Optimization of early cleaning and precommercial thinning methods in juvenile stand management of Norway spruce stands

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Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in Auditorium XIV at the University Main Building, Fabianinkatu 33, Helsinki, on January 27th 2017, at 12 o'clock noon.

The purpose of this thesis was to develop the concept of cost-efficient Juvenile Stand Management (JSM) for planted Norway spruce (*Picea abies* L. Karst) stands. The principles of time based management were followed, by integrating regeneration activities as a cost-efficient value chain and by minimizing non-value-adding work with straightforward decision making based on forest management plan data.

The effects of soil preparation and Early Cleaning (EC) on further development of the stands were studied in intensive field experiments. Extensive survey data were used to develop methods applicable for efficient decision making in JSM, such as estimating need for EC or labor time consumption of PreCommercial Thinning (PCT).

Timing of JSM had major effect on its costs; a delay in PCT increased the labor time needed to manage a stand by 8.3% annually. Moreover, 61–70% of the saplings in a typical Norway spruce stand were considered to need EC years before PCT was appropriate to be done. EC was also found to be an effective release treatment as it subsequently increased the diameter growth of crop trees by 21–32%. However, a two-stage management regimen, which included EC and PCT, appeared to be somewhat more labor consuming than the PCT only option. Soil preparation method had a major effect on emergence and growth of non-crop trees, and thus, on overall costs of JSM-program. The results showed that understanding the interactions in regeneration chain activities is important for productive forestry.

Furthermore, *a priori* information can have practical implications in decision making for JSM. Several site or stand attributes were found to explain labor consumption of PCT or the need for EC. However, decision making in daily forestry requires more reliable models. The modelling data should go beyond the data of traditional forest management planning in further research. Big data offers promising opportunities.

Keywords: vegetation management, young stand management, soil preparation, silviculture, stand establishment, productivity

ACKNOWLEDGEMENTS

LIST OF ORIGINAL ARTICLES

This thesis is based on the following articles, which are referred to in the text by their Roman numerals. The publications are reprinted here with the kind permission of the publishers.

I   Uotila, K., Saksa, T., Rantala, J., Kiljunen, N. (2014). Labour consumption models applied to motor-manual pre-commercial thinning in Finland. Silva Fennica 48(2) article id 982. 14 p.
http://dx.doi.org/10.14214/sf.982

II   Uotila, K., Saksa, T. (2013). Effects of early cleaning on young *Picea abies* stands. Scandinavian Journal of Forest Research.
http://dx.doi.org/10.1080/02827581.2013.869349.

III   Uotila, K., Rantala, J., Saksa, T. (2012). Estimating the need for early cleaning in Norway spruce plantations in Finland. Silva Fennica 46(5): 683–693.
http://www.metla.fi/silvafennica/full/sf46/sf465683.pdf

IV   Uotila, K., Rantala, J., Harstela, P., Saksa, T. (2010). Effect of soil preparation method on economic result of Norway spruce regeneration chain. Silva Fennica 44(3): 511–524.
http://www.metla.fi/silvafennica/full/sf44/sf443511.pdf

Karri Uotila was responsible for planning the analyses, analyzing the data and writing the articles. Uotila additionally took part in planning the experiments for articles **II** & **IV** and he was responsible for taking the measurements. Co-authors were responsible for the design of field experiments **I** and **III**, as well as commenting on the studies in all of the stages from planning to publications.

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ABBREVIATIONS

ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
EC	Early Cleaning
ICT	Information- and Communication Technology
JSM	Juvenile Stand Management
LC_{NPCT}	Labor consumption in precommercial thinning on stands with no early cleaning done
LC_{PCT}	Labor consumption in precommercial thinning on early cleaned stands
MT	*Myrtillus* type
OMT	*Oxalis-Myrtillus* type
PCT	PreCommercial Thinning
SE	Standard Error
TBM	Time Based Management
TQM	Total Quality Management
$trees_{TBR}$	Trees to be removed in juvenile stand management
VT	*Vaccinium* type

INTRODUCTION

Norway spruce planting and juvenile stand management in Finland

Norway spruce (*Picea abies* (L.) Karst.) is unarguably important tree in Finnish silviculture. In 2013, approximately 121 000 hectares of forest land was regenerated in Finland, 44% of this area (53 000 hectares) was planted for Norway spruce (Finnish Statistical Yearbook... 2014).

In Finland, 160 000 hectares of juvenile stands are yearly managed from competition (Korhonen et al 2010). Many hardwood species regenerate naturally on planted Norway spruce stands, mainly Pubescent birch (*Betula pubescens* Ehrh.) and Silver birch (*Betula pendula* Roth), but also Aspen (*Populus tremula* L.), Rowan (*Sorbus aucuparia* L.), Grey alder (*Alnus incana* (L.) Moench), or Willows (*Salix* L. sp.) emerge often abundantly (Raulo 1976; Lindholm & Vasander 1986; Vanha-Majamaa et al. 1996). Abundant growing hardwoods create need for Early Cleaning (EC) to control intraspecific competition. In subsequent years, also PreCommercial Thinning (PCT) is generally needed to control the overall stem density in a stand. Together EC and PCT will compound a Juvenile Stand Management (JSM) program. In addition to the JSM-activities themselves, implementation of JSM-program is partly controlled by previously done soil preparation, as it affects the emergence and growth of the trees on newly regenerated forest sites (Raulo 1976; Johansson et al. 2013; Saksa et al. 2005).

Investments in juvenile stand management

Forest regeneration and juvenile stand management, including EC and PCT, occupy only of a short period of time in a forest rotation and represent only small investments compared to the total cash flows of forestry (Finnish Statistical Yearbook... 2014). Despite this, they form the basis for sustainable and profitable wood production (Bataineh et al. 2013; Pitt et al. 2013c). The success of these early silvicultural activities largely defines the possible end uses of the roundwood crop in the future (Duchesne et al. 2013, Pitt et al. 2013b).

Investments in forest regeneration and JSM may be viewed as very long-term investments compared to those in mainstream agriculture. According to the economic theory of defining profitability of forestry (Faustmann 1849; Straka & Bullard 1996; Viitala 2002; Buongiorno & Gilles 2003; Hyytiäinen et al. 2010), the discounting of revenues generated near the end of a rotation can take a heavy toll on profitability after silvicultural costs occurring at the early stage of the rotation period are accounted for. As net present value (discounted revenues – discounted costs) defines the profitability of forestry, inefficient early stage silvicultural procedures or increased silvicultural costs may threaten how much silviculture is undertaken and, in the long-term, the sustainable environment in which forest industry must operate.

JSM activities are necessary for optimum forestry output for several reasons. First, the growth of commercially valuable stands of productive species requires that good quality stems are chosen from amongst countless stems of lower-value competitors that exist in a stand (Varmola 2001, Pettersson 2012). Second, generating adequate space for crop trees will increase diameter growth of growing stock and bring revenue yields forward in time (Pettersson 1992). Third, harvesting costs depend heavily on the average size and uniformity in size of the harvested stems (Sirén & Aaltio 2003; Kärhä et al. 2004; Heikkilä et al. 2005; Laitila et al. 2010; Plamondon & Pitt 2013). Thus, JSM is often necessary to profitably carry out the first commercial thinning in subsequent years. For these reasons, about 160 000 hectares of juvenile stands are managed in Finland annually. However, the overall need for JSM has been approximated to exceed 200 000 hectares (Korhonen et al. 2010). The total money invested in JSM was 62.4 million € in Finland in 2014, which equals 411 €/ha (Finnish Statistical Yearbook... 2014). In contrast, the total annual stumpage earnings were about 2 billion euros (Finnish Statistical Yearbook... 2014).

The cost of JSM has increased rapidly in Sweden and Finland since the 1990s (Ligné et al. 2005a; Finnish Statistical Yearbook... 2014). In Finland, the real-evaluated per-hectare cost of JSM from 1990 to 2013 has more than doubled, while actual evaluated index-linked wage levels have increased by only 40% over the same period (Fig. 1). Unfortunately, the quality and proportion of well-managed stands does not reflect the trend in higher management costs; according to Korhonen et al. (2010), the proportion of well-managed juvenile stands has decreased from 39% from the previous national forest inventory in Finland (NFI9) to just 30% 10 years later (NFI10). We know that quality and costs do not necessarily move hand in hand in silviculture (Kankaanhuhta & Saksa 2013), and there can be several reasons for discrepancies in costs and quality. However, it is likely that the reason for the discrepancy is something other than the efficiency of operational work of the clearing saw technique, as the same technique has been used in JSM for the previous 50 years (Ligné et al. 2005a).
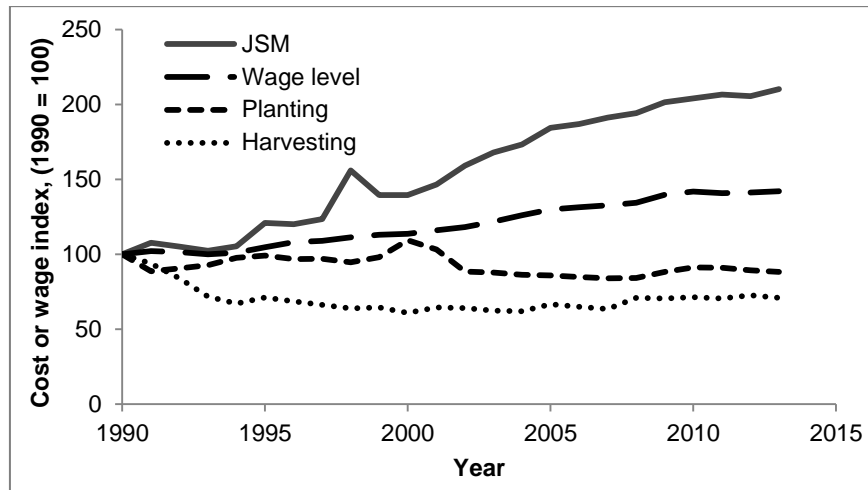
Figure 1. Development of real-valued costs of juvenile stand management (JSM), planting and harvesting, and the development of wage level in Finland since 1990s. Values have been converted into real costs by using Cost-of-living index as a factor (Finnish Statistical Yearbook... 2014; Official Statistics of... 2015).

Juvenile stand management and the techniques used for it

This study evaluates JSM in planted Norway spruce stands. Norway spruce is the most common option for planting on fertile sites of boreal forests in Fennoscandia (Finnish Statistical Yearbook... 2014; Swedish Statistical Yearbook... 2014; Äijälä et al. 2014). Fertile soils encourage Norway spruce growth, and thereby maximize timber yield on a rotation (Vuokila & Väliaho 1980). Compared to Scots pine (*Pinus sylvestris* L.), spruce still produces a fair quality timber crop, even at rather low initial density (e.g., 1600–2000 trees/ha; Johansson, K 1992; Nilsson & Gemmel 1993; Harstela 2003).

