Concepts for Mechanized Tree Planting in Southern Sweden

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Cover: A 1.5-year-old *Picea abies* (L.) Karst. seedling planted August 2014 in Småland by a Bracke Planter crane-mounted planting device. At the nursery, this seedling was subject to short-day treatments and was sprayed with both *Hylobius abietis* (L.) insecticide and browsing repellent. The top of the seedling's root plug is circa ten cm under the soil.
(photo: Hans Dahlgren)

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Abstract

The underlying reason for mechanizing tree planting in southern Sweden is the biologically good planting results produced by today's tree planting machines. Nevertheless, the productivity of these tracked excavators with crane-mounted tree planting devices is too low for them to compete economically with manual planting.

The objective of this thesis was to investigate concepts for 1) seedling packaging, 2) base machines, 3) planting devices, and 4) seedling carousels that could cost-efficiently increase the productivity of today's planting machines in southern Sweden. Article I analyzed the cost-efficiency of two seedling packaging concepts that decrease the time needed to reload planting devices with seedlings. The analysis showed, however, that machine-specific seedling packaging was costlier than delivering the seedlings in their cultivation trays, although band-mounted seedlings will probably be the most flexible and cost-efficient packaging system as mechanized planting becomes more common. Article II and III used a discrete-event simulation tool and detailed terrain, machine, and planting device models to simulate the productivity of conceptual two-armed excavators and multi-headed crane-mounted planting devices. Two arms per excavator proved to be an inefficient concept for increasing the productivity of today's planting machines when compared to multi-headed planting devices. Although four planting heads per device was the most productive configuration on easy to moderate terrain, three-headed devices were best at combining high productivity with acceptable silvicultural results on all terrain types. Article IV used a test-rig to study the feasibility of tray-wise seedling reloading on today's most common planting device. Seedling reloading was twice as fast when done tray-wise rather than seedling-wise, and deplugging proved to be a reliable method of extracting seedlings from suitable cultivation trays even when performed at the excavator's boom-tip during mounding work. Overall, this thesis confirms that there is high potential for technical improvements that increase the productivity and lower the planting costs of today's tree planting machines. Such improvements will likely include faster seedling reloading via tray-wise-loaded carousels or band-mounted seedlings, multi-headed planting devices that produce high quality planting spots using adapted soil preparation methods, and sensors that aid the operator in choosing microsites.

Keywords: planting machine, reforestation, stand regeneration, site preparation, mounding, seedling, cost analysis, discrete-event simulation, silviculture, forestry

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Koncept för mekaniserad plantering i södra Sverige

Sammanfattning

Intresset för mekaniserad plantering har väckts till liv igen i södra Sverige tack vare den goda planteringskvalitén som dagens planteringsmaskiner åstadkommer. Dock är produktiviteten med dagens kranspetsmonterade planteringsaggregat för låg för att de kostnadsmässigt ska kunna konkurrera med harvning och manuell plantering.

Syftet med denna avhandling var att analysera tekniska dellösningar, för ökad produktivitet hos planteringsmaskiner i södra Sverige, beträffande 1) plantförpackningens utformning inklusive transportlogistik (från plantskola till planteringsmaskin), 2) basmaskinens krandesign, 3) planteringsaggregatets design, och 4) utformning och laddning av aggregatets plantmagasin. I artikel I jämfördes plantladdningstid och kostnader för två plantförpackningskoncept med dagens förpackningslösningar. Förpackningskoncepten var dyrare än att leverera och ladda plantorna i odlingskassett, även om konceptet med bandade plantor troligen blir både billigare och ändamålsenligare när maskinell plantering ökar i omfattning. I artikel II och III användes händelsestyrd simulering och detaljerade terräng-, maskin- och planteringsaggregatsmodeller för att simulera planteringsproduktiviteten med tvåarmade grävmaskiner och flerhövdade kranspetsmonterade planteringsaggregat. Tvåarmade grävmaskiner visade sig vara ineffektiva jämfört med enarmade grävmaskiner med flerhövdade aggregat. Även om fyrhövdade aggregat visade högst produktivitet på lätt och medelsvår terräng var trehövdade aggregat bäst på att kombinera hög produktivitet med godtagbara planteringsresultat på alla terrängtyper. I artikel IV nyttjades en testbänk för att testa kassettvis (odlingskassetter) laddning av plantor i dagens vanligaste planteringsaggregat. Plantladdningsmomentet gick dubbelt så fort med kassettvis plantladdning jämfört med styckvis laddning. Det framgick också att principen med utstötning av plantor från kassetten fungerade tillförlitligt även ute vid kranspetsen under loppet av högläggningsarbetet.

Sammantaget bekräftar denna avhandling att det finns stor teknisk potential att öka produktiviteten och sänka kostnaden vid mekaniserad plantering i södra Sverige med dagens planteringsmaskiner. Kostnadseffektiva tekniska förbättringar kommer troligen att inkludera snabbare plantladdning genom kassettvis laddning eller laddning via plantband, flerhövdade planteringsaggregat som skapar högkvalitativa planteringspunkter med hjälp av anpassade markberedningssätt, samt genom användning av sensorer som hjälper föraren att hitta lämpliga planteringspunkter.

Nyckelord: planteringsmaskin, maskinplantering, skogsodling, markberedning, planta, kostnadsanalys, händelsestyrd simulering, skogsvård, skogsteknik

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Für meine innigst geliebte Frau und meine Kinder

Contents

List of Publications

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

I Ersson, B.T., Bergsten, U. & Lindroos, O. (2011). The cost-efficiency of seedling packaging specifically designed for tree planting machines. *Silva Fennica* 45(3), 379-394.

II Ersson B.T., Jundén L., Bergsten U. & Servin M. (2013). Simulated productivity of one- and two-armed tree planting machines. *Silva Fennica* 47(2), article id 958. 23 p.

III Ersson B.T., Jundén L., Lindh, E.M. & Bergsten U. (2014). Simulated productivity of conceptual, multi-headed tree planting devices. Accepted for publication in *International Journal of Forest Engineering*.

IV Ersson B.T., Bergsten U. & Lindroos O. (2014). Reloading mechanized tree planting devices faster using a seedling tray carousel. *Silva Fennica* 48(2), article id 1064. 14 p.

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The contribution of the authors to the articles included in this thesis was as follows:

I Ersson helped formulate the study's specific objectives, collected and analyzed all data, and wrote the manuscript. Bergsten formulated the study's initial aim, helped draw conclusions, and contributed to the manuscript's revision. Lindroos helped with the data analysis and contributed to the manuscript's revision.

II Ersson helped formulate the study's specific objectives, did the majority of the modelling, analyzed all data, and wrote the manuscript. Jundén did the rest of the modelling, all the programming, and contributed to the manuscript's revision. Bergsten formulated the study's initial aim, helped draw conclusions, and contributed to the manuscript's revision. Servin helped with the modelling and programming.

III Ersson formulated the study's objectives, did some of the modelling, analyzed all data, and wrote the manuscript. Jundén and Lindh did together the rest of the modelling and all programming. Bergsten helped draw conclusions and contributed to the manuscript's revision.

