productive variant (1214 m³). 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 19, 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

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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.

3.2.4 Case study Norway - Production 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 effect 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 2). A description of these trials are provided in Braastad and Tveite (2001).

Table 2. 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

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		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:

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

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:

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

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

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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 3). Simulated thinnings were performed based on the representative thinnings in the data used for model fitting (Table 2) 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 3. 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

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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 20).

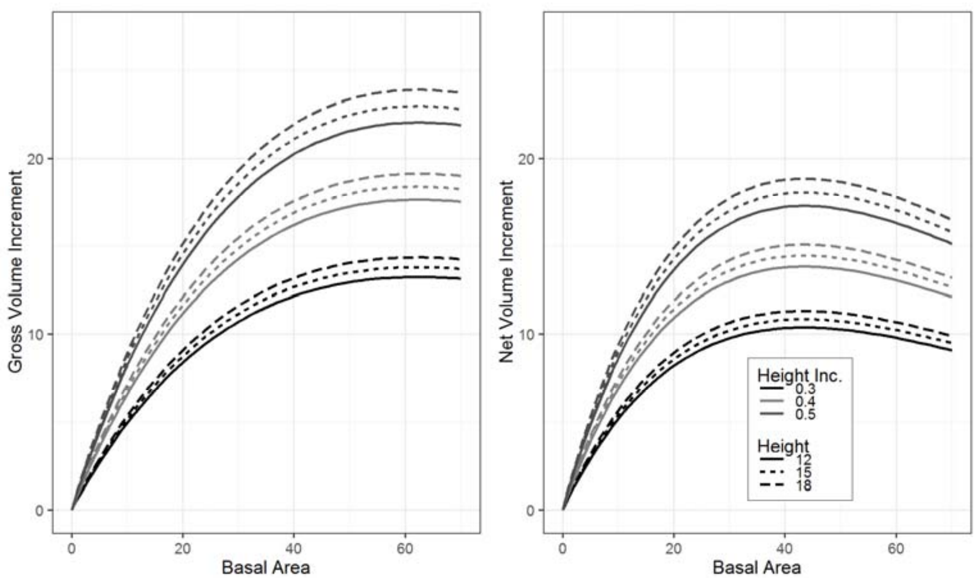

Figure 20 Implied relationship between gross or net volume periodic annual increment (m^3 ha^{-1} yr^{-1}) and basal area (m^2 ha^{-1}) based on equation (1) when stand height (m) and height increment (m yr^{-1}) are held constant.

The response of basal area development to thinning was highly dependent on site productivity (Figure 21). 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 20) the effects of thinning on basal area development can have a large effect on total volume production depending on the rotation length.

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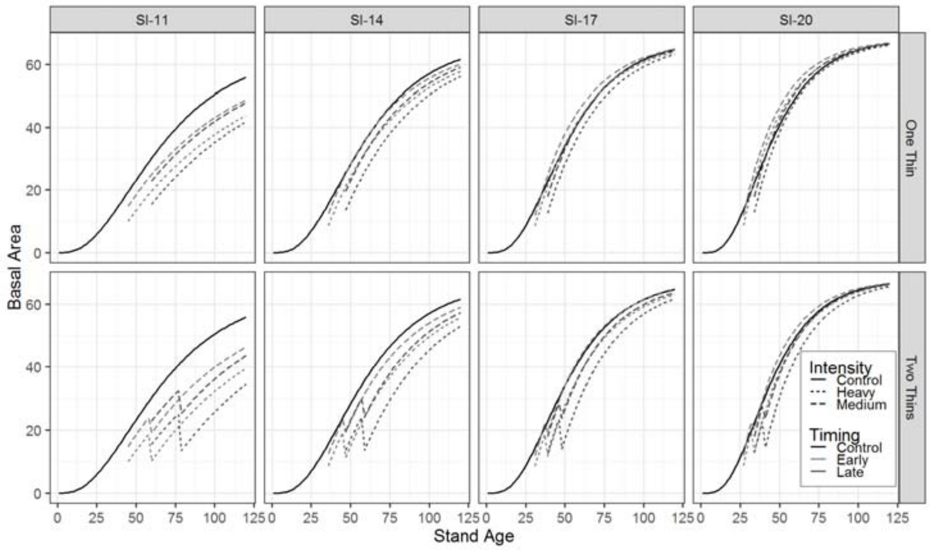

Figure 21 Basal area development of simulated unthinned and once or twice thinned stands. Thinning treatments are described with intensity as light (25% basal area reduction) or heavy (50% basal area reduction) and with timing as early (1st thin at 12m height) or late (1st thin at 16m height).

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 3, regardless of site index class (Figure 22). 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.

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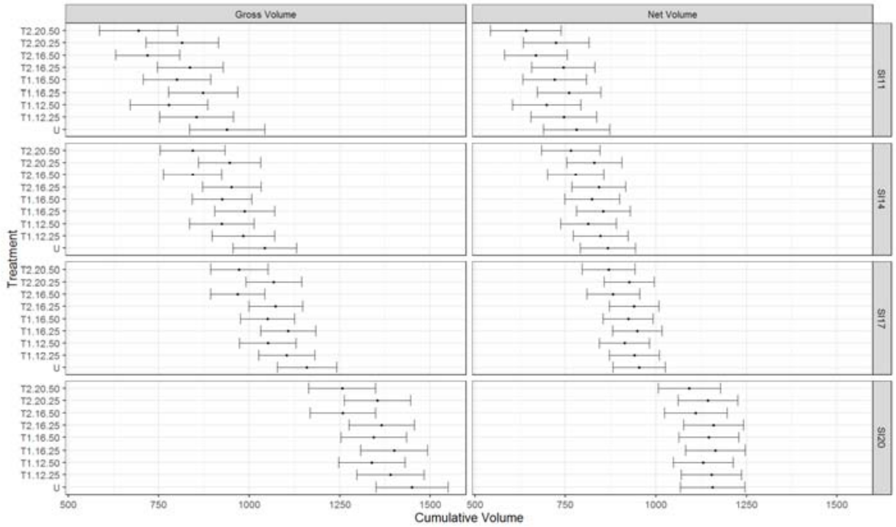

Figure 22 Means and 95% confidence intervals of cumulative gross and net volume over the simulated rotation period from a Monte-Carlo analysis of the nine thinning treatments presented in Table 3.