However, naturally regenerating hardwoods, which have a propensity to capture nearly all harvested sites, often outgrow Norway spruce seedlings within a few years after planting (Nyström 2000; Kaila et al. 2006). Hardwoods that originate from stump or root suckers grow especially rapidly in the first years (Björkdahl 1983; Johansson, T 1992a; Johansson, T 1992b; Johansson, T 2008). Vigorously growing competing vegetation can negatively affect site conditions and factors such as water availability (Nilsson et al. 1996; Nilsson & Örlander 1999), nutrients (Nilsson et al. 1996; Jobidon 2000), light (Nilsson et al. 1996; Jobidon 2000), and temperature (Jobidon et al. 2003). It is well known that high stocking densities of hardwoods can critically hinder the growth of the more desirable conifer trees (Walfridsson 1976; Folkesson & Bärring 1982; Andersson 1993; Jobidon 2000; Fu et al. 2008; Bataineh et al. 2013). Fierce competition from competing vegetation can eventually cause crop-tree mortality (Jobidon 2000). Similarly, competition amongst high densities of target stems can result in slow crop-tree growth in mono-specific stands (Pukkala & Kolström 1987; Pettersson 1992; Huuskonen & Hynynen 2006).

Juvenile stand intervention(s) are needed to optimize timber yield and growing times (Bataineh et al. 2013; Pitt et al. 2013c). There are two main approaches for such interventions: (1) the release of the target tree species from the interspecific competitive influences of other unfavorable species or (2) reduction in the spacing of crop trees to some desired level (Luoranen et al. 2012, Äijälä et al. 2014). When conducted before the trees being removed are of merchantable size, these approaches may commonly be referred to as PCT, but the first intervention is more specifically classified as EC. In EC, the stand is protected from hardwood competition, if the hardwoods have the potential to compete against the development of the target trees. After EC, it is almost certain that PCT is later needed because hardwood stumps can re-sprout intensively after the initial EC (Björkdahl 1983; Johansson, T 1992a; Hamberg et al. 2011). In PCT, a stand is thinned to a target density and all the trees except those anticipated to provide the future crop are removed. The prevalent working method is similar in both cases; i.e. the motor-manual removal of stems with a clearing saw (Ligné et al. 2005a; Pettersson et al. 2012). In the context of this study, EC is regarded separately to PCT, but collectively they are referred to as JSM.

In motor-manual JSM, Norway spruce stands are recommended for EC when they reach one meter in height (Luoranen et al. 2012). Later on, when they are 3–4 meters high, the stands are generally recommended to be precommercially thinned to the density of 1 600–2 200 stems ha^{-1} (Luoranen et al. 2012; Äijälä et al. 2014). Almost every stand needs at least one JSM during sapling stand stage (Korhonen et al. 2010; Finnish Statistical Yearbook... 2014; Swedish Statistical Yearbook... 2014).

Improving the technological efficiency of the operational work of JSM is challenging and time consuming. Nowadays, there are few truly competitive alternatives to motor-manual work techniques or methods available for JSM. Even though herbicides are effective in EC (Homagain et al. 2011) and were previously in common use (Hytönen & Jylhä 2008; Homagain et al. 2011), consumer opposition and sustainable forest certification currently restrict their use in Finland (Suomen PEFC-standardi 2009; FSC standard for Finland 2009). Furthermore, many new mechanical JSM techniques have been introduced, but they have not exceeded the anticipated cost-efficiency of motor-manual work, which is why they are still rarely used (Johansson, T 1991; Ligné et al. 2005a; Ligné et al. 2005b; Pettersson et al. 2012; Hämäläinen et al. 2013).

The complex economic problem of the regeneration chain

Juvenile forests are highly dynamic environments in which competition between individuals and species changes continuously. Thus, managing a juvenile stand is a multidimensional problem that includes: a variety of different growth dynamics between species (Nyström 2000; Kaila et al. 2006); acclimation of trees to climatic conditions (Mohammed & Parker 1999); variability of climatic conditions that result from implementing JSM; dependency of sprouting on timing of JSM and the size of the cut trees (Ferm et al. 1985; Björkdahl 1983); and also the dependency of the labor consumption of JSM as a function of the size of the cut trees (Hämäläinen 1983).Thus, the timing of JSM activity greatly affects the costs and benefits derived from it. Moreover, the implementation of preceding activities in the regeneration chain influences the costs and benefits of the later activities (A principal scheme, Fig. 2). For example, soil preparation affects soil conditions in such a way that it influences productivity in planting, the growth of the trees, and productivity and the need for EC, PCT and the first commercial thinning. Furthermore, EC greatly affects stand structure, composition of the species, and growth of the trees. Thus, EC eventually influences productivity of the PCT and also the first commercial thinning. It can be seen from this standpoint that the increasing cost level of JSM shown in Fig. 1 is not necessarily caused by the technique of the JSM operation itself; rather, it is a cumulative outcome of the earlier stages of the regeneration chain and the timing of the activity.

The optimum solutions for the forest regeneration chain from establishment to final harvest are complex to solve for a given site. Economic theory is based on profit maximization (Venugopal & Ramachandra 2006) and bare land valuation has often been considered as the best option in economic modeling and optimizing profits of even-aged forestry (Faustmann 1849; Viitala 2002; Tahvonen et al. 2013; Tahvonen 2016). However, the method of bare land valuation is of little use in analyzing different JSM programs, especially when there is a lack of knowledge about the interactions of the effects of the activities in the regeneration chain and also about their net impact, on growth of the established stand.

There have been a few attempts at building simulation or decision making systems for juvenile stands in Finland (Parviainen et al. 1985, Räsänen et al. 2004). However, these complex systems have not yet been seen as practical tools. One of the main reasons for poor practical applicability of these systems is the lack of empirical data of the effects between the different silvicultural activities in a regeneration chain (Parviainen et al. 1985, Räsänen et al. 2004). However, large and long-term field experiments are laborious, time demanding and expensive to carry out. Nonetheless, a couple of such studies have recently been published by Bataineh et al. (2013) and Pitt et al. (2013c).

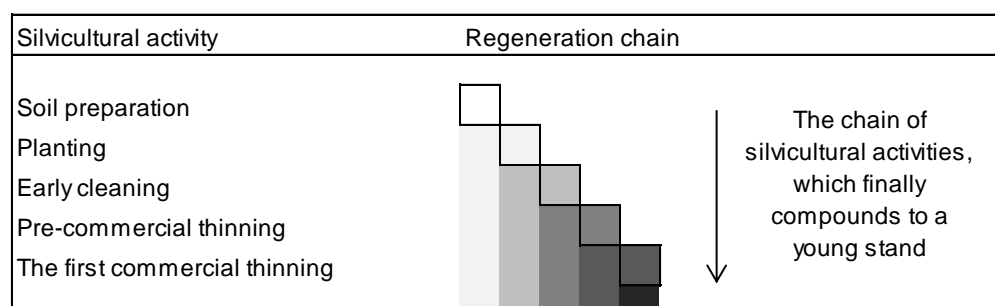| Silvicultural activity	Regeneration chain
Soil preparation	
Planting	
Early cleaning	The chain of silvicultural activities, which finally compounds to a young stand
Pre-commercial thinning	
The first commercial thinning	

Figure 2. Sequential silvicultural activities in planted spruce stands are strongly linked together. Later activities are always affected by their predecessors, especially with regard to optimizing costs or gains of tasks and how these can be implemented.

Bataineh et al. (2013) analyzed data from a controlled experiment- in which the growth responses of various combinations of early herbicide and PCT treatments were studied for 40 years. They simulated stand growth for the various treatment combination from 40 years to rotation end, and were able to show positive net present values for EC and EC + PCT. A similar, full-rotation study was conducted by Pitt et al. (2013c), also showing positive net present values for both EC and PCT. These studies improve our understanding of the rotation-length effects of JSM on growth and yield and economics, however, there is still much to learn about the interacting effects and efficiencies of combined early treatments. For example, a lack of important information exists about the effects of different silvicultural management treatments on costs of the activities that follow them. Furthermore, the technological and silvicultural development of JSM is an ongoing process. Even though herbicides were the most suitable method in the early release treatments cited above, alternate methods must be used today in Finland. Thus, there is a paucity of knowledge about the effects of the modern silvicultural methods throughout the entire rotation cycle.

An approach to optimize the regeneration chain

An appropriate approach to optimize the regeneration chain within the reasonably short-term would be to empirically study the effects on costs of the following activity of each step in a regeneration chain, and then opt for the least-cost combination. This approach will produce a cost-effective and more profitable option when the final benefits of the selected method is the same or better than the compared methods (Willis & Affleck 1990). Furthermore, the other tasks of the JSM process should also be optimized, not just the operational work. The automation of decision making is one of these tasks. With these kinds of approaches, it would be possible to use short-term experiments or surveys in the optimization of JSM programs.

Process management can be applied to optimize work allocation in JSM. According to the "*Theory of Swift, Even Flow"* labor time can be divided between value-adding times and non-value-adding times (Schmenner & Swink 1998). Value-adding time is the labor for which the customers are willing to pay, whereas non-value-adding time is the opposite of value-adding time, i.e. wasted time labor. A process is made more efficient, swifter, when the non-value-adding wasted time has been removed from the process. Reducing this waste is one of the main principles in "*Time Based Management"* (TBM).

In TBM, costs are minimized by allocating resources in such a way that the production cycle time is shortened by reducing or eliminating non-value-adding time from the production process and also by reconfiguring the process as an integrated system to increase efficiency of the value-added time (Hannus 1994; Kujala et al. 2006). The principles of TBM can be efficiently adapted to the optimization of the forest regeneration chain. This can be achieved when resources are allocated in such a way that the total costs of the integrated regeneration chain process are minimized.

TBM can be considered as a part of "*Lean management"* (Hannus 1994; Oakland 2014). *Lean management* originates from the leadership and manufacturing principles of the Toyota Motor Company, and it was introduced by Womack et al. (1990) in their evaluation of manufacturing practices of the automobile industry. The main idea in *Lean management* is to minimize the production costs of the entire integrated production system instead of discrete operations in the production (Hannus 1994; Oakland 2014). Today, these methodologies are widely used in many business environments and public services, for example in health care (Kujala et al. 2006; Oakland 2014) and agriculture (Lätti et al. 2015). The basis of these methodologies lay in Quality Management (TQM), and in the aim of producing what customer wants (Hannus 1994; Oakland 2014). In this study, it is assumed that, according to the present demand of roundwood (Finnish Statistical Yearbook... 2014), the customer will especially demand spruce logs and pulpwood in the future.

Certain management programs, such as the regeneration chain of planting of Norway spruce, have proved to be sustainable and economically viable in wood production in practice (Kubin 2001; Luoranen et al. 2012; Äijälä et al. 2014). If these programs could be completed more efficiently or for less cost by means of TBM measures, then the final solution would evidently be closer to the economic optimum (Willis & Affleck 1990).