IV Ersson helped formulate the study's specific objectives, collected and analyzed all data, and wrote the manuscript. Bergsten formulated the study's initial aim, helped draw conclusions, and contributed to the manuscript's revision. Lindroos helped with the data analysis and to draw conclusions, and contributed to the manuscript's revision.

1 Introduction

1.1 Reforestation in southern Sweden

In southern Sweden, as well as the rest of Fennoscandia, forest owners are legally obliged to reforest stands after clearcutting. Similar to Norway, Finland, and the rest of Sweden, planting tree seedlings is the preferred method of stand regeneration in southern Sweden (Eriksson, 2013b; Granhus *et al.*, 2013; Juntunen & Herrala-Ylinen, 2013). In 2012, tree planting was the preferred reforestation method on 83% of the southern Swedish regeneration areas while the rest were naturally regenerated (Eriksson, 2013b). In comparison, the proportion of Swedish regeneration areas planted, naturally regenerated, and direct seeded/sown in 2012 were 75%, 20%, and 5%, respectively.

Despite comprising only 22% of Sweden's 22.38 million ha of productive forest area available for forestry, forest land in southern Sweden (named Götaland, or Gothia, Figure 1) is fertile and yields 31% of Sweden's total annual volume increment (Skogsdata, 2013). This high fertility results in high levels of vegetative competition (Nilsson & Örlander, 1999) on typical clearcuts, which precludes successful reforestation using direct seeding (Bergsten & Sahlén, 2003). Typical forest terrain in southern Sweden comprises moraine (glacial-till) soils (Ståndortskarteringen, 2014), have varying prevalences of stones (Stendahl *et al.*, 2009) and stumps (Skogsdata, 2013), and lack most slash because branches and tops are harvested for bioenergy on >75% of the clearfelled area in southern Sweden (Joshi & Eriksson, 2013).

Like elsewhere in Fennoscandia, forest regeneration in southern Sweden is aided by site preparation (Örlander *et al.*, 1990; Johansson *et al.*, 2013a; Johansson *et al.*, 2013b). Today, 77% of all regeneration areas in southern Sweden are site prepared before regeneration; and although 17% of southern Swedish regeneration areas are still reforested using natural regeneration, this proportion has been steadily decreasing over several decades in favour of planting (Eriksson, 2013b). Generally, stem volume production is higher for coniferous than deciduous stands (Bergquist *et al.*, 2005). And because of high ungulate pressure, planting seedlings of *Picea abies* (L.) Karst. is preferred over *Pinus sylvestris* (L.) (Bergquist, 1998). Although up to 21% of all *P. abies* seedlings planted in Sweden are bareroot stock (Eriksson, 2013b; of which the majority are planted in southern Sweden; Wennström *et al.*, 2008), this proprtion has decreased over the last forty years in favour of containerized seedlings (Johansson, 2010). Thus, reforestation of regeneration areas in southern Sweden is principally about planting containerized *P. abies* seedlings (Ersson, 2010).

Figure 1. Southern Sweden (Götaland, in grey) in relation to the rest of Sweden.

Because of high risks of *Hylobius abietis* (L.) predation (Örlander & Nilsson, 1999; Petersson & Örlander, 2003), successful reforestation of typical regeneration areas in southern Sweden requires good quality site preparation (Petersson *et al.*, 2005) and planting (Örlander *et al.*, 1991). For *P. abies* seedlings, good quality site preparation generally means making mounds with a capping of pure mineral soil (Örlander *et al.*, 1990), although seedling survival is often even higher on mesic and spring-dry areas with inverting than mounding (Hallsby & Örlander, 2004). In any case, seedling survival and growth is lower when *P. abies* seedlings are planted in scarified patches than on mounds (Örlander *et al.*, 1990; Sutton, 1993; Saksa *et al.*, 2005). Disc trenching is a form of patch scarification, resulting in continuous strings/strips of exposed mineral soil without any underlying humus (Löf *et al.*, 2012). Advantages offered by the mound's buried humus layers include higher nutrient availability (fertilization effect; Sutton, 1993) and lower soil water potential (potentially lowering frost heaving; Goulet, 1995). Good quality planting generally means planting the seedling in the most optimal position: and where that position is exactly, depends on the microsite in question (Adelsköld & Örlander, 1989).

Nevertheless, when planted in mounds, deeply planted seedlings (Figure 2) survive better than seedlings planted at normal depths (Örlander *et al.*, 1990; Örlander *et al.*, 1991; Nyström, 1994). As defined by Örlander *et al.* (1991), normal planting depth means that the top of the seedling's root plug is just a few cm below the soil surface, implying that none or very little seedling green mass is buried. Deep planting, meanwhile, means that the seedling is planted significantly deeper, with the top of the root plug being circa ten cm below the soil surface. This depth implies that some green mass is buried, with up to e.g. one-half stem being underground if the seedling is 20 cm tall. When planting in mounds, deep planting is especially important in areas prone to spring drought (Örlander *et al.*, 1991; e.g. eastern south Sweden) or to avoid frost heaving (Adelsköld & Örlander, 1989; Goulet, 1995).

Figure 2. A deeply planted *Picea abies* seedling in a compressed mound with a capping of pure mineral soil. This seedling is well guarded against vegetative competition and *Hylobius abietis* predation. Being deeply planted, the bottom of the seedling is below the two buried humus layers, which increases water supply while reducing the risk of frost heaving compared to seedlings planted at normal depths. In this case, the distance between the top of the seedling's root plug and the soil surface is ten cm. Over the next few years, the buried humus layers will decompose and provide nutrients to the seedling.

Other factors that influence reforestation in southern Sweden include many non-industrial private forest owners, small average area of regeneration, and high prevalences of cultural remains on forest land. Circa 78% of the productive forest land in southern Sweden is owned by non-industrial private owners (Christiansen, 2013). Since these owners are increasingly living in cities (Umaerus *et al.*, 2013) and do not necessarily rely on their forest estates for their main source of income, their willingness to invest (e.g. in high quality reforestations) in their forest holding may be lower than those companies or owners whose holdings are an important income source (Lönnstedt & Svensson, 2000). Based on the number of registered clearfellings in 2012, the average regeneration area in southern Sweden is 2.8 ha (Joshi & Eriksson, 2013); although the actual average area is most likely smaller since the registrations only concern regeneration areas >0.5 ha and each registration may contain more than one block/site. In any case, this figure is small compared to the national average of 4.4 ha (Joshi & Eriksson, 2013), and smaller average regeneration areas lead to more machine relocations (Rantala *et al.*, 2010; Hallongren *et al.*, 2014). Compared to the rest of Sweden, cultural remains are especially prevalent in southern Sweden (Ersson, 2010) – and many of these cultural remains bring with them restrictions on site preparation methods. For example, ancient arable land (abandoned agricultural fields cleared pre-modern age) often precludes site preparation using continuously advancing machines, meaning that only directed methods of mechanical site preparation might be permitted when reforesting such sites (Torstensdotter Åhlin, 2001).