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3.3 Measures for early treatment and stand establishment

3.3.1 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

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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

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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

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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.

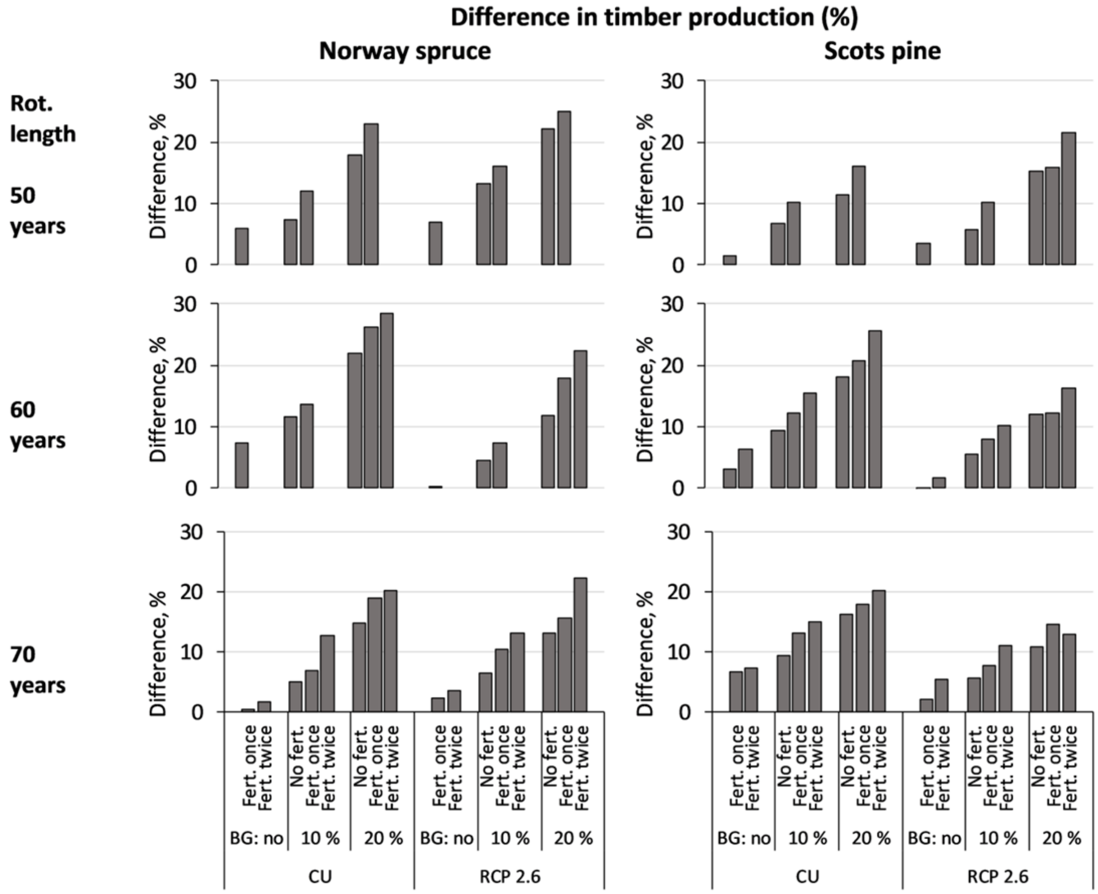

Figure 23 Effects of fertilization and improved regeneration materials on annual timber production (m3 ha^{-1} a^{-1}) as a difference (%) from baseline management, with rotation lengths of 50, 60 and 70 years under the current (CU) and changing (RPC2.6) climate in Norway spruce and Scots pine.

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 2019, https://doi.org/10.1093/forestry/cpz043

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3.3.2 Case study Denmark - Power cultures; fast growing species on skid roads

Niels Strange and Karsten Raae

Power cultures; fast growing species on skid roads

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

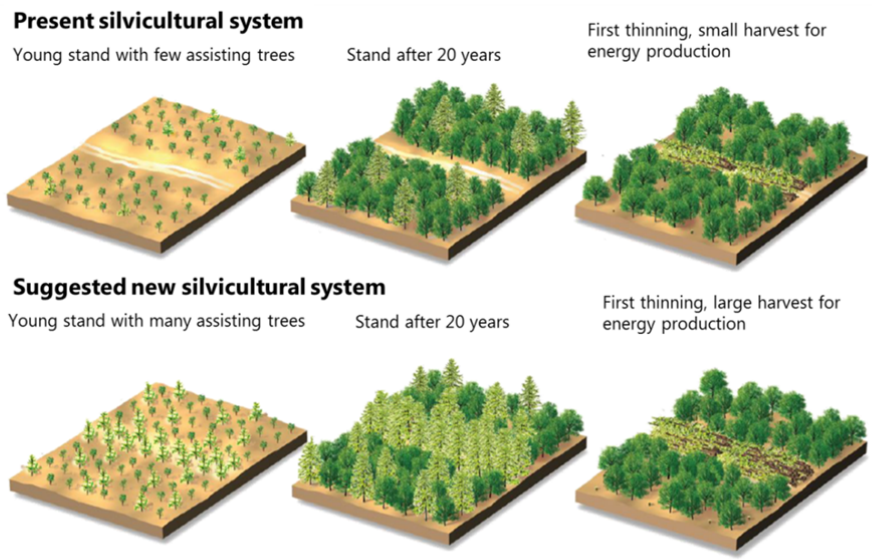

Figure 24 Presentation of the suggested new silvicultural system (so-called power cultures) and a silvicultural system with prepared skidding roads.