Applying Time Based Management to the forest regeneration chain

The cost structure of JSM was found to be an important factor that implies TBM in optimization of the regeneration chain. For example, the labor spent in JSM depends largely on the density and size of the trees to be removed (Hämäläinen & Kaila 1983; Kaila et al. 1999; Ligné et al. 2005a; Ligné et al. 2005b; Kaila et al. 2006). The results reported by Kaila et al. (2006) indicate that labor consumption can greatly increase with growth of a stand; a two-year delay in JSM increased labor consumption by between 8–42%. However, the dataset of Kaila et

al. (2006) comprised a rather small number of homogenous stands. The design of a similar study must involve data gathered over a wider range of age variation and sites to be statistically robust. Furthermore, the effect of EC on growth of the stand and total costs of the JSM program has yet to be determined. The effect of early timing EC can be desirable as hardwood stumps sprout less intensively the smaller the trees are when they are cut (Ferm et al. 1985; Björkdahl 1983; Johansson, T 1987; Johansson, T 2008).

Moreover, soil preparation is essential in successful Norway spruce planting. It promotes soil conditions to be suitable for seedlings and increases survival and growth of them (Örlander et al. 1990; Nordborg 2001; Hallsby & Örlander 2004; Luoranen & Kiljunen 2006). One of the main ideas in soil preparation is to expose mineral soil and to reduce competition between the crop trees and other competing vegetation (Nordborg 2001; Saksa et al. 2005). Unfortunately, hardwoods also germinate vigorously on the exposed mineral soil in planted conifer stands (Raulo & Mälkönen 1976; Valtonen 1988; Saksa et al. 1990), which in turn, increases removal and time consumed in JSM. Consequently, soil preparation methods should maximize spruce survival and growth, but minimize mineral soil exposure to optimize the allocation of value-added time in JSM. In addition, the soil preparation method should be as affordable as possible in line with optimizing the cost-efficiency of the whole regeneration chain.

Furthermore, planning and supervision work of the silvicultural activities should be reduced to make JSM more cost-effective (Kiljunen 2006). One objective should be the more efficient use of real-time information and communication technology (ICT) based management systems in decision-making of JSM. Real-time forest management plans are suitable for keeping the state of the forests on track and for maintaining communication between forest owners and forest service providers for the planning and implementation of silvicultural activities (Kalland & Harstela 2003). Today, real-time forest management plans are in general use in industrial forest companies (Metsä Forest 2010; Illi 2013; Metsä Forest 2014).

The visibility of the demand-supply chain is according to the concept of visibility-based service (Holmström et al. 2010), important for the service business to work efficiently. Visibility-based service refers to provider's deeper access to information about the customer´s business, in which both the customer and provider benefit from a situation that leads to lower costs or better timing of the services (Holmström et al. 2010). Thus, it can be considered as one of the methods to reduce non-value adding work through the optimum application of TBM. The use of the visibility-based service concept has lately become more general in silviculture. One example is an ICT-based forest management plan system, metsaan.fi, which is offered by The Finnish Forest Centre for forest owners and silvicultural service providers (The Finnish Forest… 2016). Through the system, forest owners can get real-time information about the state of their forest estates, and they can also share the information with silvicultural service providers.

Unfortunately, the real-time forest management plans generally still lack much information related to JSM, and these often include the estimates for need and costs, which are the most required in decision making about JSM. Therefore, forestry officials must often inspect the stands "in the field". The field inspection, according to TBM, is considered as non-value-adding labor. The *a priori* information available before decision making should be utilized as efficiently as possible in JSM. Thus, in principle, decision making methods based on models could decrease costs by reducing non-value-adding labor needed for measuring and estimating the need, timing, labor consumption, and cost of JSM.

Aims of the research

The purpose of the research described in this thesis was to construct and develop the concept of cost-efficient JSM and test it in planted Norway spruce stands. The construction, development and testing of the cost-efficient JSM is based on TBM and the theory of "*Swift, Even Flow*" by Schmenner & Swink (1998), where the labor time can be divided to value-adding time or non-value-adding time. The overarching objective of this thesis is to increase the cost-efficiency of JSM. Schmenner & Swink's (1998) concepts and TBM were applied and tested for two goals:

1) Analysis and optimization of value-adding time in regeneration chains as an integrated value chain.

2) Reduction of non-value-adding time in decision making of JSM.

These two goals were further divided to study separate components of the JSM.

For value-adding time, the following questions were posed:

1. How does labor consumption vary in JSM with stand age and other site and stand characteristics (**I**)?

2. How does EC affect stand growth and labor consumption in PCT (**II**)?

3. How does the cost-structure of the regeneration chain vary according to the soil preparation method (**IV**)?

For non-value-adding time, the questions pose were:

4. Are forest management plan data alone suitable for estimating the labor consumption in JSM (**I**)?

5. Are forest management plan data alone suitable for estimating the need for JSM (**III**)?

MATERIAL & METHODS

General information about datasets, analysis and statistics

The data for this thesis comprised four datasets that had been collected using two different approaches. The datasets were used to analyze both the value-adding work and the non-value-adding work. Intensively measured experimental areas were studied to determine the effects of EC (**II**) and soil preparation method (**IV**) on the growth of typical sapling stands of Norway spruce. These field experiments were used to eliminate the effects of other factors and focus on the specific treatment studied. On the other hand, the modeling of labor consumption of PCT (**I**) and the need for EC (**III**) were studied on extensive survey studies. These surveys were used to generalize the factors affecting EC and PCT over different situations. Surveys are useful for building decision making tools.

In three of the four studies, existing theory was used to determine the labor time consumed for JSM (**I**, **II**, and **IV**). Labor time for JSM in studies **I** and **II** was estimated using the model described by Kaila et al. (2006 Eq. 3). In contrast, labor time in study **IV** was calculated according to the collective labor agreement (Metsäalan työehtosopimus 2008). Both methods are based on the results of work studies by Hämäläinen & Kaila (1983) and they determine the time consumed in JSM according to density and size of trees removed during JSM. Productivity functions of labor consumption in JSM are recognized as an appropriate alternative to work-time measurements in studying cost-efficiency of JSM (Kaila et al. 2006).

The data from studies **I**, **II** and **IV** were analyzed using SPSS (SPSS Base 16.0 User's Guide 2007). Study **III** was analyzed using MLwiN 2.25 (Rasbash et al. 2009). Experimental designs and data analyses are briefly described below and in more detail in the original published articles.

Modeling labor time consumption in PCT (I)

The consumption of labor time in PCT was modeled using data from the inventory dataset of 448 stands (age max 20 years, diameter at breast height max 8 cm), which had been measured in 2005–2006. The sample was measured by personnel of The Finnish Forest Centre during their inspections of young stand management standards established by the Act on the Financing of Sustainable Forestry (1094/1996). Thus, all stands were privately-owned young forests that had recently been obliged to conform with a PCT management protocol in accordance with the abovementioned Sustainable Forestry Act. For the stands to be compliant with this act, they had to consist of commercially valuable species and have no evident threat from other forest vegetation after the PCT. A total of 319 stands were categorized as having had "no EC" upon PCT inspection, whereas 129 contained obvious stumps and debris and were categorized as "EC done" (notice the different terminology used in the original article **I**). Sample stands were located in Pohjois-Savo in Central Finland between 62°40´ and 64°00´ N, and 26°50´ and 28°50´ E.

The inventory method comprised a transect survey of five sample plots (50 m^2) per stand (**I**). Crop trees were tallied by species and their mean heights on a plot were estimated. Soil was classified either as a mineral soil or as peatland, and site fertility was recorded according to Cajander's (1926) site type classification from more fertile to less fertile; *Oxalis-Myrtillus* type (OMT), *Myrtillus* type (MT) and *Vaccinium* type (VT). Soil preparation and regeneration methods were deduced by inspecting the site. Stand age was determined from the annual growth increments of crop trees and stand areas were provided by The Finnish Forest Centre. Trees in removal were tallied for 10 m^2 subplots, and diameters of 3–5 sample stumps were measured; the labor consumption in PCT was estimated from the data.

Mixed linear regression models were constructed separately for stands with no EC (LC_{NPCT}) and for those with EC (LC_{PCT}). Separate models were used because timing of EC was not known. Logarithmic transformation of calculated labor consumption was the dependent variable in both models. The independent variables tested were as follows: dominant tree species, site type, regeneration method, soil preparation method, and area and age of the stand. The base model was described by the equation:

$$Ln(LC_{ij}) = \mu + X'a + u_j + e_{ij} \tag{1}$$

where LC_{ij} is labor consumption of PCT for the plot i ($i = 1,..,k$.) for the stand j ($j = 1,..., n$.), μ is a fixed intercept parameter, X and a represent independent variables and their fixed effect parameters, and u_j and e_{ij} are stand and plot level error terms.

The final model predicts labor consumption on a logarithmic scale. Back-transformed and bias-corrected values can be calculated using the following equation based on that described by Pokharel & Dech (2012):

$$\widehat{E[LC]} = e^{Ln\widehat{(LC)}+\frac{1}{2}\left(Var(u_j)+Var(e_{ij})\right)} \tag{2}$$

Where $\widehat{E[LC]}$ is the expected back-transformed value of $Ln(LC)$ and, $Var(u_j)$ and $Var(e_{ij})$ are the stand and plot level variances for $Ln(\widehat{LC})$, respectively.

Similar kinds of models were constructed for stump diameter determinations and for estimating the density of the removed trees, but only for those stands in which no EC had been done. The modelling procedure followed the description above (Eq. 1), but without the logarithmic transformation of the dependent variables.

Analyzing the effects of EC (II)

The effects of early cleaning were studied from three experimental sites: Karttula, Jäppilä, and Kangasniemi. The sites represented typical mesic soils used for planting of Norway spruce. The stands were established in 2002. The first measurements were carried out in 2006 at the end of the summer. Then, EC and control treatments were carried out in Karttula during the late summer of 2007, and in the Jäppilä and Kangasniemi sites in late summer 2008. Treatments were arranged in randomized complete blocks, with 18 blocks at Kangasniemi and Jäppilä, and 4 at Karttula. The second set of measurements took place in Karttula in the autumn of 2009, and in Jäppilä and Kangasniemi sites in the autumn of 2010. The experimental sites were initially established to study the effects of soil preparation methods and slash removal on the establishment of Norway spruce stands; detailed descriptions of the study sites including planting and treatment history are provided in the publication by Saarinen (2006).

Two sample plots (50 m^2) were measured for each treatment per block in Kangasniemi and Jäppilä sites, and six in Karttula site. Each planted Norway spruce was measured on a plot. A sub-plot (r = 1.50 m) was marked around each of them. Sub-plots were divided into three concentric rings (0–50, 51–100 and 101–150 cm). All the trees to be removed (TBR) by EC from each ring were tallied and a sample of three trees$_{TBR}$ was measured; the labor consumed by the EC was estimated on the data attained. The measured attributes for all of the measured trees in the first measurement were density (N, ha), height (h, cm), and stem diameter, ($d_{0,1}$, mm). In the second measurement, crown width (cm) and annual height growth (cm) of the planted spruces were measured in addition to all of the attributes of the first measurement. In the second measurement, non-crop trees were tallied only if they were taller than 50 cm.