1.2 Why mechanized tree planting?

Ever since the invention of the first tree planting machine in USA during the late 1800s (Hallonborg, 1996), tree planting has been performed either manually or mechanically. Of the circa 374 million seedlings planted in Sweden during 2012, less than one percent were planted mechanically, meaning that >99% of the seedlings were planted manually. In Finland, less than five percent of seedlings are planted mechanically (Laine & Rantala, 2013), and tree planting machines are practically non-existent in Norway and Denmark. Obviously, mechanized tree planting is rather uncommon today in the Nordic countries, so why do we care about it? More specifically, what are the advantages of mechanized tree planting compared to manual tree planting?

1.2.1 Historical reasons

Historically, the main reason why the Swedish forestry sector has striven to mechanize tree planting is a feared shortage of labour (Skogssektionen, 1971). Traditionally, trees have been planted mostly in springtime, and as the mechanization wave swept over the Swedish logging industry during the late 1960s, the once bountiful supply of forest workers started to dry up as workers left forestry to work in the cities. Thus, mechanized tree planting was seen as a way of rationalizing afforestation and reforestation by reducing the number of people planting trees (Sirén, 1969b). In the 1950-60s, another reason as good as any was the general faith in technology (Ros, 1969), i.e. that technological advances could solve most problems. Simultaneously, a less technologically utopian reason was mentioned – the wish to replace a physically demanding job with a less arduous one (Sirén, 1969b; Skogssektionen, 1971; Figure 3). Other reasons included a drastically increasing total annual area to be afforested and reforested, and the desire to reduce overhead costs, increase productivity and seedling survival when tree planting, and reduce the total cost of stand regeneration (Sirén, 1969b; Bäckström, 1978).

In the 1980s, a few more reasons were mentioned. Tree planting machines would be able to plant large seedlings more cost-efficiently than people could (Berg, 1985). Also, by replacing the forest workers who motor-manually thinned in winter but were needed to plant seedlings during spring and summer, tree planting machines would help to further mechanize the logging industry (Berg, 1983; 1991). Then, with the invention of crane-mounted tree planting devices, mechanized tree planting was considered as a way to reduce unnecessary soil disturbance during reforestation (Hallonborg, 1997; Frank, 2006).

Figure 3. With the memory of hand-scarification still ringing in their bones, Swedish silvicultural researchers started in the 1960s the quest to invent machines that would take over the toilsome task of planting trees. This search is still continuing today, although the task of preparing the soil has long been successfully mechanized. The photo shows a time study of manual scarification on heathland in Halland during 1946 (source: Skogsbibliotekets bildarkiv, SLU).

1.2.2 Today's reasons

Some of the historical reasons for mechanizing tree planting are still valid today, while some are not. The fear of labour shortage is still present (Petersson, 2008), although the mobility offered by the EU has helped Swedish silvicultural contractors to overcome the lack of Swedes willing to manually plant trees (Lefévre & Persson, 2009). Also, there is still hope that mechanization will reduce the total cost of tree planting; if not already today through lower overhead costs then at least in the near future if technical developments to the machines can be made (Petersson, 2008). Moreover, because today's tree planting machines exclusively prepare the soil using directed methods (which minimizes soil disturbance, see Löf *et al.* (2012) for explanation of directed site preparation), tree planting machines can be used to plant trees on or near historical remains, especially ancient arable land (Södra, 2012).

Most importantly, though, is the better work quality shown by today's planting machines than the standard reforestation method of disc trenching and operational manual planting in southern Sweden (Figure 4). This betterment was first shown by planting trials in the mid-2000s (e.g. site preparation trials reported in Agestam *et al*. 2006), and has since continued unabated in the form of higher seedling survival three years after planting. When planted by contractors working on a piece-rate basis for Södra Skog, mortality for manually planted (after disc trenching) and mechanically planted seedlings has averaged 26.5% versus 4.9% respectively over the three surveyed years. These surveys were performed according to Södra Skog's standards for regeneration control, and the results should be directly comparable despite not always being sourced from the same years. Clearcut selection for manual planting was essentially random within Södra's districts, while mechanized planting entailed a census survey of all larger clearcuts planted mechanically during a few months of each year in 2008-2010. There might also be a tendency that seedlings grow better when planted mechanically by today's machines in southern Sweden (Ersson & Petersson, 2013b). Mounding as the soil preparation method, deep-planting of seedlings, and better educated machine operators are three of the main reasons for the better quality planting with today's planting machines.

On the other hand, the present-day reasons given by Finnish researchers for mechanizing tree planting are mainly two, namely future labour shortages and the desire to lower silvicultural costs (Rantala *et al.*, 2009; Rantala & Laine, 2010). There, future labour shortages will probably result from a combination of an aging labour force and the tendency that forest owners are less able and keen to plant trees themselves. In any case, the possibility for cost-savings through technical development has for many years been deemed vastly greater with mechanized tree planting than with manual planting, in both Finland (Hallongren *et al.*, 2014) and Sweden (Hallonborg *et al.*, 1995).

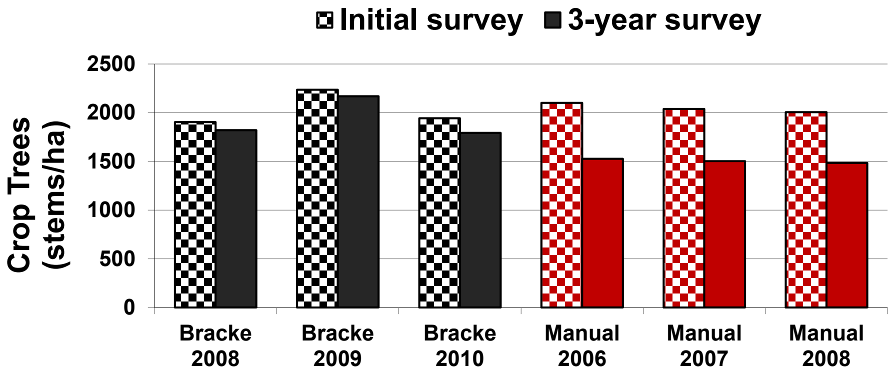

Figure 4. The number of mechanically (Bracke) and manually (Manual) planted trees alive at the year of planting (Initial survey) and three years later (3-year survey). Mechanized planting meant site preparation via spot mounding while manual planting was performed following disc trenching. All seedlings were planted by contractors working for piece-rate remuneration from Södra Skog. For manual planting, surveys were evenly distributed throughout southern Sweden on 62 different clearcuts per year. For mechanized planting, the number of surveys ranged from five to eleven clearcuts per year, and they were concentrated to Småland where the planting machines were operational. The surveys were performed according to Södra Skog's standards for regeneration control. Reworked from Ersson and Petersson (2013b).