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

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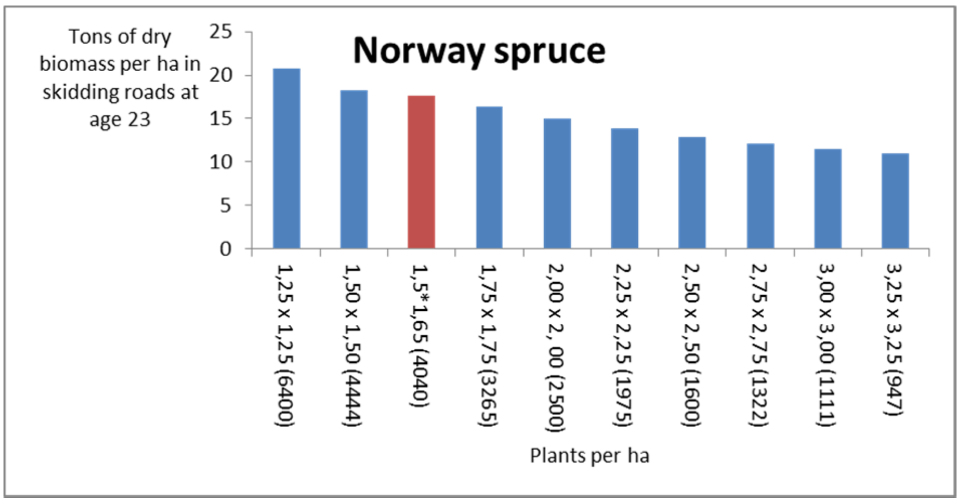
same way and develop along the same pattern. The planting distances presented above are based on current practice.

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. 2 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.

Achievement of goals / Future practice

A.



B.

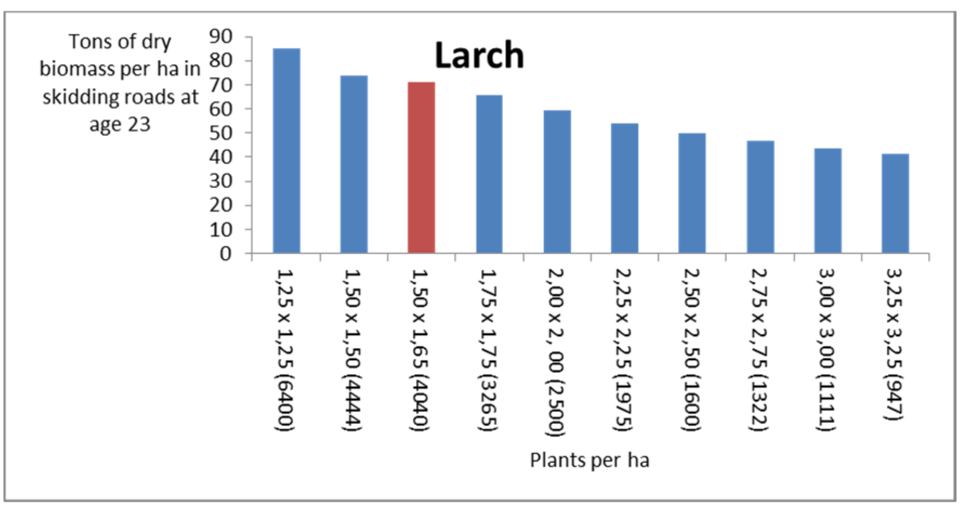


Figure 25 The biomass production of Norway spruce (A) and Hybrid Larch (b) in skidding roads covering 20% of the area. First axis shows the number of plants per ha and in parentheses the number of plants per ha skidding roads. The assumed reference for spacing distances in current

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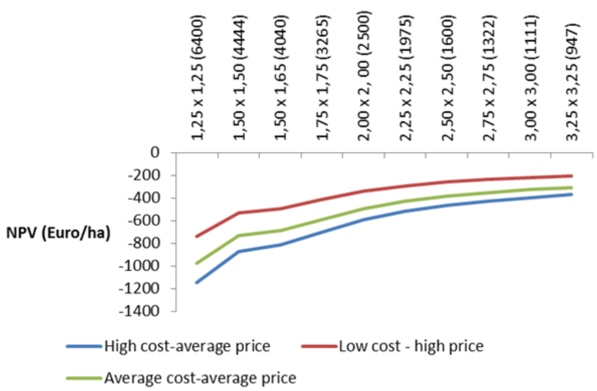
practice is marked with red columns.

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 26). 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

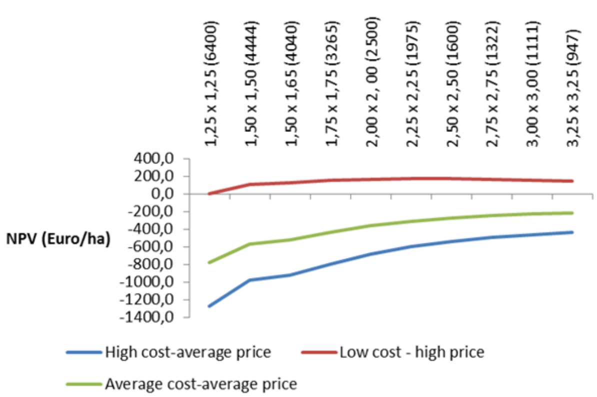


Figure 26 Net present value at various planting densities and cost and price scenarios for Norway spruce (A) and hybrid larch (B) assuming a 2 per cent discount rate.

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We estimated the net present value of planting Norway spruce respectively hybrid larch in the skidding trails at a range of discount rates (Figure 27). 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.