The first measurements and the treatments had a time gap. The diameter growth of Norway spruce after EC was corrected to reflect differences in annual growth after EC based on the annual growth cycle of Norway spruce (Leikola & Rikala 1983; Kaakinen et al. 2004). Diameter growth was assumed to be linear during the measurement period.

Data from each site were analyzed separately. The data were converted to mean values of treatment plots in each block. The effect of EC on spruce mortality, as defined by the difference in the number of the living spruces between the first and the second measurement, was statistically analyzed using the χ^2-test. The effect of EC on crown diameter of Norway spruce was tested by an analysis of variance (ANOVA). An analysis of covariance (ANCOVA) was used to examine the effects of EC on all of the other attributes, with the value of the respective variable on the first measurement being used as a covariate. Soil preparation and slash removal treatments were tested to have no significant effect on stand growth after EC, why they were averaged over EC treatments.

Modeling the need for EC (III)

The need for EC in 4–7 year-old planted Norway spruce stands was modeled for 197 sites. The stands were established over the 2000–2003 period and inventoried in 2007 (see Table 1). The sampling of the stands used information on the obligatory declarations of the establishment of a seedling stand that is a statutory requirement in Finland (Forest Act 1224/1998), and which had been sent to the Pohjois-Savo Forestry Centre. The sample was stratified according to stand ages and the six Forest Management Associations in the territory covered by the Forestry Centre. The stands were located between 62–64°N latitude and 26–29°E longitude in WGS84 coordinates. Time intervals between harvest, and the subsequent establishment of a stand (regeneration delay) were approximated according to the time interval between the Forest use declaration and the declaration of the establishment of a seedling stand (Forest Act 1224/1998).

The inventory method was a systematic line survey of 8–23 sample plots (20 m^2) per site (Kankaanhuhta et al. 2009). Site fertility was classified according to Cajander's (1926) site type classification. Soil texture was determined in accordance that described by Luoranen et al. (2007). Excessive soil moisture (dampness) and soil preparation method were subjectively determined in the field. Luoranen et al. (2007) has described the

characteristics of the soil preparation methods in more detail. The crop trees were classified into three Need for EC -categories on the basis of their competitive position according to the following criteria: 1 = Low (No taller hardwoods than the crop tree within one meter radius of the crop tree), 2 = Substantial (hardwoods near a crop tree are as tall as the crop tree or the crop tree is slightly overtopped), 3 = High (a crop tree has already suffered from overtopping or hardwoods near the crop tree are substantially taller than the crop tree).

The data were analyzed using a multinomial logistic regression. A multinomial logistic regression model consists of J-1 logistic regression models, where J is the number of categories for a dependent variable (Agresti 1990). One category is a reference class (J, for identifiability $\beta_J = 0$), and the logarithm of the odds of the reference class and class $j = 1, \ldots, J$-1 is expressed as a linear combination of parameters. Random stand (v_{jl}) and plot (u_{jlk}) level effects were included in the multilevel multinomial logistic regression model used [Eq. 3 (the equation is in different form than in the original article, although the purpose is the same)].

$$Ln\left(\frac{\pi_{jlk}(x_{lk})}{\pi_{Jlk}(x_{lk})}\right) = x'_{lk}\boldsymbol{\beta}_j + v_{jl} + u_{jlk} \tag{3}$$

where $\pi_{jlk}(\boldsymbol{x}_{lk})$ is the probability of jth category for tree in a plot k at stand l with explanatory variables $\boldsymbol{x}'_{lk} = (1, x_{1lk}, \ldots, x_{tlk})$.

After estimating the fixed parameter vector $\boldsymbol{\beta}_j$, predicted probabilities of trees belonging into different need for EC -categories were calculated using equations 4 and 5 by assuming that random effects are zero.

$$\pi_{jlk}(\boldsymbol{x}_{lk}) = \frac{exp(x'_{lk}\widehat{\beta}_j)}{1+\sum_{j'=1}^{J-1} exp(x'_{lk}\widehat{\beta}_{j'})} \tag{4}$$

$$\pi_{Jlk}(\boldsymbol{x}_{lk}) = \frac{1}{1+\sum_{j'=1}^{J-1} exp(x'_{lk}\widehat{\beta}_{j'})} \tag{5}$$

The dependent variables were assigned to the three categories as follows: Low ($n = 3855$), Substantial ($n = 3446$), High ($n = 1966$). The group needing the least cleaning (Low) was used the reference category. The tested categorical independent variables were: excess soil moisture, EC, site type, soil texture, and soil preparation method. The tested continuous independent variables were: area of a site (1.6 ± 1.1 ha), stand age (5.6 ± 1.1 years), regeneration delay (1.4 ± 1.1 years), and stand density ($1\,569 \pm 839$ conifer crop trees ha^{-1}). Standard errors of parameter estimates and results of likelihood ratio test were examined when selecting the variables to the model.

Analyzing the effects of the soil preparation method (IV)

The effects of the soil preparation method on the condition of a seven-year-old planted Norway spruce stand were studied in Southern Finland in Suonenjoki (62°33N, 27°15E). The mesic mineral soil site represented a typical Norway spruce planting site (Luoranen & Kiljunen 2006). The experiment was initially established in 2000 to study the effects of planting time on the success of spruce seedlings, and the initial experimental design is described in more detail in Luoranen et al. (2006). The soil preparation methods, spot mounding and disc trenching, are described in Luoranen et al. (2007).

The experimental area was measured in 2007 using a systematic grid of circular (r = 100 cm) sample plots, which formed the attributes of the trees$_{TBR}$: density, height, diameter class, and stump diameter. Height of the nearest crop tree from the centre of the sample plot was measured, and from three concentric rings around the crop tree (0–25 cm, 26–50 cm, 51–100 cm), the surrounding trees were measured and categorized as trees disturbing crop trees according to their position and diameter class. A total of 255 and 246 plots were measured from the spot-mounded and disc-trenched treatment areas, respectively. The statistical significance of the difference between soil preparation treatments in the height of crop trees was calculated by an independent-samples t-test. All the other differences between treatments were tested by an analysis of covariance (ANCOVA). The covariate was the thickness of the humus layer, which was determined according to the earlier measurements described in the study by Luoranen et al. (2006).

The effect of soil preparation method on the economic result of the regeneration chain was analyzed by simulating stand development that occurred subsequent to the EC and up to the first commercial thinning. The input data for simulations were taken from the results of the field experiments. Planting density was assumed to be 1 800 seedlings per hectare and the mortality of crop trees before EC as 13.3% in spot mounding and 26.0% in disc trenching (Kuitunen 2001, Luoranen & Kiljunen 2006 and Saksa & Kankaanhuhta 2007). Density of the

complementary coniferous crop trees was assumed to be 300 and 330 ha^{-1} on the spot-mounded and disc-trenched management options, respectively (Saksa & Kankaanhuhta 2007).

Height growth of the crop trees was estimated according to Norway spruce dominant height growth models described by Kaila et al. (2006) and Valkonen (1997), respectively on spot-mounded and disc-trenched management options. However, above the height of eight meters, the dominant height of both management options were simulated according to dominant height growth model described by Valkonen (1997) because of the possible unreliability of the optional extrapolation on spot-mounded management option with the model of Kaila et al. (2006). The growth of mean height of crop trees was estimated by the single tree model presented in the study by Valkonen (1997). Height development of hardwood sprouts following cutting was estimated for birch (*Betula* ssp.) with height growth models of Björkdahl (1983), which were evaluated to be adaptable to local conditions when compared to the results reported by Jokinen (1973). The density of hardwood sprouts following EC was simulated based on the studies of stump sprouting by Johansson, T. (1992a), and by Hakkila (1985) and the study about spruce branch length development of Kantola & Mäkelä (2004).

The timings of JSMs were based on two criteria in the simulations: 1) the need for EC arising when the mean height of birch overgrew the dominant height of the spruce saplings, or 2) the need for PCT arising when, after the EC operation, at least one meter height difference between the mean birch sprout and the mean crop spruce remains up to the first commercial thinning.

Finally, the management options were compared to each other by carrying out an investment analysis that was based on growth and stand management simulations. Soil preparation costs were assumed to match the statistical mean values for Finland reported by Juntunen & Herrala-Ylinen (2007). The costs of the JSMs were estimated according to the density and diameters of the removed trees. The yield from the first commercial thinning was estimated using MOTTI-simulator software (Metla Metinfo 2009). The input data for the Motti-simulator was the simulated mean values of the stands at the dominant height of 14 meters.

Cost-efficient JSM

In the final part of the thesis, the results of the studies **I**, **II**, **III** & **IV** were combined as the concept of cost-efficient JSM and its practical implications. Answers for initial aims of the thesis were approached step by step. First, the implementation of silvicultural activities and their effects on efficiency of value-adding time in JSM-program were analyzed from PCT back to soil preparation. Then, the practical possibilities of the models constructed to decrease non-value adding time in estimating need for EC or labor consumption for PCT were analyzed.

RESULTS & DISCUSSION

Labor consumption in PCT (I)

Data collected in the survey of precommercially thinned stands (Study **I**) showed that the stump diameter of removal increases over time, and even though the density remains rather constant, labor consumption in PCT increases with stand age (LC_{NPCT}). The rate of increase for Norway spruce stands in LC_{NPCT} per year was high, 8.2% (Fig. 3). Such a rate translates to the labor consumption effectively doubling in nine years. For comparison, the estimated annual increase was 5.2% in Scots pine stands, and 3.3% in hardwood stands.

Growth dynamics of different tree species offer a rational explanation for the result, in that early (<20 years) growth of Norway spruce is slower than that of birch or Scots pine (Vuokila & Väliaho 1980; Kaila et al. 2006). Thus, in the stands dominated by hardwoods and Scots pine, many of the largest trees are crop trees, whereas the largest trees are typically removed in Norway spruce stands.

The impact of stand age on LC_{NPCT} is quite similar to that found in an experiment carried out in Norway spruce stands by Kaila et al. (2006). However, the increase of labor consumption in PCT of the smallest stands (<4 m) was even higher (27% over two years) according to Kaila et al. (2006). The stand selection in study **I** may not have been random because of the sampling method used. Moreover, the slope of the labor consumption curve in study **I** may consequently be biased in relation to the development of labor consumption in a certain stand, i.e., the method used by Kaila et al. (2006). Nonetheless, the method used in study **I** is appropriate in modeling time consumption of different worksites in practice.