1.3 Nordic tree planting machines

1.3.1 Past

Ever since its start in the 1960s, developmental work on Nordic tree planting machine has progressively focused on designing planting machines that can work more and more selectively. Planting machine design has progressed from continuously advancing machines with continuously ploughing planting heads to intermittently advancing machines with crane-mounted planting devices. Below, I categorize the most important examples of Nordic planting machines according to how they advance and how their planting heads work, and provide selected facts about the machines and the developmental work surrounding them.

Continuously advancing machines with continuously ploughing planting heads: similar to planting machines elsewhere in the world (Germany, USSR, USA, Canada, etc.), the first Nordic machines were designed for obstacle-free terrain, e.g. afforestation of abandoned farm land (Skogssektionen, 1971).

Bäckström *et al.* (1970) reported on studies of the YLÖ/Finn Forester (Figure 5, top left) and Silvaco tractor-towed planting units and concluded, as others had previously done as well, that continuously ploughing planting heads were inappropriate for reforestation.

Continuously advancing machines with intermittently ploughing planting heads: recurrent up-and-down motion was the logical next step when trying to make ploughing planting heads suitable for reforestation (Bäckström, 1978). Examples of machines in this category included SHS V (Figure 5, top right) and ÖSA 650 (Bäckström *et al.*, 1970). Rather quickly, though, it was established that making holes rather furrows was more effective when planting seedlings on moraine/glacial-till soils (Vikström, 1972; Andersson *et al.*, 1977).

Continuously advancing machines with hole-making planting heads (dibbles): using dibbles to perform the planting task allowed for more ergonomical and more productive planting machines (Bäckström, 1978). From the early 1970s and onwards, this machine category was deemed the most promising one (Bäckström & Wahlqvist, 1972), resulting in many proposed concepts in both Europe and North America during the 1970-80s (Lawyer & Fridley, 1981), and at least four different machine designs being built in Sweden and Finland (Berg, 1991).

In Finland, developmental work on this machine category peaked with the Serlachius planting machine (Kaila, 1984), a rather advanced, one-operator machine that prepared the soil by inverting, planted using dibbles mounted on glide bars that could support sensors (Lammasniemi, 1983; Figure 5, bottom left), and supported two different types of automatic seedling feeding systems (Stjernberg, 1985; Malmberg, 1990). At least two machines were built.

Meanwhile, developmental work in Sweden culminated in the Silva Nova (Figure 5, bottom right). Although being defunct since 2002 (Nyström, 2001) and having cost over 150 million SEK during circa 25 years to develop (Davner, 2000), the Silva Nova was an impressive planting machine (Malmberg, 1990). At least ten different machines were built (Hallonborg *et al.*, 1995) and worked commercially throughout Sweden for circa 20 years (Nyström, 2000). The Silva Nova used several types of seedling feeding systems (some automatic; Hallonborg *et al.*, 1995) and could sustain a productivity of over 2000 seedlings per productive work hour (pl/PWh). In 1997, the Silva Nova was instrumental when mechanized tree planting stood for 9% and 12% of the area planted in north and central Sweden, respectively (Lindholm & Berg, 2005).

Figure 5. Continuously advancing Nordic tree planting machines of the past: the tractor-drawn YLÖ/Finn Forester planting unit with a one-row, continuously ploughing planting head (top left); the forwarder-mounted, two-rowed SHS V planting unit with intermittently ploughing planting heads (top right); the forwarder-mounted, two-rowed Serlachius planting unit with dibbles on glide bars (bottom left); the forwarder-mounted, two-rowed Silva Nova planting unit with dibbles on planting arms (bottom right). Top row photos from Skogsbibliotekets bildarkiv, SLU. Bottom row photos from Stjernberg (1985) and Åhlund (1995) respectively.

Intermittently advancing machines with hole-making planting heads: concurrent with the development of large and expensive continuously advancing planting machines materialized the desire to design cheaper machines more suitable for smaller clearcuts (Malmberg, 1990) and obstacle-rich terrain (Berg, 1991). In Sweden, this resulted in the Hiko/Hilleshög machine (Myhrman & Zylberstein, 1983) whose three arms planted seedlings at a fixed distance from each other (Figure 6, top left). This design, however, was ineffective on obstacle-rich terrain, and the rotating scarifiers unfortunately rather pitted than mounded the soil, which lowered seedling survival (Malmberg, 1990). Arguably, the Canadian prototype planting machine named Reforester (Walters & Silversides, 1979), and the Hevotrac (Figure 6, bottom right) and Silviplant semi-/partially mechanized planting machines (Hallonborg *et al.*, 1995; von Hofsten, 1996) can be considered to belong to this category.

Intermittently advancing machines with crane-mounted planting devices: as predicted by Sirén (1969a), planting machines using crane-mounted planting devices were initially built to work on terrain that continuously advancing machines (i.e. the Silva Nova) could not. The first such device was the Doppingen, a one-headed device that surface planted seedlings with shortened root plugs and then added supplementary soil around them (Adelsköld & Myhrman, 1985). The device was crane-mounted on a forwarder and was designed to plant in rocky/boulder-rich terrain (Figure 6, top right). However, despite much research and effort, productivity and seedling survival rates were too low for the machine to survive past the prototype stage (Malmberg, 1990).

In 1991, a more successful one-headed planting device was invented in northern Sweden, namely the Bracke Planter (von Hofsten, 1993). Initially, this device was also meant to supplement the Silva Nova by being able to work on soft soils and moist sites, i.e. sites where the Silva Nova was too heavy to operate on (von Hofsten, 1992). Hence, the Bracke Planter was designed to prepare soil via spot mounding and be crane-mounted on tracked excavators (Figure 7). Unlike with the continuously advancing planting machines, the Bracke Planter's planting quality was good right from the start (von Hofsten, 1993; Hallonborg *et al.*, 1997), which has contributed to its relative success. And because the device has a robust and fairly cost-efficient design, several other countries became interested over the years in testing this planting machine configuration (Arnkil & Hämäläinen, 1995; Drake-Brockman, 1998; Nieuwenhuis & Egan, 2002; Lazdiņa *et al.*, 2008; St-Amour, 2009).

As highlighted by e.g. Bäckström already in the 1970s (Bäckström *et al.*, 1970; Bäckström, 1978), having two planting heads per crane-mounted device can offer substantial productivity benefits for crane-mounted planting devices. The EcoPlanter, invented in 1993 (Normark & Norr, 2002), was the first crane-mounted device to take advantage of this benefit (Figure 6, bottom left). The EcoPlanter was mounted on a harvester's crane (Mattson, 1997), planted two seedlings simultaneously, and reached a productivity of >600 pl/PWh during both time (Klasson & Norr, 2003) and follow-up studies (Normark & Norr, 2002). Although the last reported use of the EcoPlanter was in 2009, meaning that the EcoPlanter was in commercial use for circa 15 years, at least 12 devices were in use during the 2002 planting season (Normark & Norr, 2002). An interesting feature with the EcoPlanter was that it prepared the soil with obstacle-avoiding, telescopic milling wheels. However, on sites with thick humus layers, it needed long milling (rotovation) times to reach enough mineral soil to create soil-capped mounds. This meant that in comparison to using planting devices equipped with mounding blades on such sites, the

EcoPlanter's productivity was either lower or that seedlings planted by the EcoPlanter became more susceptible to predation by *Hylobius abietis* (Saarinen, 2006; Luoranen *et al.*, 2011).