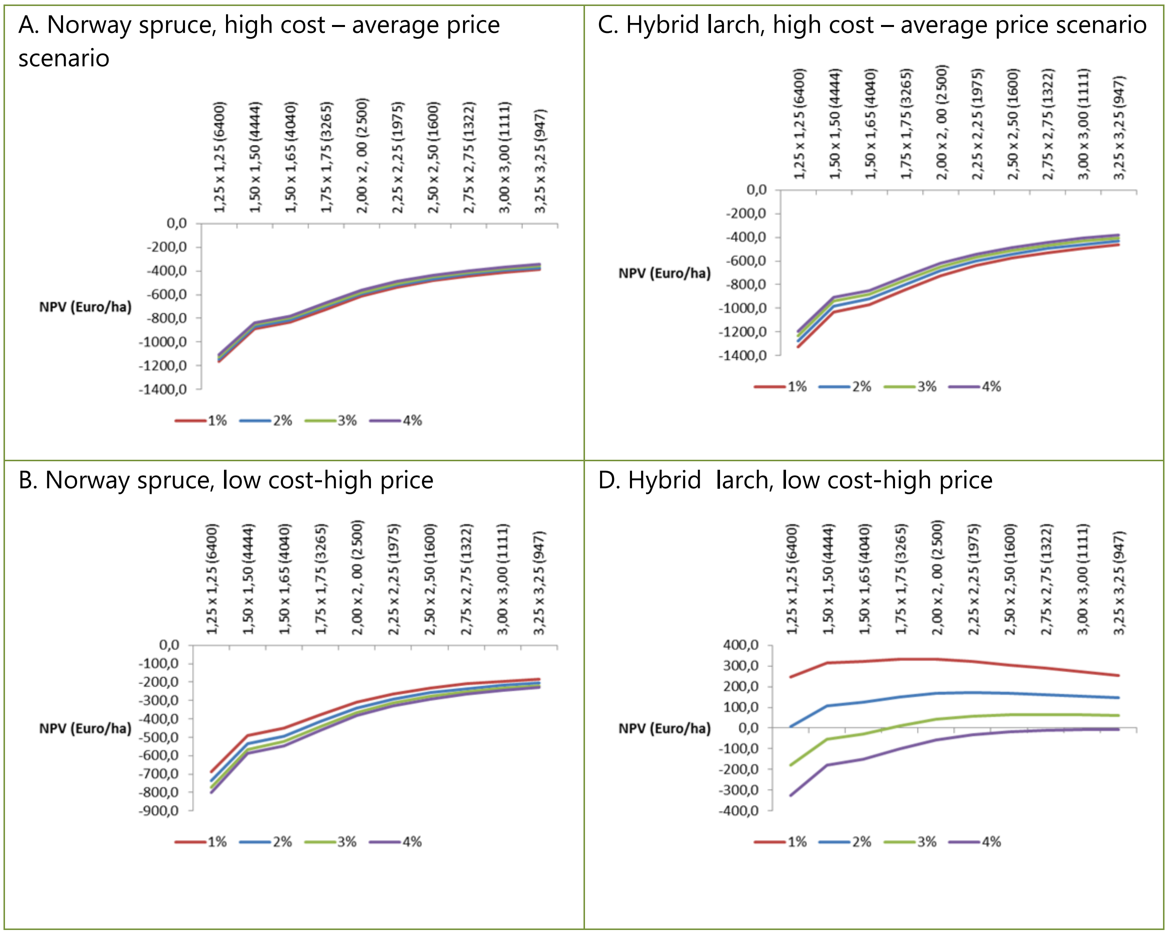

Figure 27 Net present value at various planting densities and cost and price scenarios for Norway spruce (A+B) and hybrid larch (C+D). We assumed high cost – average price scenario in A and C, and a low cost-high price scenario in B and D.

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.

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Figure 27 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 28) 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.

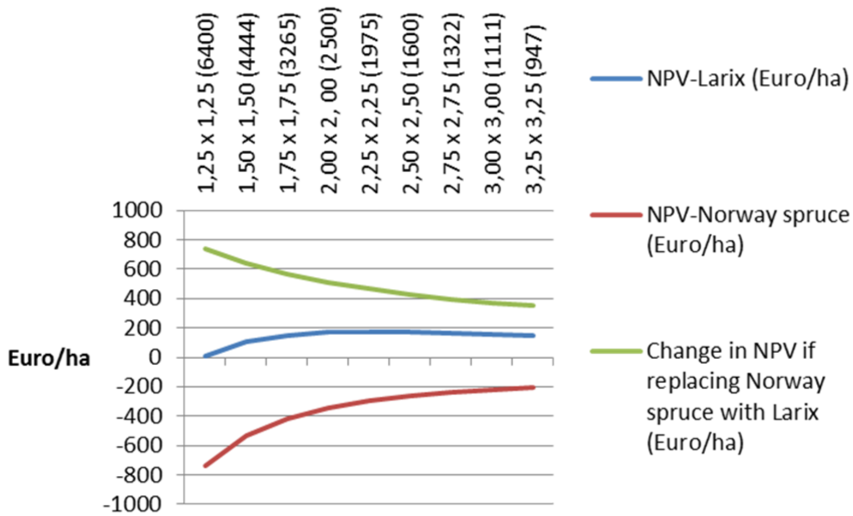

Figure 28 The estimated change in net present value (NPV) and production of dry biomass by replacing Norway spruce with hybrid larch in the skidding roads. Assuming low cost- high price scenario and a discount rate at 2 per cent.

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 man power 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.

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3.3.3 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 m3 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

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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

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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 29 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%).

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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.