Fertile sites consumed more labor for PCT activities than drier ones; fertile OMT was 114% higher and mesic MT was 66% higher than dryish VT (Fig. 3.). Fertile sites are known to encourage height and diameter growth of hardwoods (Jokinen 1973; Mielikäinen 1980; Björkdahl 1983) and, at least to some extent fertile sites also increase the amount of hardwoods (Valtonen 1988). Thus, it was no surprise that fertile sites also encouraged diameter and density of the trees$_{TBR}$ in this study. However, the interaction between stand age and site type was not significant in terms of labor consumption, but one must take into account that the logarithmic model was used. Soil preparation also increased labor consumption, mainly because soil-prepared sites had more trees$_{TBR}$ than unprepared sites, as was suggested by Raulo & Mälkönen (1976). In addition, larger sites were more time consuming for PCT than smaller sites. Both stump diameter and density of the trees$_{TBR}$ increased with area of a site. According to Siipilehto (2006), a larger adjacent stand can strongly affect the growth of smaller trees next to it. Thus, mature adjacent stands can substantially reduce the growth of trees to be removed from small sized stands.

Forestry officers can optimize costs of PCT with the decisions of timing of PCT. PCT should be implemented as early as possible to minimize costs, but not so early that the risk of regrowth is high. However, from the standpoint of growth and quality losses for crop trees, the need for JSM arises much earlier than the risk for JSM to recur as a result of the stump sprouting being bypassed (**II**, **III**). Thus, a management regimen of more than one JSM can be rational, and this is analyzed in the next section.
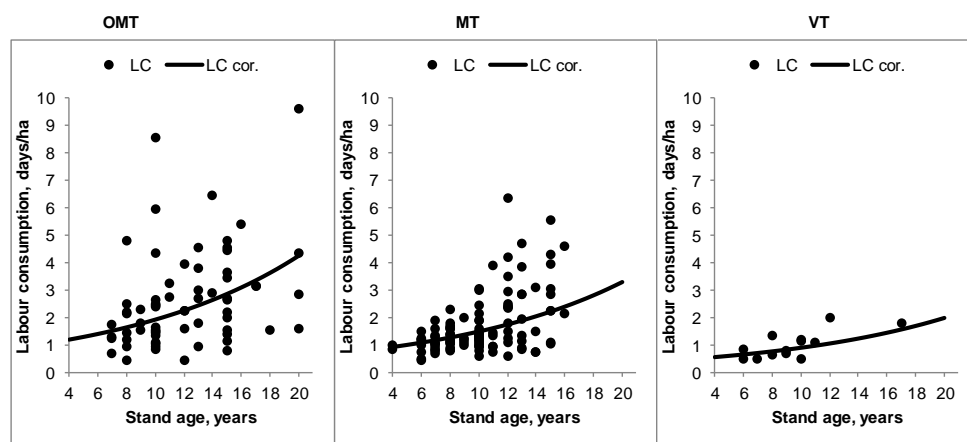
Figure 3. The back-transformed and bias-corrected *a priori* estimates (LC cor.), and the calculated values (LC) of labor consumption of PreCommercial Thinning (PCT) according to site type (OMT = *Oxalis-Myrtillus* type, MT = *Myrtillus* type, VT = *Vaccinium* type) stand age, and removal in Norway spruce stands which have no EC done (LC_{NPCT}). In the estimates, variables "area" and "soil preparation" were set to "2.2 ha" and "Continuous trace".

The Need for and effects of EC (II, III)

In the survey study of 4–7 year-old Norway spruce stands 58.4% of the conifer crop trees were considered to belong to high (21.2%) or substantial (37.2%) need for EC categories (**III**). The compounded percentage in typical MT–OMT site types of uncleaned Norway spruce stands was even higher, 61–70%. The observations for the need for EC from the earlier studies are of the same magnitude. Kiljunen (2004) reported that 58.9% of Spruce stands needed EC, 64% and 57%, respectively on OMT and MT site type. According to Korhonen et al. (2010), 75% of under 1.3 m tall Spruce stands were considered to need JSM within the next 10-years.

Study **III** results indicated the need for EC (i.e., a high proportion of substantial and high categories) is typically high on damp soils, peatlands and on fertile sites (Table 5). For example, on peatlands the odds ratio of a crop tree to belong to substantial or high category over low category was 1.30 or 1.68 fold of that what it was on medium coarse mineral soil. Previous studies by Jokinen (1973) on damp soils and by Kiljunen (2004) on peatlands found that both types of soil encourage the emergence of hardwoods and the need for EC. Furthermore, in this study, the need for EC was especially low on unprepared, and on early cleaned sites. The odds ratio of a crop tree to belong to substantial or high need for EC categories over low on unprepared soils compared to disc trenching was 0.60 and 0.48. In comparison to an earlier study, Kiljunen (2004) did not find similar effect of need for EC being especially low on unprepared sites. Figure 4 illustrates the proportions of crop trees belonging in to different need for EC categories estimated with the model represented in table 5.

Stand age did not have a significant effect on need for EC, which was unexpected. Actually, the distribution of trees in different need for EC categories was almost stable between 4–7 years from establishment. According to Kaila et al. (2006), the mean height growth of Norway spruce established by modern methods increases rapidly in 4–7-year-old stands, but only equals that of the growth of birch after 11–12 years (Kaila et al. 2006). On the other hand, it is known that the variation of height and height growth are high between individual trees (Saksa et al. 2005). Thus, spatial variation of growth of spruce and birch can explain the constant state found in the need for EC. Locally, the height growth rate of freely grown 4-year-old spruce may already equal the growth of birch. However, study **III** was not a follow-up study and yearly climatic variation can be one cause for a variation in the need for EC. This may explain why the need for EC as a function of stand age was not recognized in study **III**.

EC demonstrated effective crop-tree release in study **II** (Fig. 5). EC increased the growth of stem diameter by 21–32% (15–19% without correction) in 6–7-year-old spruce stands. Height growth and mortality rate were not significantly affected by EC during the 3-year study period. However, it is well known that the diameter growth of northern conifers reacts to release treatment 2–3 years earlier than does height growth (Jobidon 2000; Zenner 2008). The, height growth eventually exhibits a similar response when the observation period is extended (Jobidon 2000; Krasowski & Wang 2003; Hoepting et al. 2011).
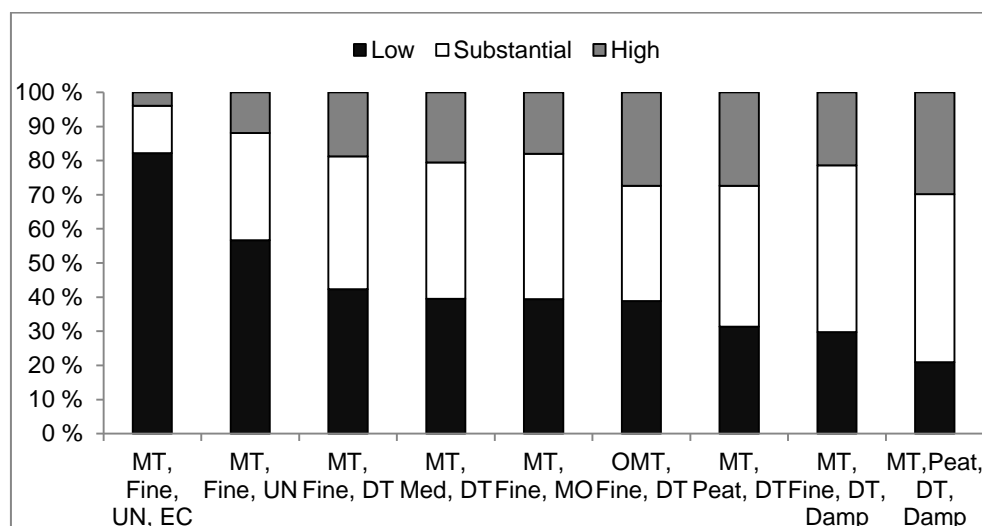

Figure 4. Examples of how conifer crop trees distribute into the three different (low, substantial and high) need for early cleaning categories according to site type (MT = *Myrtillus* type, OMT = *Oxalis-Myrtillus* type), soil texture (Fine, Med, Peat), soil preparation method (UN = no soil preparation, DT = disc trenching, MO = spot mounding), dampness (Damp), and early cleaning (EC).
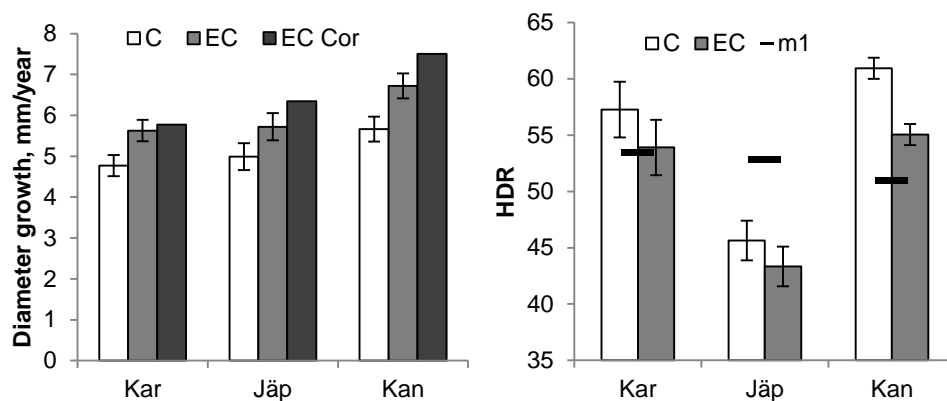
Figure 5. Mean diameter growth and corrected mean diameter growth (EC cor), and height to diameter ratio (HDR) of Norway spruce on early cleaning (EC) and control (C) treatments in Karttula (Kar), Jäppilä (Jäp), and Kangasniemi (Kan) sites (m1 = initial value of the respective variable in the first measurement, error bars are 95% confidence intervals).

Good diameter growth after EC led to decreased *Height/Diameter Ratio* of the released saplings. Jobidon (2000) and Wagner et al. (1999) have suggested that a high *Height/Diameter Ratio* is an indicator of competition. However, in study **II**, initial *Height/Diameter Ratio* did not show a clear response to EC (Fig. 5). Thus, in this particular study high initial *Height/Diameter Ratio* was not a good indicator of a tree's ability to recover after EC.

A high enough *Height/Diameter Ratio* might, however, indicate that EC was too late when it was carried out, and that therefore the EC itself caused the stress reaction in these trees. Stress can suppress the growth of released conifers. Cleaning can drastically affect the microclimate around the released tree, and such sudden changes can cause physiological shock (Mohammed & Parker 1999), which in turn reduces the growth rate (Krasowski & Wang 2003). Cleaning can suppress the growth of previously heavily-shaded conifers for several years, but once new needles are grown and physiological adjustments are made, the released saplings tend to grow quickly (Krasowski & Wang 2003). Therefore the stress caused by shading from the hardwood should be avoided and Norway spruce stands should be released from competition before the saplings adjust their physiology to low-light and sheltered conditions. Study **III** showed that Norway spruce saplings usually become overtopped by hardwoods as early as 4–5 years after their establishment.