In 2006, yet another device called the M-Planter further developed the two-headed planting device concept (Figure 8, right). The M-Planter is crane-mounted on tracked excavators, prepares the soil by mounding, can plant two seedlings simultaneously, and has a relatively low purchase price (Rantala et al., 2009).

Arguably, two-headed crane-mounted planting devices work less selectively than one-headed crane-mounted devices, a detail mirrored by the abundance of one-headed devices still in use today and their relative effectiveness compared to two-headed devices on obstacle-rich terrain.

Figure 6. Intermittently advancing Nordic tree planting machines of the past: the forwarder-mounted, three-rowed Hiko/Hilleshög planting unit (top left); the crane-mounted, one-headed Doppingen planting device which planted using extra-added soil (top right); the crane-mounted, two-headed EcoPlanter planting device carried by a harvester (bottom left); the semi-mechanized Hevotrac planting machine with two manually operated planting drills (bottom right). Photos from SLU's Skogsbibliotekets bildarkiv, Adelsköld and Myhrman (1985), Staffan Mattson/Skogforsk, and Henrik von Hofsten/Skogforsk, respectively.

1.3.2 Present

During 2013, there were fewer than ten planting machines working throughout Sweden, of which four were contracted by Södra Skog in southern Sweden. All tree planting machines in Sweden presently comprise a tracked excavator with a crane-mounted Bracke Planter planting device (Figure 7). In southern Sweden, these planting machines are recommended for mesic and moist sites since mounding is unsuitable on dry sites (Adelsköld & Örlander, 1989) and wet sites are not to be soil prepared at all (Petersson & Lindén, 2010a). In Finland, there are up to 35 tree planting machines (Laine & Rantala, 2013), of which most have the Bracke Planter, several have the two-headed M-Planter, and a few have the one-headed Risutec planting devices (Kärhä *et al.*, 2014; Figure 8). In Sweden, all seedlings planted by the planting machines are delivered to the contractor in cultivation trays or cardboard boxes. Seedlings are mostly *P. abies* but sometimes *P. sylvestris* or other conifers like *Larix* spp. In 2013, of the circa 4.7 million seedlings planted by Finnish tree planting machines, 90% were estimated to be *P. abies* and 10% to be *P. sylvestris* (Kärhä *et al.*, 2014).

Figure 7. One of the four tree planting machines contracted by Södra Skog in 2013. All four machines consist of a medium-sized tracked excavator with a crane-mounted Bracke Planter planting device. This contractor purchased his device in 1994 and has been planting with it ever since (e.g. in the UK during the trials of Drake-Brockman, 1998), although completely refurbishing it once and upgrading to newer excavators over the years.

During productive work, the procedure with all types of today's available crane-mounted planting devices begins with the base machine moving (with the aid of the crane when necessary for excavators) to a suitable stationary point. Then, the operator chooses three (Laine & Rantala, 2013) to 30 (Drake-Brockman, 1998) microsites (depending on the target stocking rate, obstacle prevalence, number of planting heads per device, visibility, crane reach, and preferred width of the work sector), moving the planting device sequentially between them. At each microsite, a mound (or hopefully two with the M-Planter) is formed, the soil compressed, and a seedling planted on the mound (Figure 9). This procedure is then repeated until the device needs to be reloaded with seedlings or the clearcut is fully restocked. When reloading seedlings, the operator exits the cab, fetches boxes or trays of seedlings from a storage box or rack, and manually refills the carousel's cavities with seedlings. The task of reloading seedlings generally takes 15-20% of productive work time (von Hofsten, 1993; Öhman, 1994; Rantala *et al.*, 2009). Depending chiefly on terrain difficulty, operator experience, and if sourced from time study or follow-up data, the productivity of planting machines with the Bracke Planter and M-Planter has been reported to range from 130-260 pl/PWh (von Hofsten, 1993; St-Amour, 2009) and 150-300 pl/PWh (Rantala & Laine, 2010; Laine & Rantala, 2013), respectively.

Figure 8. Crane-mounted planting devices currently manufactured and used in Finland, the one-headed Risutec (left) and two-headed M-Planter (right). Photos from Risutec Oy and Heidi Hallongren, respectively.

In comparison to disc trenching and operational manual tree planting, reforestation in southern Sweden with Bracke Planter planting machines requires a circa 25% higher capital expenditure for forest owners. However, disc trenching provides only continuous scarification (which is similar to patch scarification from a seedling growth point-of-view), while the planting machine creates mounds. Since mounding renders higher seedling growth

(Örlander *et al.*, 1991; Saksa *et al.*, 2005), especially for *P. abies* on moister soils, forest owners often wish to prepare the soil using mounding instead of disc trenching. In that case, most forest owners in southern Sweden have no other choice than contracting excavators to spot mound. Using excavators to create at least 2000 mounds per ha costs approximately double that of scarification with disc trenchers (Henrik Holmberg, Södra Skog, pers. comm. 2013). In turn, this makes manual tree planting and excavator-based mounding equally expensive to mechanized planting. However, manual tree planters are not able plant deeply all day long (at least not if they are working at piece-rate and want to be remunerated sufficiently at today's prices), which means manually planted trees in mounds with thick capping of mineral soil are susceptible to frost-heaving on fine-grained soils (de Chantal *et al.*, 2009). These above-mentioned factors are together the main reasons why there actually is a demand for today's relatively expensive planting machines.

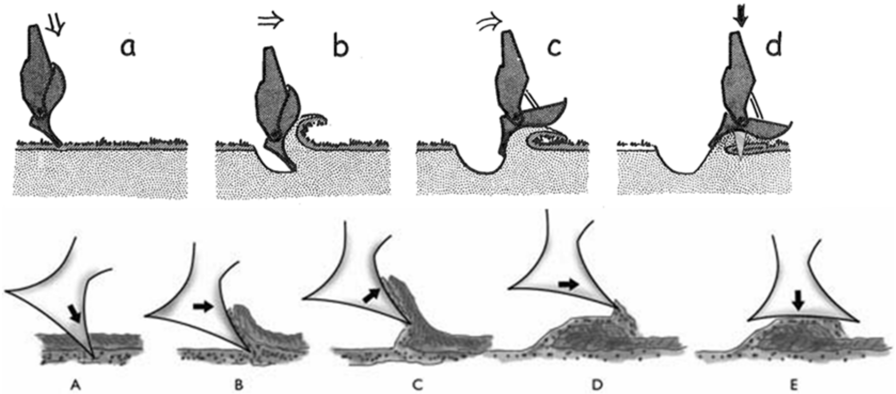

Figure 9. The work method when mounding with the Bracke Planter (top, from Hallonborg *et al.*, 1997) and M-Planter (bottom, from Laine & Rantala, 2013). According to the manufacturers, the planting dibble can extend maximum 19.5 cm and 15 cm below the mounding blade on the Bracke Planter and M-Planter respectively.