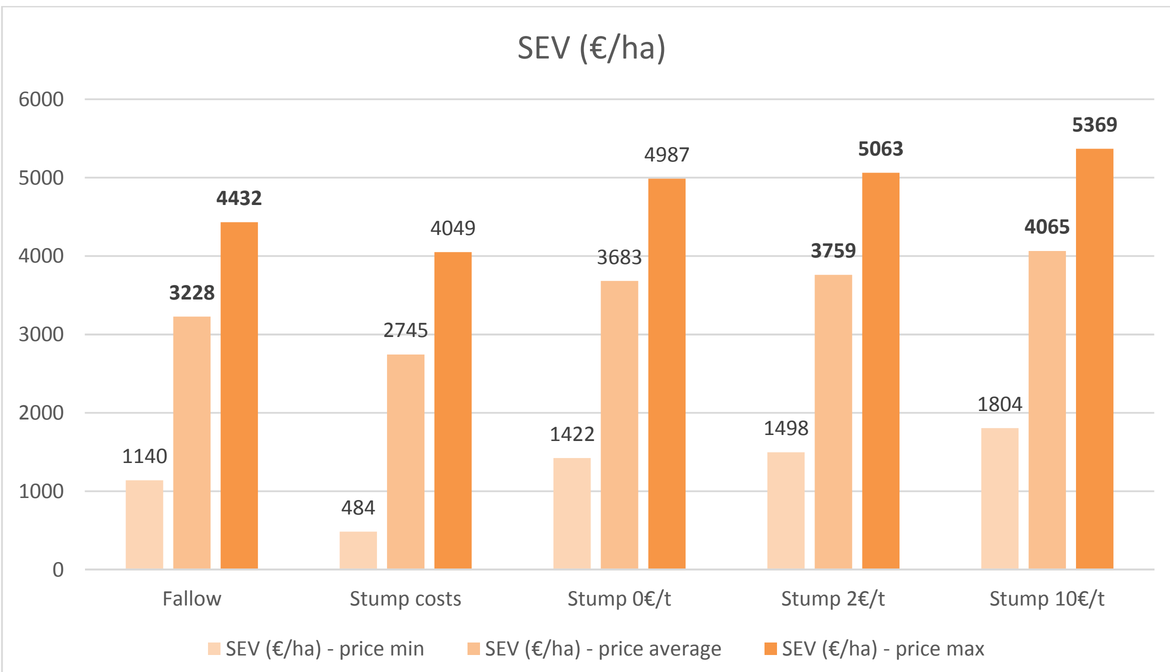

Figure 29 Sensitivity analysis of financial performance in terms of SEV (€/ha, discount rate 3%) from different economic scenarios of stump extraction of a maritime pine stand in the French Landes, compared with the conventional stand preparation practice of fallow period after clearcut.

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).

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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).

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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.

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4 Conclusions

In the course of our research, by elaborating increase potentials for European silviculture, we have identified two key themes: early operations on the one hand, and tending/thinning on the other hand. In addition, the enhancement of mechanization in forestry in Europe has been seen as a necessary measure to improve the cost-efficiency and safety at forest work.

As to the issue of the early operations, three case studies were conducted. A first study evaluates 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. Although the study reveals that the net present value under the tested scenarios is largely negative, it also states that this result is highly dependent on the assumptions for discount rate, costs and prizes. Still this measure is highly 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.

Another study deals with the effects of intensified early silvicultural treatments. Previous experimental trials have demonstrated that both the use of improved regeneration material as well as N-fertilization can increase the timber production noticeably. Yet the interesting question is: what is the effect of a combination of such measures, respecting different environmental conditions and assuming various climate change scenarios? Thus, the special approach of the study consists in process-based forest ecosystem simulations. The results are valid for Norway spruce and Scots pine on mesic upland forest sites under middle boreal conditions. The study shows that a combination of intensified silvicultural measures, such as appropriate thinning, improved plant material and N-fertilization, leads to an increase of total forest yield, an increase of the proportion of saw logs, to earlier commercial thinning and a shortening of the rotation length. Each of the measures per se produces positive effects, but a combination of better plant material and N-fertilization is the best performing variant, increasing the timber yield up to 28%. Under minor climate change scenarios the suggested measures even have the higher impact.

A final study in connection with early operations was carried out in the context of intensive plantations forestry, which includes highly mechanized silviculture on monoculture plantations of fast growing tree species that pursues mainly economic objectives. One major risk in the management of such monocultures results from phytosanitary uncertainties, especially due to the risk of infection by *Heterobasidion annosum* and *Hylobius abietis*. The traditional countermeasure consists in leaving the stand for a fallow period of 2-3 years after clearcut. The study evaluates the financial effects of an alternative measure, the removal of stumps after clear-cut, in comparison with the conventional practice. This study focuses on the specific case of the maritime pine plantations of the Landes region in France, considering a context of favorable conditions for stump extraction. Beside the reduction of phytosanitary threats, 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. By taking into account all of these beneficial effects, the suggested method is remarkably superior to the traditional variant from a techno-economical point of view. In terms of the soil expectation value (SEV)

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and under the current economical conditions favouring the stump extraction without extra cost for the forest owner, the superiority amounts up to 13-58%, depending on the assumed price scenario for timber and stump wood biomass. However, the study also recognises that the environmental impacts of this method, such as effects on carbon balance, soil nutrient balance and biodiversity, still remain to be researched in long-term investigations. While the sustainable development of this technique may largely differ beyond the favourable specificities of this case study, its applicability and profitability in different contexts will also depend on the specific technical, economic, and environmental conditions. Besides early operations, another fruitful starting point for our case studies was the observation that we have numerous forest stands in Europe where necessary tending as well as thinning have been omitted. In order to clarify this issue and to make suggestions for improvement, we have conducted six case studies. These studies pursue two objectives, an improvement of the concepts for tending/thinning on the one hand, and an enhanced mechanization of tending and thinning operations on the other hand.

The first study aims at intensifying the tending activities by adopting the Cutlink device, which is a fully mechanized system for tending. Although it suggests that the motor manual tending still is superior to fully mechanized tending with the Cutlink device, in terms of productivity as well as quality, it also states that on a technical level the device already runs very smoothly, without any work interruptions. Furthermore, it has been observed that the superiority of the motor manual variant decreases with an increasing duration of the operations. A further argument that favours the mechanized tending is the labour shortage due to the highly seasonal character of silvicultural work. According to the results of the study, the main challenge for an improvement of the work with Cutlink device is the efficiency increase in cutting small seedlings, and the appropriate training of the operators.

A further study in this context emphasises 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. The study points out that a delay of only few years might cause considerable losses in both regards. It is extremely important to increase the knowledge about the importance of early cleaning and precommercial thinning among forest owners.

Here follow the case studies that examine the improvement of thinning activities. A first study investigates the effect of thinning on the volume production of stands. Based on a large dataset of observations, in a first step a model is created that calculates the annual volume increment according to the height, the height increment and the basal area of a stand. The basal area is the key explanatory variable of the model, since it is sensitive to the various thinning scenarios, including different numbers, different schedules and different intensities of thinning. An application of the model shows that the zero variant (no thinning) at low yield classes is superior to all the tested thinning variants. That means it generates the highest basal area and consequently the highest volume. Hence we might conclude that the main purpose of thinning is not an increase of productivity, but an improvement of quality. Yet, at an increasing yield class the superiority of the zero variant decreases, and on very productive sites, some thinning variants are even slightly superior. Thus, the study also clearly shows

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that thinning makes sense especially in good stands. Besides that we have no productivity losses, quality as well as stability of the remaining trees after thinning are much higher.