Regardless of treatment, most of the shortest trees at the Jäppilä site were badly damaged by frost (**II**). Young saplings are sheltered from frost by the surrounding hardwoods if the latter are sufficiently tall and dense (Leikola & Rikala 1983; Heikurainen 1985; Örlander & Karlsson 2000). At Jäppilä, however, those plots containing short Norway spruces actually benefitted from EC, which suggests that any shelter from adjacent hardwoods was ineffective. However, our findings suggest it would appear that the positive effects of EC are enhanced in frost-free locations.

Sprouting intensity after EC varied considerably among the sites (**II**). However, EC significantly lowered hardwood density in two of the three sites studied (Fig. 6). This is unexpected given that many studies report high survival and resprouting rates for cut hardwood stumps (Johansson, T. 1987; 1991; 1992a; 1992b; Rydberg 2000). The stands in our study were cleaned during the late summer and cleaning date is known to affect re-sprouting of hardwoods, i.e., cleaning during the growing season prevents intense sprouting of young hardwoods (Stoeckler 1947; Johansson, T. 1992a; Bell 1999; Xue et al. 2013). Moreover, small diameter stumps (< 3 cm) do not sprout as intensively as larger ones (Hakkila 1985; Johansson, T 2008), which might explain how sprouting can be very mild after EC. The findings from study **I** support the result of low intensity sprouting after EC; as there were 17% fewer trees$_{TBR}$ at PCT of spruce stands, when the stands had had EC compared to the uncleaned stands.

Sprouts that re-grew after EC were much smaller than those that had grown freely since the stands had been planted (Fig. 6). As might be expected based on the findings of Björkdahl (1983) and Johansson, T. (1987; 1992a), sprout dominant height was related to the dominant height of those cut in the EC (Fig. 7). Whether this relationship is due to the size of the rootstock, the soil fertility, or a combination of both is difficult to determine in this study. In addition, a released spruce would already hinder the growth of the closest neighboring sprout rivals; the sprouts that were closest to the spruce grew slower than sprouts further away from the spruce sapling (Fig. 7). The result is logical as most competition indices are based on the size difference and distance between the neighboring trees (Thåm 1989; Canham 2004). This result indicates that removing only hardwoods within one meter from the crop trees can be an efficient method to restrict sprouting after EC.
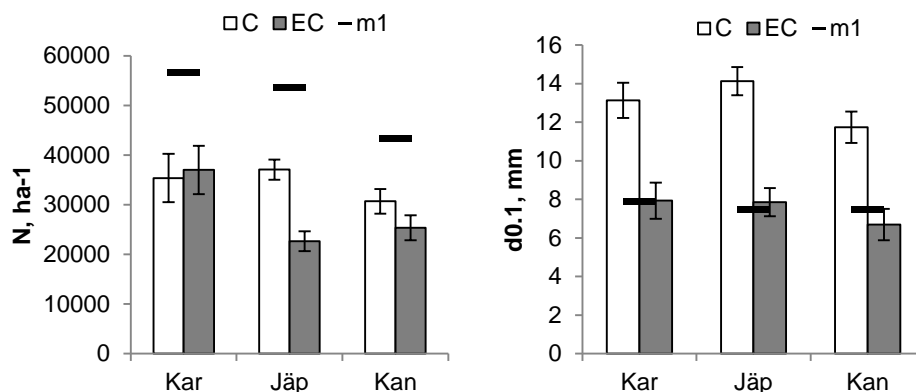
Figure 6. Density (N, ha^{-1}) and mean stem diameter (d$_{0.1}$) of non-crop trees in early cleaned (EC) and control (C) treatments in three Norway spruce stands (m1 = initial value; error bars are 95% confidence intervals).
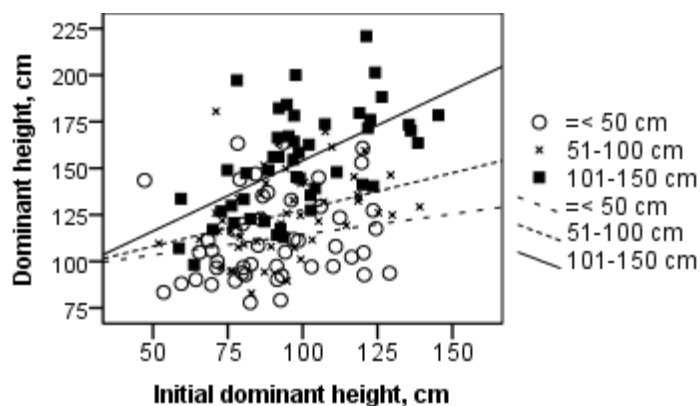
Figure 7. Dominant height (H$_{dom}$) of hardwood sprouts 0–50 cm (*r* 0.19), 51–100 cm (*r* 0.35), and 101–150 cm (*r* 0.57) from the central spruce three growing seasons after early cleaning. Data combined from all of the three sites in study **II**.

In the study **II**, The estimated time required to clean control plots during the first measurements (5-year-old stands) was 1.5–1.8 days per hectare. During the second measurement, the time required to clean the same plots was 1.6–2.0 days per hectare (Fig. 8). A delay of 3–4 years increased the time required to clean the stands by 2–16%. The difference was less than expected according to the study by Kaila et al. (2006) and study **I** (Fig. 9). It seems that the increase in work time due to delay of the cleaning in study **II** was not typical for Norway spruce stands. However, hardwoods of <0.5 m were not tallied in the second measurement, which accounts for the difference between the first and second measurements. In addition, the measurers changed between the different stand measurement times, which may also account for the difference.

The estimated time required to clean EC plots during the second measurement, 2–2.5 growth seasons after EC, was 1.0–1.5 days per hectare. Dealing with the sprouts required 18–49% less labor time than cleaning control plots depending on the study site. Consequently, because need for subsequent operation is very likely after having EC, a management regimen that includes EC appears to be a bit more labor time consuming than the PCT-only option. The results of study **II** are in line with the findings of study **I**, in which most EC stands required much less labor time at PCT than the MT and OMT spruce stands that had no EC (Fig. 9). Furthermore, Saksa & Miina (2010) ended up with similar result for Scots pine stands for which PCT required 35% more labor time in PCT only option, but the total JSM program 22% less than if also EC was included.

Figure 8. The estimated mean labor time consumed (LC) at the start of the follow-up period (m1), and at the end of the follow-up period in control (C) and early cleaning (EC) treatments in three study sites (error bars are 95% confidence intervals).
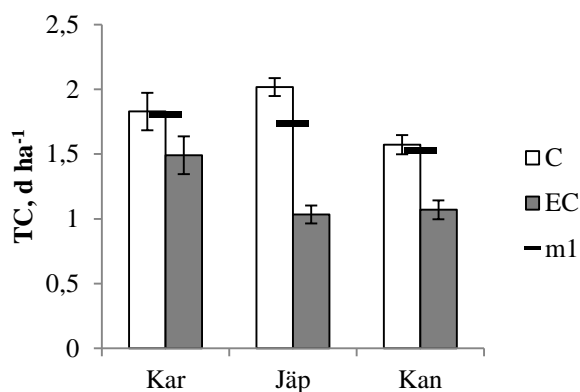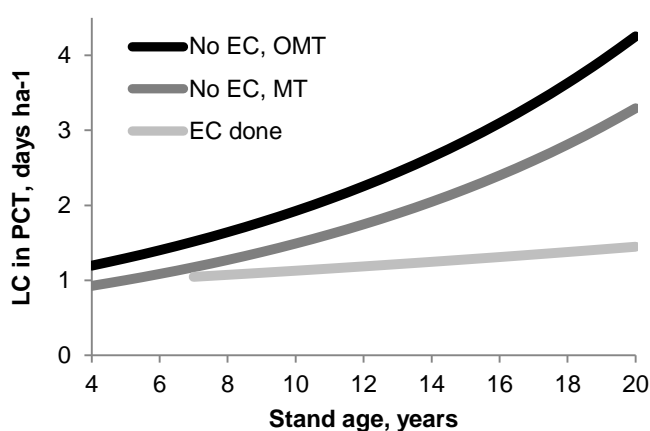

Figure 9. The estimated labor time consumed (LC) in precommercial thinning (PCT) generally in early cleaned (EC) stands (LC_{PCT}, study **I**) and in OMT and MT spruce stands which have had no EC done (LC_{NPCT}, study **I**).

The effect of the soil preparation method on JSM (IV)

The soil preparation method in the field experiment of study **IV** affected establishment of trees$_{TBR}$. Density of the trees removed in EC was 56% higher in disc-trenched treatment (22 570 ha^{-1}) compared to that of spot-mounded treatment area (14 490 ha^{-1}) (Fig. 10). The trees$_{TBR}$ were also larger and spatially closer to the crop trees for disc trenching treatment compared to spot mounding. It is typical that the soil preparation method that exposes much mineral soil, such as disc trenching produces a great amount of hardwood generation and growth to compete with conifer crop trees (Raulo & Mälkönen 1976; Valtonen 1988; Saksa et al. 1990; Agestam et al. 2003; Lorenzetti et al. 2008). According to Raulo & Mälkönen (1976), the numbers of hardwood seedlings increases by 55% when the prepared area increases from 15% to 33%. This is a plausible difference between disc trenching and spot mounding, and it nearly equals the 56% increase in hardwood found in the study **IV**. The mean height of spruce trees was 110 cm for spot mounding and 68 cm for disc trenching treatments, which is consistent with the previous findings of Hallsby (1994), Nordborg (2001), Örlander et al. (2002), and Saksa et al. (2005).

Although the site in study **IV** was highly representative with a typical Finnish regeneration site for Norway spruce, the lack of statistically valid blocks and geographical limitations must be taken into account when generalizing the results of that study. After all, generalization of the results of the soil preparation effects on hardwood establishment in large scale survey studies **I** and **III** was not achieved. Even though soil preparation generally increased the need for EC (**III**) and labor consumption in PCT (**I**), the differences between soil preparation methods were mostly insignificant. However, it should be noted that the choice of work sites in practice will also affect the results in the survey studies because soil preparation techniques are site dependent. For example, mounding methods are generally applied to damp and fertile sites that favor hardwoods, whereas disc trenching is the recommended choice on drier sites (Hyvän metsänhoidon suositukset 2002; Hyvän metsänhoidon suositukset 2006). The effect of soil preparation may also vary under different site conditions. Interactions between soil

preparation methods and soil textures were evaluated in the need for EC analysis in study **III**. Some differences were found, but they were not large enough to be included in the final model.