2 Objectives

With this thesis, research on mechanized tree planting was meant to reawaken in Sweden. Since today's existing mechanized tree planting production chain in southern Sweden relies exclusively on excavators with crane-mounted, one-headed planting devices which integrate the soil preparation and planting tasks, the thesis' four studies were devised to investigate each of the following bottlenecks (Figure 10): how seedlings are transported from the nursery until they're fed into the planting tube (seedling packaging, I); the design of the base machine carrying crane-mounted planting devices (II); the crane-mounted planting device's design (III); how the planting device is reloaded with seedlings (carousel design, IV). The resulting seedling establishment from mechanized tree planting in southern Sweden was kept under continuous scrutiny throughout the PhD-project via follow-ups reported by Ersson and Petersson (2009; 2011a; b; 2012a; b; 2013a; b). Because there was so much knowledge available from the 1990s and 2000s that had yet to be synthesized from the mechanized tree planting perspective, a modelling approach using data from as far back as the 1970s was chosen for three of the four studies (I-III).

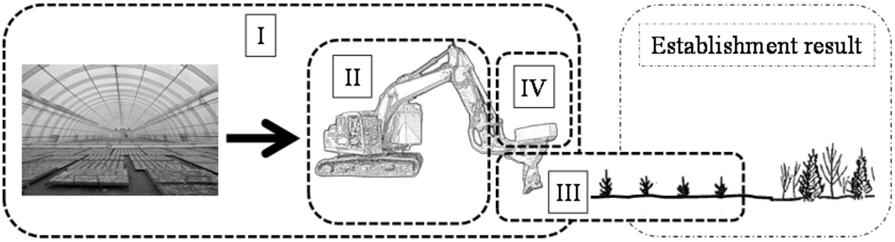

Figure 10. Schematic illustration of the foci of this thesis' four studies. Article I analyzed seedling logistics, or more specifically the entire planting chain from nursery to planted seedling; article II focused on the base machine/prime mover's design; article III focused on the planting device´s design and how it affects seedling dispersion/spatial distribution immediately upon planting; article IV focused on the design of the planting device's seedling carousel. Seedling establishment after planting with today's planting machines in southern Sweden was reported as the work quality immediately after planting and the seedling survival three years after planting by e.g. Ersson and Petersson (2013a) and Ersson and Petersson (2013b) respectively

The overall objective of this thesis was to develop knowledge that can help to increase the productivity – and thus decrease the total cost – of mechanized tree planting systems relevant for conditions in southern Sweden. For this purpose, four studies were performed (articles I–IV) which had the following specific objectives:

- define seedling packaging concepts specifically designed for tree planting machines (I).

- compare the total cost of two machine-specific seedling packaging concepts with today’s two most common containerized seedling packaging systems used during manual planting in southern Sweden (I).

- simulate semi-automated, two-armed excavator-based planting machines and compare their potential productivities under Nordic clearcut conditions with today’s one-armed planting machines (II).

- compare the simulated productivities of feasible, crane-mounted, multi-headed planting devices on Nordic clearcut terrain with today’s commercially available one- and two-headed varieties (III).

- quantify the reduction in time consumption when reloading the Bracke Planter with seedlings in cultivation trays using the MagMat tray-wise-loaded seedling carousel compared to today’s standard seedling-wise-loaded carousel (IV).

- analyze the cost-efficiency of MagMat carousels on today’s two most common crane-mounted planting devices (IV).

3 Materials and Methods

3.1 Seedling packaging (I)

In essence, this study was a classic system analysis. System analysis can be defined as an "analysis [which] focuses on a problem arising from the operations of a sociotechnical system, considers various responses to this problem, and supplies evidence about the costs, benefits and other consequences of these responses" (Miser & Quade, 1985). As such, we took the problem of how to most cost-efficiently move a seedling from a southern Swedish nursery to its planting spot via an excavator-mounted Bracke Planter planting device; proposed four different systems for moving the seedling; and calculated the total cost of each system as well as highlighting some of their additional pros and cons. Although system analyses of mechanized tree planting had been made already in the early 1970s (Bäckström & Wahlqvist, 1972), there had been calls to thoroughly study seedling logistics for tree planting machines ever since the 1990s (e.g. Hallonborg, 1997; Normark & Norr, 2002; Rantala *et al.*, 2009).

3.1.1 The packaging systems

The four seedling packaging systems (abbreviated s1-s4) used in article I are described below. Seedlings in Hiko cultivation trays (s1) were the starting point for all systems, but with additional seedling packaging in s2-s4 (cardboard boxes, band-mounted seedlings, and container modules, respectively).

Existing systems developed for manual planting (Figure 11):

s1) Cultivation trays: cultivation trays in which seedlings are also transported to the planting machine. From the nursery, trays are handled individually by hand and distributed to the contractor's depot by light (3 ton) courier trucks. Trays are returned to the nursery for reuse.

s2) Cardboard boxes: single-use boxes packed by a packing line at the nursery. Boxes are stacked onto Euro pallets and distributed to the contractor's depot as standard shipping units by general groupage delivery trucks (e.g. DHL or Schenker trucks). From the depot, individual boxes are handled manually and transported by the contractor. Boxes are recycled after use.

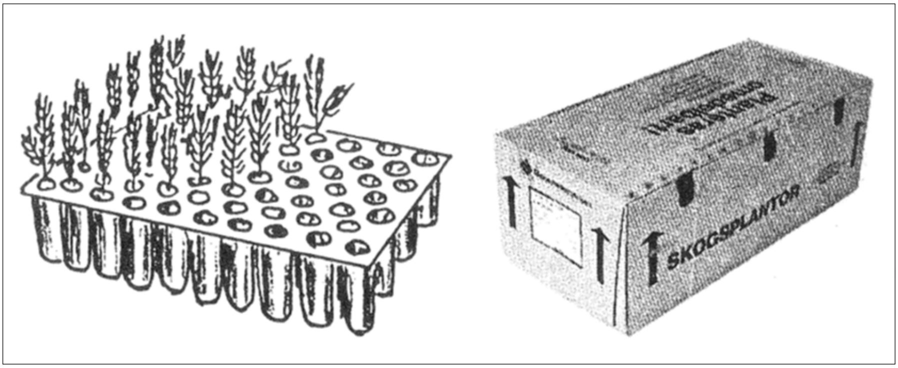

Figure 11. Existing packaging systems for manual tree planting, cultivation trays (left, abbreviated s1 in I) and cardboard boxes (right, abbreviated s2). Images from Malmberg (1990).

Conceptual systems adapted for mechanized planting (Figure 12):

s3) Band-mounted seedlings: seedlings are lifted from the cultivation trays, mounted between strips of paper, rolled into a vertically-standing coil, and then packed into cardboard boxes at the nursery. Handling, transportation, and recycling of boxes is otherwise equal to s2.

s4) Container modules: seedlings are transplanted from cultivation trays into linked cells/pots, 1500-2100 of which are then packed in a container the size of a Euro pallet. Containers are distributed to the contractor's depot by general groupage delivery trucks. From the depot, the containers are handled individually by the contractor using a small truck-mounted crane and a hydraulic lift on the planting machine. The containers are returned to the nursery for reuse.