Further two studies aim at simplifying thinning methods, with the purpose of making thinnings more profitable. The question about which thinning method should be applied to a particular stand can only be answered by knowing the preparation and the history of the stand. In stands where no tending or insufficient tending or late tending had occurred, stem density is normally high. Under such circumstances, a selective thinning requires intensive pre-clearing, which is cost- and work-intensive. Moreover, a stand under these conditions is not prepared for selective thinning, that intervenes in the top layer of the stand and aims at removing also the thicker trees, because the remaining trees are not stable enough.

Under such conditions, boom corridor thinning (BCT) is the most appropriate alternative than the selective thinning. According to study, a significant advantage of BCT is that the number of boom movements are reduced, an advantage that increases with stem density. The study clearly shows that in stands with rich undergrowth the advantages of BCT over selective thinning become much more visible than in stands with less undergrowth. Therefore, BCT makes the thinning in young dense stands more profitable. Existing growth losses compared with selective thinning are negligible. 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, trees are stable enough to tolerate a stronger opening-up. In this case, selective thinning is more advisable. Our study demonstrates that there are savings potentials for thinnings that include the following two work steps: treemarking by forest manager and harvester operation. The study figures out that a thinning conducted without any thinning expertise, (represented by random thinning in the study), generates stands that are less productive and remarkably less stable than stands after treemarking by a professional. That means that on the one hand tree marking is a useful practice, but on the other hand, it does not necessarily have to be carried out by a forest manager, who marks the trees in advance. The study demonstrates that harvester drivers, provided that they are well trained in silvicultural thinking, achieve a high compliance with the forest managers prescriptions concerning tree selection. As a result these stands are as stable as stands after tree marking by a forester, while work, productivity is slightly superior.
A final study in this context aims at discovering the limiting factors for the application of harvesters in thinning operations. Apart from the commonly reported obstacles such as topography, tree species composition and insufficient soil bearing capacity (water content), the study identifies some organizational background as being responsible for the situation. 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.

A last study with regard to the promotion of mechanization of harvesting operations highlights that coppice management is a noticeable segment in European forestry, since we are talking about 16% of the European forested land. First results of the study are very promising and support the thesis that

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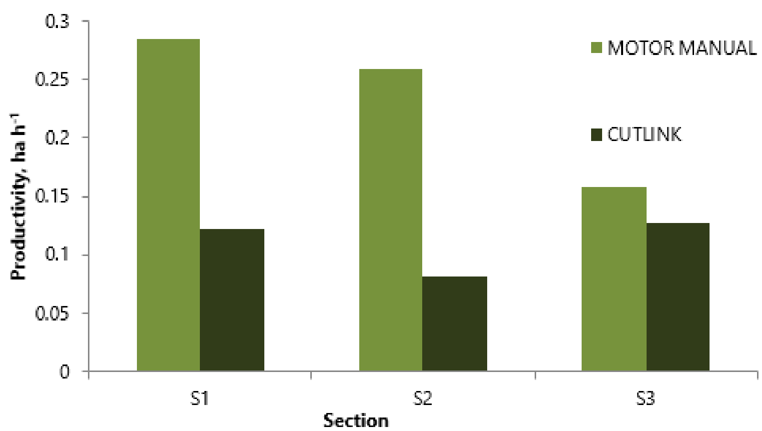
mechanized harvesting has no negative effects on the stumps. The benefits are striking: Reduction of the fatalities by factor 4, reduction of harvesting costs, increase of wood supply, reduction of wildfire risks, and last but not least beneficial consequences for environmental and cultural values.

A summary of the 10 described case studies is available in the following section, including main results, strengths (+) and weaknesses (-) of the tested measures, and outstanding research issues (?).

Enhance mechanization

Case study Finland

Tending with Cutlink device



Productivity (ha h-1) of motor-manual tending and Cutlink device in average of each section.

Routa, J., Nuutinen, Y. and Asikainen,A. 2019.Productivity in Mechanizing Early Tending in Spruce Seedling Stands. CROJFE, doi: https://doi.org/10.5552/crojfe.2020.619

−	In terms of productivity (ha/h) motor manual is superior to Cutlink	+	The superiority of motor manual decreases with duration increase It helps out in labour shortage (highly seasonal character of silvicultural work).	?	Appropriate training of the operators

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Case study Italy

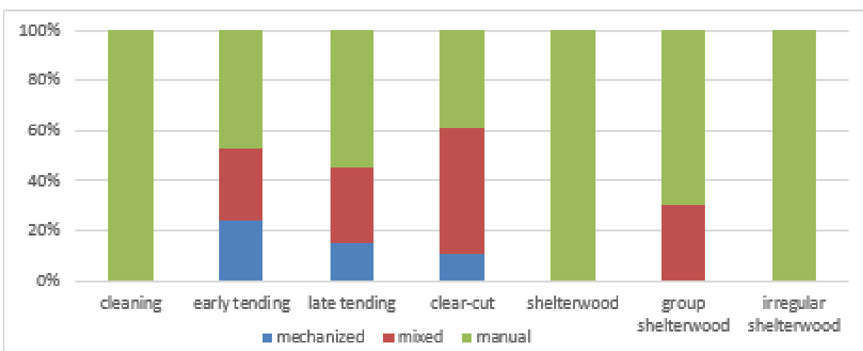
Mechanized harvesting in coppice with standard

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

➕
- Reduction of fatalities
- Reduction of harvesting costs
- Increase of wood supply
- Reduction of wildfire risks
- Environmental and cultural values

Case study Poland

Mechanization of thinnings in conifer forests



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

➖ Limiting factors for the use of harvesters:
Topography, tree species composition, soil bearing capacity..., traditional contract system, established by State forests