Even though the results of the study **IV** were expected and the effect of soil preparation method on trees$_{TBR}$ were congruent with those reported by Raulo & Mälkönen (1976), the results of the studies **I** and **III** suggest that intensive experiments about the effects of different soil preparation methods on the establishment of hardwoods would still be needed. The possible effects of geographic locations and varying conditions of forest sites should be clarified further.
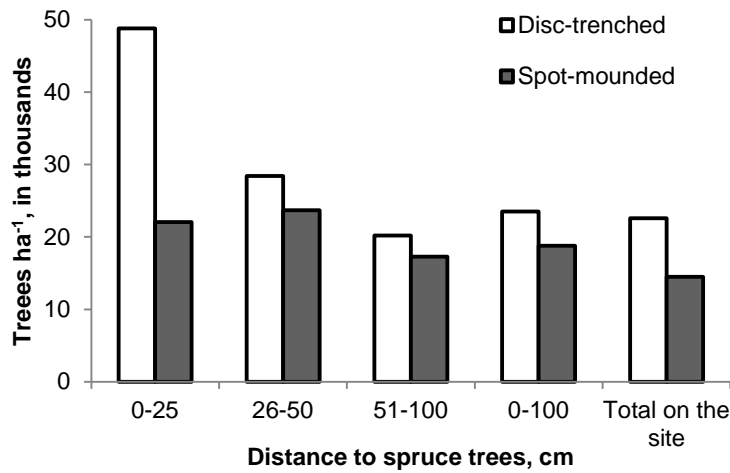
Figure 10. The densities of the trees to be removed by EC in disc-trenched and spot-mounded areas according to the distance to crop spruce.

COST-EFFICIENT JSM

Optimizing the regeneration chain

Stand establishment is a sequential chain of activities, in which the earlier activities inevitably affect those that occur later in the sequence via the mechanisms of growth of crop trees and abundance of competing stems. Value-adding work time has to be efficiently used in the integrated regeneration chain process as a whole. For the regeneration chain to be optimized, each activity in the chain must be lowest cost, and aim to serve the overall objectives of minimizing the growth and development of competitors and maximizing the growth of the crop trees.

Juvenile stands are highly variable and dynamic environments, and the effects of the silvicultural activities are complex to handle using broadly generalizable stand simulators (Parviainen et al. 1985; Räsänen et al. 2004). Thus, the behavior of costs of JSM has often been simplified in forest management simulators and economic analyses of stand establishment. They have been included in analyses as fixed variables, independent of timing of the activity or of implementation of earlier activities (Hyytiäinen et al. 2006; Metla Metinfo 2009; Bataineh et al. 2013; Sved & Koistinen 2015). However, ignoring timing of the activity or the interactions between different early silvicultural activities can produce a rather incorrect result as a whole. The research for this thesis specifically focused on the key components of the regeneration chain from PCT back to soil preparation to determine the most crucial interactions and their cost-effective integration. The conclusions for practical implications of cost-efficient JSM in a regeneration chain are the following:

PCT

1. The cost of PCT accrues as a juvenile stand grows (**I**). The increases in costs are high, especially in spruce stands for which the labor consumption doubles in nine years. Thus, PCT should be implemented as soon as post-treatment re-sprouting is expected to cause minimal risk of JSM to recur. The growth simulations of study **II** suggest that a well-established stand will be safe for PCT when the stand exceeds the dominant height of three meters.

The timing of PCT is an important variable in a cost-efficient JSM. The labor time needed for PCT in Norway spruce stands increases by more than 8% annually (**I**). Thus ending this increase should be done as early as possible. However, it is not exactly known how the need for clearing before the first-commercial thinning depends on the timing of PCT. This also includes the optimal timing of PCT. Rather long-term field experiments are needed to fulfill this gap in information.

EC

2. EC is an effective release treatment in spruce stands (**II**). It increases growth of the crop trees and decreases further costs of PCT overall. However, the management strategy that includes EC appears to entail higher costs for EC + PCT than the PCT only option. Neither of the strategies turned out to be superior over the other in the case of typical spruce stands. However, a consideration of the growth benefits to spruce caused by EC and the risks generated by not carrying out EC (later growth losses and wind, ice, and snow damage), suggests that EC is recommended to be done when needed. A Norway spruce stand most likely needs EC further on and the need typically emerges as early as in 4–5-year-old stands (**III**).

On the sites studied, sprouting of hardwoods after EC was mild compared to earlier studies in the literature (Ferm et al. 1985; Johansson, T. 1987; 1991; 1992b; Rydberg 2000, Johansson, T 2008). However, most of the previous studies on sprouting have been made on stands that had already exceeded the optimum age of EC, and where the trees had grown larger and were vigorously sprouting compared to those in the EC stands. On the other hand, Johansson, T (1992a) studied sprouting of 2–5 year-old birches with results similar to those of this present study. He reported that 47% of Silver birch stumps were living four years after cleaning, with 1.7 sprouts per stump, and, at five years after cleaning, 86% of Pubescent birch stumps were living, with 1.8 sprouts per stump. It seems, therefore, that EC has the potential to substantially decrease the costs of PCT. The decrease according to study **II** was 18–49%. However, variation in sprouting is known to be high, which is why these results should be generalized with caution.

Table 1. The effect of soil preparation on the costs of regeneration chains and revenues from the first commercial thinning (NPV = net present value, PCT = precommercial thinning).

	Stand age, years	Cashflow with discount rate of		
		0%	3%	5%
Disc-trenched				
Costs, € ha^-1		*1 625*	*1 423*	*1 319*
Soil preparation	0	152	152	152
Planting	0	588	588	588
Early cleaning	6	230	193	172
2. Cleaning	8	352	278	238
PCT	12	303	213	169
Incomes, € ha^-1				
Thinning	28	1198	524	306
NPV, € ha^-1		-427	-899	-1 013
Spot-mounded				
Costs, € ha^-1		*1 278*	*1 175*	*1 122*
Soil preparation	0	270	270	270
Planting	0	549	549	549
Early cleaning	6	158	132	118
PCT	10	301	224	185
Incomes, € ha^-1				
Thinning	26	1 304	605	367
NPV, € ha^-1		26	-571	-755

Soil preparation

3. Soil preparation methods can have a large effect on JSM-costs compared to the costs of the soil preparation work itself (**IV**). The total cost of the regeneration chain is what matters when comparing different kinds of soil preparation methods. Desired methods expose just enough mineral soil to promote good spruce growth, without encouraging excessive hardwood germination and growth. With respect to this, spot mounding is a cost-effective soil preparation method for a typical Norway spruce planting site, even though it is initially a more expensive method than disc trenching. Another useful method can be invert mounding, as it has similar benefits for spruce as spot mounding, but it exposes even less mineral soil (Löf et al. 2012; Johansson, K et al. 2013).

Depending on the discount rate and the soil preparation method used, the present value of the costs of the later activities in a regeneration chain was 4–10 times higher than the soil preparation cost (**IV**). Thus, instead of the direct costs of the activity itself, it is even more important to consider the effects it can cause in terms of cost savings or extra expenses of the subsequent activities in the regeneration chain.

The investment analysis in study **IV** revealed that the cost of disc trenching was 152 €/ha and the cost of spot mounding 270 €/ha (Table 1). On the other hand, the costs of the later activities in the regeneration chain were respectively 1 473 €/ha and 1 008 €/ha. Even though disc trenching is a less expensive soil preparation method than spot mounding, the total expenses were 347 €/ha higher for the disc-trenched management option than for the spot-mound method. The difference was mainly caused by the disparity in JSM-costs because disc trenching increased the costs of EC and also created the need for an extra cleaning.

The only possibility to evaluate the cost-efficiency of the alternatives in the present study was to simulate the management programs scheduled after EC. Thus, the result of the investment analysis is strongly dependent on the model projections and the assumptions of the simulation system. Proper long-term experiments were unavailable under the conditions described, therefore there is a high risk of errors in the results of the simulations (Pitt et al. 2013a).

Repetition and generalization of the result of the soil preparation effect on the establishment of hardwood was not achieved in large-scale survey studies (**I, III**). Thus, the results should be generalized cautiously. Further research would be needed about the effects of soil preparation methods on the costs of JSM under varying site conditions.

Regeneration chain

Overall, the principle of efficient integrated process of TBM can also be valuable in forestry. Reallocating the resources from the standpoint of the whole regeneration chain process can give instant savings for the business, in which increasing operational efficiency through technological development has proven to be time and resource demanding.

Optimizing the decision-making of JSM

Decision making tools based on forest management plan data would be beneficial for reducing non-value adding time in JSM. The purpose of such methods is to take advantage of *a priori* information available from the sites and stands, and use it in ICT-based systems to predict the need for JSM and the labor consumption of JSM. More precise and accurate information in real-time planning systems can increase the visibility between the silvicultural services provider and the customer (forest owner) in the demand-supply chain of silvicultural services. The greater the visibility of the demand-supply chain, the more efficient the relationship between forest owner and silvicultural service provider can be (Holmström et al. 2010).

A successful estimation of labor consumption or classification of the need for having JSM would be valuable information. Such could diminish the number of field inspections and thereby reduce the labor consumed and its cost in JSM. Field inspections are relatively expensive compared to the costs of a typical JSM operation. They are also rather unreliable, as affordable field inspections can only provide a snapshot and thus give a cursory measurement of the stand. The inspection can also be mistimed. For example, the forthcoming need for JSM could be challenging to estimate, or, the JSM could already have been delayed. Thus, *a priori* predictions in real-time planning systems could also enhance the quality and effectiveness of JSM by enabling new opportunities to approximate the correct timing of JSM activities.

The potential of modeling the need for EC (**III**) and for estimating labor consumption in PCT (**I**) were examined in this thesis. Attributes used in forest management plans such as site type, stand age, soil preparation method, stand density, or area of the stand were found to be significant predictors, at least in either of the models (see the later parts of this section and tables 2 & 3). However, only the model that estimated labor consumption in PCT was found to be encouraging for practical implications of such models (**I**). The ability to categorize typical Norway spruce sites according to their need for EC was relatively weak (**III**). The conclusions for practical implications on optimizing decision making in JSM are given as follows:

Labor consumption in PCT

4. Labor consumption in PCT varies greatly between different sites and stand variables. Thus, labor consumption models of PCT could be efficiently used in estimating the costs of PCT in forest simulation systems and real-time forest management plans (**I**). For example, the models would be useful in planning and analyzing different kinds of management programs, or in budgeting forthcoming JSM tasks. However, models that are based on traditional forest management plan data are rather inaccurate for *a priori* pricing of PCT. Nonetheless, if non-value-adding labor of pricing of a worksite forms a high part of the total costs of the work, and especially if the pricing consists of large set of small individual worksites, *a priori* pricing could be rational. Unfortunately, the dataset analyzed in this study lacked the exact timing information of EC, which is why estimates of the stands that had no EC done are the only accurate estimates in the management program of PCT alone.

The fit of the labor consumption models of PCT were explored by comparing stand level variances with fixed effects in the model and without them (Table 2). Attributes that affect LC_{NPCT} (no EC done) were main tree species, and in spruce stands, age of the stand, site type, soil preparation method and area of the site. These fixed effects accounted for 47.6% of the variance at stand level. This kind of model might be used in planning and implementing cost-effective management programs for commercial forests.