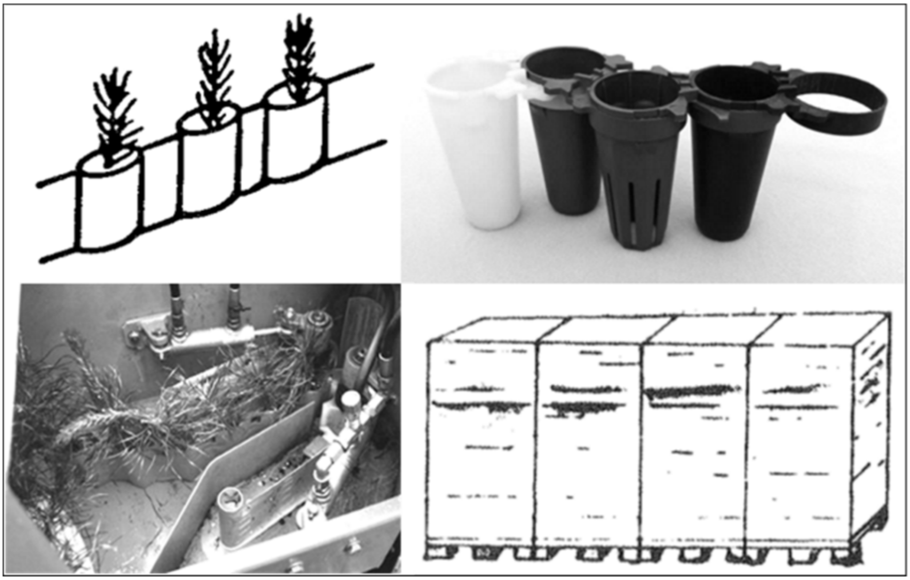

Figure 12. Machine-specific packaging systems for mechanized tree planting, band-mounted seedlings (top left, abbreviated s3 in I) and how such seedlings looked when feeding the EcoPlanter as part of the EcoBandPak-concept (lower left, photo from Normark & Norr 2002); seedlings in Pot Link System cells (PLS, examples of PLS cells, top right) packed into container modules (lower right, abbreviated s4). Sketched images from Malmberg (1990).

3.1.2 From nursery to planted seedling: model descriptions

The packaging systems were expressed as models based on the activities of the generic transportation chain shown in Figure 13. The chain starts at the nursery with the seedlings still being in their cultivation trays while aggregated on large frames after having been sorted and sprayed with insecticides. The chain ends after outplanting when the empty seedling packaging has either been returned to the nursery for reuse or recycled. Cultivation trays and container modules assumed hot-lifted seedlings which required daily watering while cardboard boxes and band-mounted seedlings assumed frozen-stored seedlings which did not require watering the initial three days after thawing.

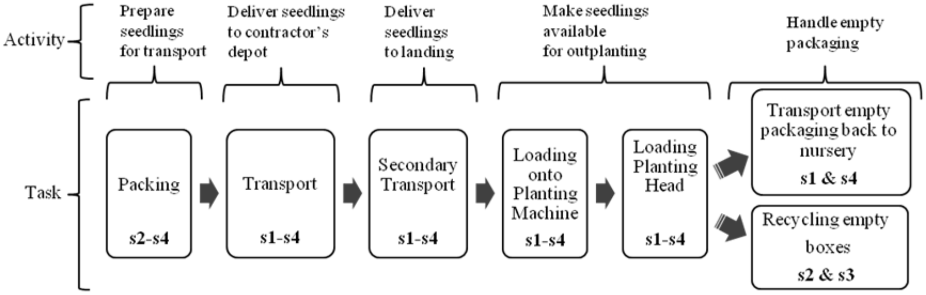

Figure 13. Schematic activity chart of the four seedling packaging systems in article I (see 3.1.1 for description of packaging systems).

3.1.3 Cost analysis

In the cost analysis, the total cost per planted seedling was calculated for each packaging system as the sum of all costs from nursery to the recovery of empty packaging. All activity costs were expressed in SEK per seedling (SEK/pl). The hourly cost for an activity and the time consumed for the performed work were sourced mostly from a nursery company, a planting machine contractor, and other relevant companies in southern Sweden. For example, the assumed annual productive work time, productivity, and total hourly cost of the planting machine was 1000 productive work hours (PWh) per year, 200 pl/PWh, and 550 SEK/PWh, respectively.

3.2 Base machine and planting device design (II & III)

Both article II and III used discrete-event simulations to test potential solutions that realistically might increase the productivity of today's intermittently advancing planting machines. Discrete-event simulation is defined by Banks (1998) as a simulation model "in which the state variables change only at those discrete points in time at which events occur". In turn, he defines simulation as "the imitation of the operation of a real-world process or system over time". To enable this imitation, models of the real-world are constructed. If the simulation is made using computer programming, these models must be mathematical ones (Rajagopal, 1978). Typically, these simulation models are classified as being stochastic, dynamic, and discrete (Asikainen, 1995). There are several advantages with computer-aided simulations, like affording the possibility to compress time, explore new types of systems/machines without having to build them, and visualize their work (Banks, 1998).

Simulations have supported decision making concerning forest machine development and construction since the 1960s (Newnham, 1968; Sjunnesson, 1970), and discrete event simulations have been particularly useful when evaluating the design of harvesting (Talbot *et al.*, 2003; Wang & LeDoux, 2003; Wang *et al.*, 2005; Ringdahl *et al.*, 2012) and logistical systems (Asikainen, 1995; Asikainen, 2010). Also, Andersson et al. (1977) used simulation to evaluate the suitability of three different planting heads during stand regeneration with continuously advancing planting machines on moraine/glacial-till soils.

The simulations in article II and III were performed using a simulator programmed in Python on top of the SimPy discrete-event library (cf. Jundén, 2011). The simulation tool allowed for visualization of the planting machines' work (Figure 14), and outputted time consumption values per planted seedling which were subsequently converted into productivity figures (pl/PWh) for the sake of comparisons. In accordance with the mechanized tree planting simulations of Andersson *et al.* (1977), which seems to be the only other published study of computer-simulated tree planting, the simulation tool required the input of terrain, machine/device, and simulation models, of which selected features are highlighted in the following sections.