➕ Lot of potential for mechanized harvesting operations

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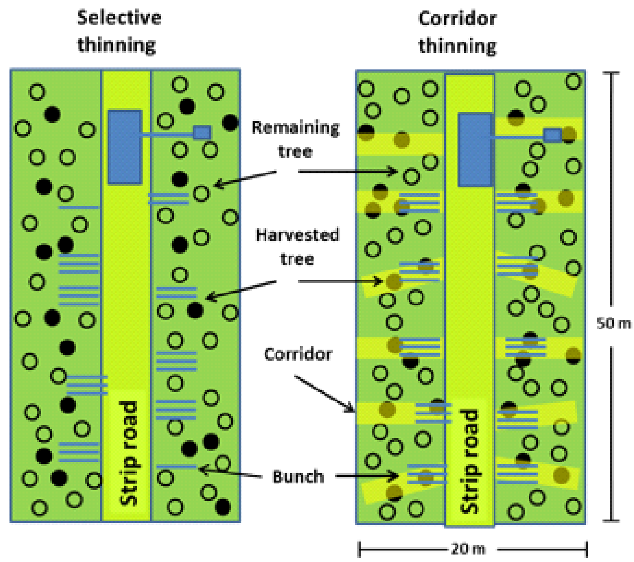
Intensifying tending and thinning practices

Case study Finland

Corridor thinning



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

+ Superior to selective thinning in stands with rich undergrowth.
  Reduction of boom movements.
  More undergrowth remains in stand -> benefits for biodiversity...

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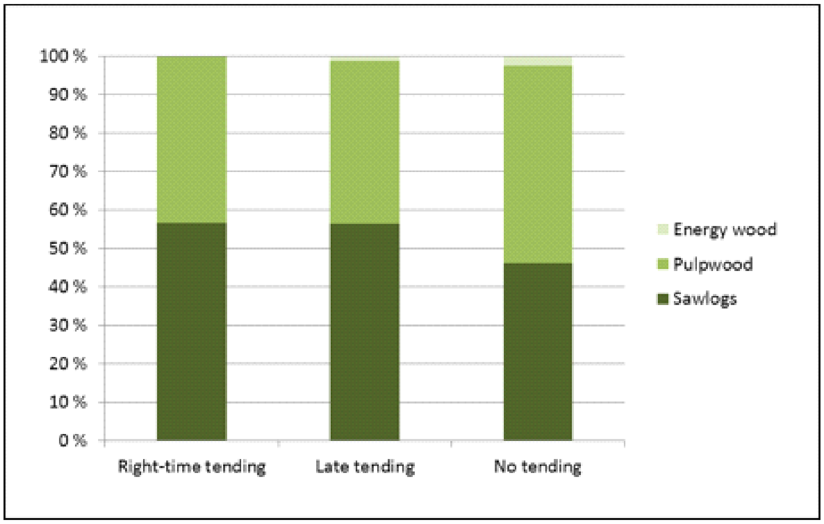
Case study Finland

Regional effects of timing of seedling stand tending

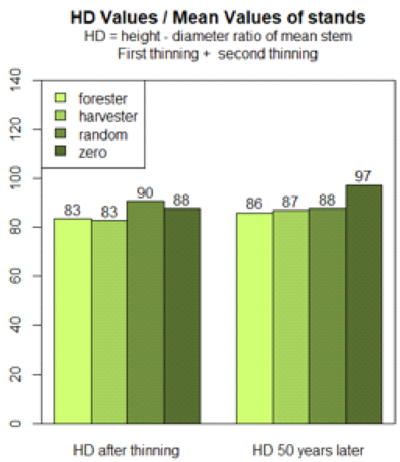


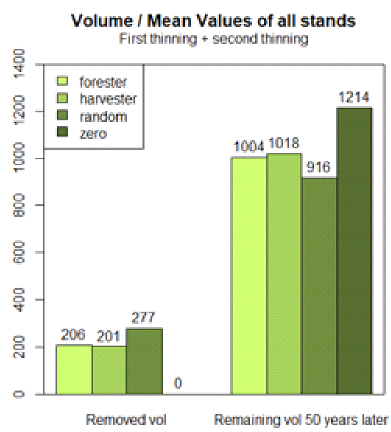
Structure of harvesting removals (%) in different 100-year scenarios.

- Right time of intervention controls diameter growth
- Earlier first commercial thinning possible
- Higher saw log yield (18% compared to scenario without tending)

Case study Austria

Effects of thinning by tree marking vs harvester selection





HD-values (stability) and stem volume (productivity) after the four tested thinning scenarios.

- High match between forester and well trained harvester (70% of selected trees)
- Difference in stability and productivity after forester and harvester not significant
- Random thinning -> unstable stands in first thinning

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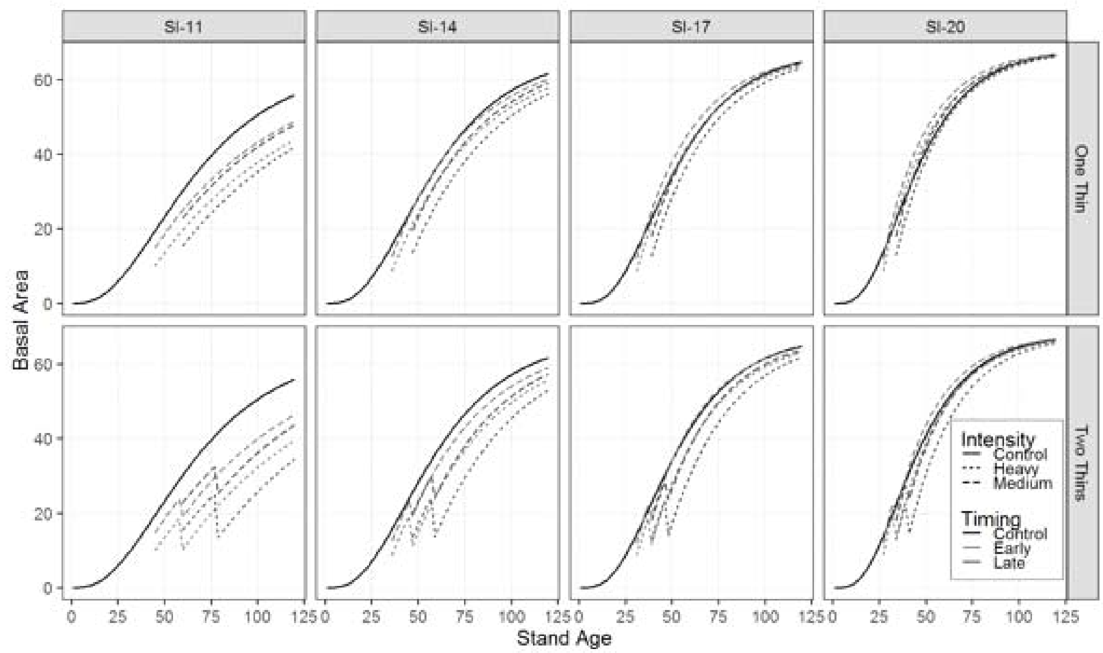
Case study Norway

Production of thinned and unthinned Norway spruce stands



Basal area development of simulated unthinned and once or twice thinned stands.