The fit of the model of the EC stands (LC_{PCT}) was poor; the fixed effects accounted for only 6.7% of the stand level variance, and the only significant independent variable found was stand age. Timing of EC was impossible to reliably determine in the dataset, as forest owners are not obligated to keep records of EC activities. For that reason, the model may not be practical. However, comparison of the LC_{NPCT} and LC_{PCT} models (Fig. 9) suggests that EC does reduce labor consumption in PCT in spruce stands by substantial amounts. Thus, with such adequate precise timing information of EC, this kind of model could be improved, and likely be as effective as the LC_{NPCT} model.

Table 2. Mixed linear regression model for labor consumption of precommercial thinning on conifer and hardwood stands with no early cleaning done. The dependent variable is $Ln(LC_{NPCT})$ in days ha^{-1}, the random stand and plot level effects are u_j (Var = 0.379^2) and e_{ij} (Var = 0.542^2), all variables had 308 df, and the model fit is 47.6%. OMT = *Oxalis-Myrtillus* type, MT = *Myrtillus* type, VT = *Vaccinium* type. The p-values lower than 0.001 are rounded to 0.001.

Parameter	Estimate	SE	t	p-value
Intercept	-0.976	0.230	-4.245	0.001
Dominant tree species (Ref. Hardwood)				
Scots pine	0.014	0.279	0.050	0.960
Norway spruce	-0.355	0.239	-1.486	0.138
Stand age	0.032	0.018	1.797	0.073
Stand age * Scots pine	0.018	0.023	0.809	0.419
Stand age * Norway spruce	0.047	0.021	2.267	0.024
Stand age * Hardwoods	0.000	0.000		
Site type (Ref. VT)				
OMT	0.761	0.106	7.189	0.001
MT	0.506	0.088	5.719	0.001
Soil preparation method (Ref. not prepared)				
Continuous trace	0.107	0.096	1.106	0.270
Spots	0.316	0.097	3.271	0.001
Ln(Area), ha	0.136	0.035	3.918	0.001
Variance components [Stand (u_j), Plot (e_{ij})]				
Var(u_j)	0.144	0.016		0.001
Var(e_{ij})	0.293	0.012		0.001

Need for EC

5. The model for predicting the need for EC was not applicable in practical forestry (**III**). It seems that an inspection of a juvenile stand is still the only way to ascertain if a stand needs EC. However, the option for large scale forest owners could be to send a forest worker to do the inspection in 4–6-year-old stands, and for that worker to clean the stand simultaneously, if needed. This could be a rational strategy, because of the high likelihood of spruce stands of that age needing EC. Implementing EC systematically would increase the growth of sapling stands and possibly save JSM-costs by decreasing non-value-adding work in the forest regeneration chain.

The model for predicting the need for EC of a Norway spruce sapling stand was relatively ineffective as the model's overall classification efficiency to predict the three categories was only 42.5%. The age of the stand did not have significant effect on the need for EC in the model simulations, which is the most significant reason for poor applicability of the model in practice. The distribution of saplings in the different categories was almost stable in 4–7 year-old stands. Even though site type, soil texture, soil preparation method, EC, stand density and site dampness explained variation between the categories, the distributions of the categories did not vary much between the most common site conditions. Thus, the model is highly limited in facilitating decision making about EC. The conclusion of *a priori* estimation of need for EC is the same as that reported by Kiljunen (2004) in that a survey of young stands is necessary.

Studies **I** & **III** are explanatory surveys. Thus, it has to be remembered that the validity of the results, especially of those results that were not handled in studies **II** & **IV**, should be re-examined by more rigorous testing.

Table 3. The multinomial multilevel logistic regression model for the probability of a crop tree needing early cleaning categorized as: Low (reference category), Substantial or High. The parameter of stand density has been centered on the mean density of the estimated trees per plot. Therefore, by dismissing the variable, the model can be easily used when the density of the stand is unknown. If stand density is known, for example 1 600 trees per hectare, then the parameter value will be 1.6 - 1.9927 = -0.3927.

Parameter	Estimate	SE	Odds ratio
Sub-model 1: Substantial need for cleaning			
Intercept	-0.047	0.070	0.954
Site type (ref. OMT)			
MT	0.059	0.070	1.061
Soil texture (ref. Medium)			
Fine	-0.094	0.072	0.910
Peat	0.265	0.152	1.303
Soil preparation (ref. DT)			
Unprepared	-0.507	0.224	0.602
Patching	0.011	0.106	1.011
Mounding	0.159	0.125	1.172
Early cleaning	-1.190	0.172	0.304
Stand density, th. conifers/ha (ref. 1.9927)	0.211	0.036	
Dampness	0.578	0.124	1.782
Early cleaning * Site type (ref. Uncleaned, OMT)			
Early cleaning * MT	0.496	0.211	1.642
Sub-model 2: High need for cleaning			
Intercept	-0.191	0.144	0.826
Site type (ref. OMT)			
MT	-0.463	0.084	0.629
Soil texture (ref. Medium)			
Fine	-0.161	0.088	0.851
Peat	0.521	0.173	1.684
Soil preparation (ref. DT)			
Unprepared	-0.745	0.321	0.475
Patching	-0.074	0.158	0.929
Mounding	0.031	0.183	1.031
Early cleaning	-1.484	0.218	0.227
Stand density, th. conifers/ha (ref. 1.9927)	-0.015	0.042	
Dampness	0.486	0.148	1.626
Early cleaning * Site type (ref. Uncleaned, OMT)			
Early cleaning * MT	-0.137	0.302	0.872

Random part of the models: The variances (var) and the covariances (Cov) of the random stand (v_{jl}) and plot (u_{jlk}) effects for the sub models 1 and 2

Stand	Estimate	SE	
var(v_{1l})	0.284	0.040	
var(v_{2l})	0.808	0.097	
cov(v_{1l}, v_{2l})	-0.186	0.047	
Plot			
var(u_{1lk})	0.140	0.039	
var(u_{2lk})	0.099	0.051	
cov(u_{1lk}, u_{2lk})	0.065	0.033	

Generalization of the results

This thesis focused on planted Norway spruce stands and their cost-effective JSM-programs. All the data for the study were gathered in 2005–2010 from stands located in central Finland.

Even though all the stands were recently measured saplings stands, the establishment techniques used may have differed from those of the most recent practices, especially in the data from the oldest stands of the survey. Young stand establishment techniques keep evolving, thus early height development of planted spruce saplings has become faster (Örlander et al. 1998, Saksa et al. 2005, Kaila et al. 2006). This may reduce the need for JSM and also the

growth response of the released saplings subsequent to JSM. The intensive field experimental sites were established using modern forest regeneration techniques and container-grown quality seedlings. The results can be considered to be valid as long as the establishment techniques are similar to those techniques used in the study material.

The field experiments from the soil preparation to EC were rather short-term trials, and they only continued for two to three years past the EC phase. Thus, the experimental period was only a relatively short part of the stand rotation age and about one third of a period from the stand establishment to the first commercial thinning. It is therefore highly likely that all the possible effects of the treatments cannot be detected during such a short time period. In addition, the datasets of the intensive field experiments were regional, which thus further limited the extent to which results can be generalized.

The generalizability of the experimental results was enhanced by the extensive surveys of sapling stands produced by forest regeneration practices. The survey approach yielded a good understanding of cost development of JSM in different kinds of stands. However, the survey data did not consistently support the results of the field experiments. For example, there was a disparity in the effect of different soil preparation methods on subsequent labor consumption estimated for the forthcoming JSM. Indeed, soil preparation generally added labor time consumed in JSM, but then, the differences between soil preparation methods were minor in the survey data. Survey data can be problematic to analyze statistically because, the establishment methods are not randomly set. Instead, the choice of the establishment methods is the result of human decisions, and thus it is possible that the selection of the establishment methods in practice may explain hardwood development better than the information provided by forest management plan. Thus, the results of the survey studies are valid only when the distribution of the establishment methods follows the decisions of the original dataset, i.e. the establishment methods are selected in the same way as they were selected when the stands whose information are in the datasets were established.

By taking into account these possible limitations, the results are valid for the planted Norway spruce stands in central parts of Finland. Especially in the most typical cases of soil prepared mineral soil sites. Even though the exact results are not totally generalizable on a larger scale, the phenomena described are broadly applicable for boreal spruce forests. The clear conclusion is that the soil preparation method comprehensively affects the whole process of regeneration and the costs of the process depend on the number and timing of JSM-activities.

Conclusions and further perspectives

The findings of this thesis indicate that long-term, outcome-based thinking is important in silvicultural decision making in order to optimize economics of the regeneration chain. Cost-effective decisions are possible only when the effects of the activities are accounted for years ahead. It is possible to integrate the regeneration chain to use the value-adding work more efficiently. It is also possible to reduce non-value-adding work in the regeneration chain by more efficient decision making. Thus, silvicultural costs can be reduced with effective operations management, while maintaining or even increasing the production of commercially valuable wood.

Forest management plan data have formerly been used mainly for decision making about the timing and implementation of wood harvesting, and such data are also suitable for estimating the development of the growing stock of mature crop trees. However, this study showed that such data can have limited value when applied to JSM. Thus, any new hitherto undiscovered attributes that are applicable for the modeling of JSM-activities could enhance the effectiveness of a modeling approach in decision making of JSM. "Big data", referring to all aspects of collecting, storing, and utilization of large amounts of data (Hämäläinen et al. 2014), may offer potential. Räsänen (2016) named worksite design in silviculture as one of the aspects to develop through big data, for example, the use of more detailed classification of sites according to fertility, soil texture, stoniness and dampness. There were few candidates for affordable and reliable variables for decision making of JSM found during this present study.

One of the most important development stages in enhancing the decision making of JSM is to define more precisely, and preferably quantitatively, any methods to determine soil moisture. The precise mapping of contours or vegetation cover of certain species could provide further appropriate estimates. Digital elevation model and topographic wetness index based on Airborne Light Detection and Ranging (LiDAR) could offer one possibility (Murphy et al. 2009; Sørensen & Seibert 2007). For example, Peuhkurinen (2016) described a moisture level model that is designed to help decision making of harvesting operations. Similar model could be suitable for estimating hardwood development in sapling stands.

Information about precise timing of the previous early silvicultural management tasks and activities would also be essential information. The timing of the earlier JSM is especially important, but also the time lags between clear-cut, soil preparation and regeneration events increase the number or size of hardwoods (Raulo & Mälkönen 1976; Lehtosalo et al. 2011). Likewise, information on the hardwood basal area prior to clear-cut and information about surrounding stands could be valuable for explaining the establishment of hardwoods. Such information would include the height and volume of surrounding stands through the edge stand effect (Siipilehto 2006). All this

information is easy to collect and store in modern ICT-based forest management platforms. Even though some work has to be done to collect, compile and store the data in appropriate systems, the development of big data makes it possible and affordable.

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