The no-thinning variant generally is more productive than thinning variants
At increasing yield class this superiority decreases
Top yield classes, when thinned, are slightly more productive than when unthinned

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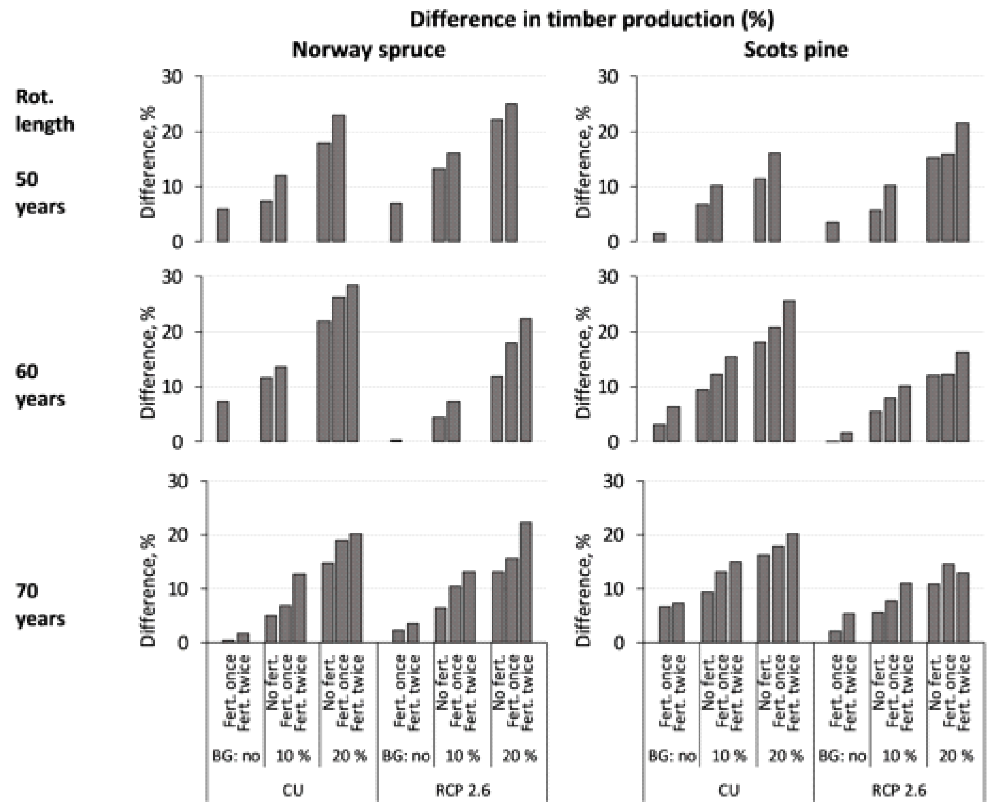
Measures for early treatment and stand establishment

Case study Finland

Effects of improved regeneration material and fertilization on timber production



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.

+

- Shorter rotation length
- Earlier commercial thinning
- Higher forest yield
- More saw logs

?

Future biotic and abiotic threats

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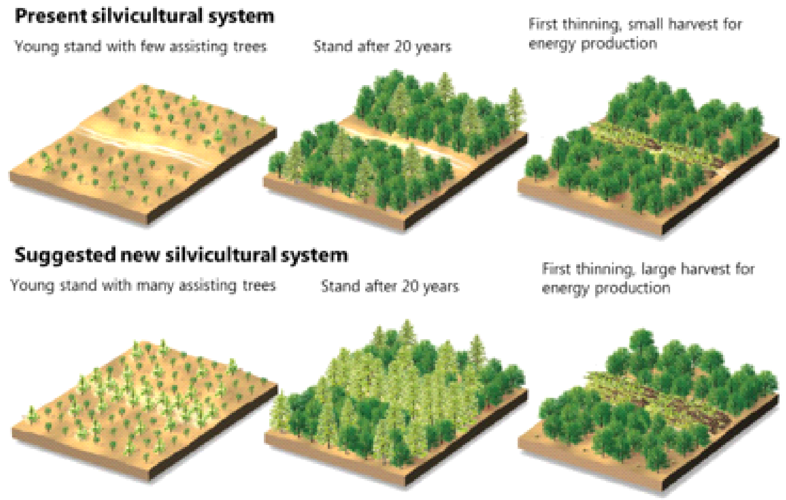
Case study Denmark

Power cultures; fast growing species on skid roads



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

– NPV for tested scenarios negative

+ Savings for clearing

Positive effects on stem quality

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Case study France

Stump removal in maritime pine plantations

+ Reduction of phytosanitary threats
+ Biomass supply
+ Savings in preparation costs
+ No fallow period required

? Long term effects on:
- Carbon balance
- Nutrient balance
- Biodiversity

To sum up, in 8 out of 10 case studies conducted in the course of our research, Norway spruce is the main tree species, and age class forest is the practised management form. In addition, 6 out of these 8 studies are concerned with tending and thinning. More specifically, 4 out of the last-mentioned 6 studies suggest improvements by altering the concept of tending/thinning, and 2 studies suggest the enhancement of mechanization. Hence, we consider that one of the principal increase potentials for European forestry is located in this complex: To do tending and thinning in Norway spruce age class forests more intensively, more properly and more cost-effectively. Yet, we have a second focus on early operations, in which context we presented very innovative and versatile suggestions. One additional study on coppice, addressing an essential increase potential for forestry in the South-West European countries, completes the range of our investigations.

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