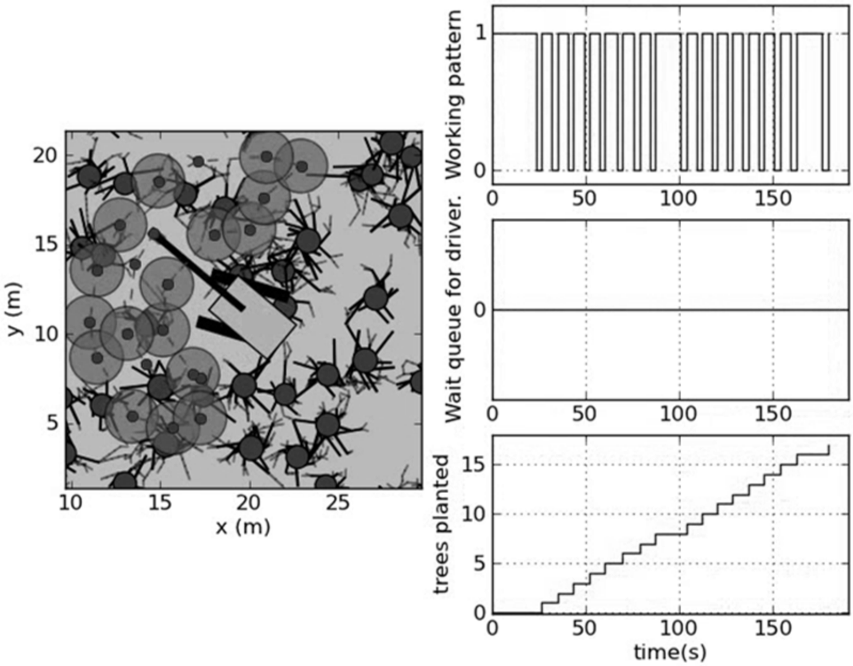

Figure 14. Screen snapshot from the visualization feature of the discrete-event simulation tool used in article II and III.

3.2.1 Terrain models

The foundation of the terrain models was always Herlitz's (1975) type stands for clearcutting, which measured 40 × 50 m. Article II's terrain models comprised stumps, roots, and underground stones, while humus layers and surface boulders were added to the terrain models of article III (Figure 15). Herlitz's type stands also provided the input data necessary for sizing and spatially allocating stumps. To all stumps, we attached a root plate according to the deterministic data from Björkhem *et al.* (1975) and a stochastic root architecture inspired by Kalliokoski *et al.*'s (2010) root models. Consequently, each modelled stump occupied a non-plantable area encompassing the stump itself, a 50 cm wide annular root plate, and all roots over 20 mm in diameter. In Article II, roots could be both visible and non-visible obstacles, while the roots were only non-visible obstacles in article III.

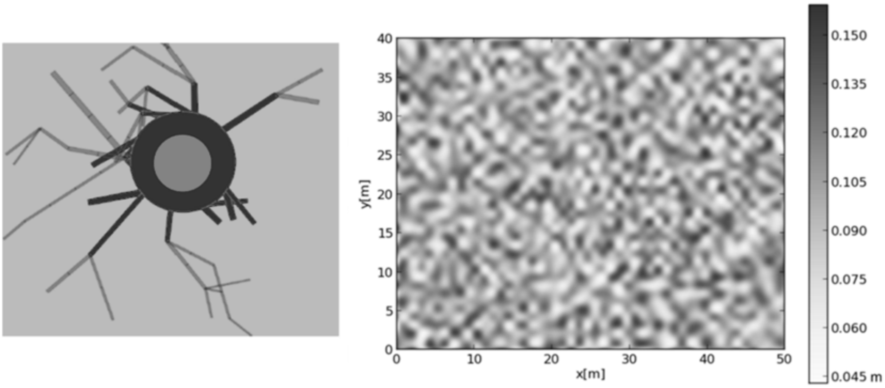

Figure 15. Left: a modelled stump comprising the stump itself (inner grey circle), the annular root plate, main lateral roots (darker in shade), and secondary roots (lighter in shade). Right: screen snapshot of moderately thick humus whose depth varies from 5 cm (light shade) to 15 cm (dark shade).

As concluded already during the 1960s, it is the presence of non-visible, underground stones and boulders which makes mechanized reforestation on moraine/glacial-till soils so difficult (Bäckström, 1978). To model this difficulty, we used parameter values from Andersson *et al.* (1977) to define incidences of underground stones (i.e. the boulder quota or stoniness, c.f. Berg, 1982) and mean stone sizes. Then, we chose an exponential distribution to link stone frequency to stone diameter (Figure 16, left). In article III, the space available for microsites was further reduced by visible obstacles in the form of surface boulders. The boulders' diameter distribution was sourced from the second Swedish National Forest Soil Inventory 1993-2001 (Figure 16, right).

In accordance with Eriksson and Holmgren (1996), our modelled stones and surface boulders were spherical in shape and were spatially allocated in a random manner.

Since the presence of humus layers affects the productivity of boom-tip planting devices (Sønsteby & Kohmann, 2003; St-Amour, 2009; Rantala & Laine, 2010), LFH layers (organic horizons, hereafter collectively termed humus) were added to our terrain models in article III. These layers of biotic material covered the soil; consequently, they lessened the chance of striking underground stones when digging and made all roots become non-visible obstacles. Based on the categorization of Berg (1982), we modelled three classes of humus thickness as follows: thin (triangular distribution: 0-5 cm; mode at 1 cm), moderately thick (triangular distribution: 5-15 cm; mode at 10 cm), thick (triangular distribution: 15-30 cm; mode at 22 cm). In each terrain model, a certain humus thickness class was applied and a grid of 1 m spacing was laid out. Then, a value was randomly drawn from the relevant triangular distribution and allocated to each node (Figure 15, right). Thicknesses between each node were interpolated with cubical splines.

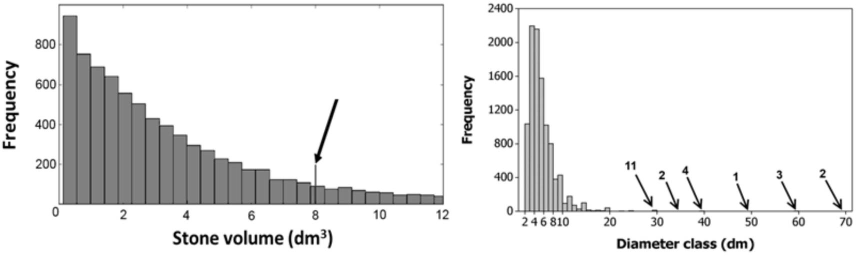

Figure 16. Left: underground stone volume distribution for 75% boulder quota. The arrow points to 8 dm^3 which was the assumed largest size of individual stones which the mounding blade could move. Right: the diameter class distribution of surface boulders >2 dm on moraine soils as measured on 1019 variably sized sample plots during the second Swedish National Forest Soil Inventory 1993-2001. Minimum value: 2 dm; maximum value: 69 dm. n = 10187. Data labels and arrows are provided for diameter classes >25 dm that contain at least one boulder.

In both article II and III, five types of clearcuts were modelled (although article II had a sixth clearcut which totally lacked obstacles). These clearcuts were broadly categorized using chiefly boulder quotas as obstacle-sparse, moderate, and obstacle-rich terrain, with boulder quotas of 25%, 55% and 75% respectively. Moderate terrain was meant to resemble typical southern Swedish clearcuts.

3.2.2 Machine and crane-mounted device models

In article II, two types of base machines were modelled, one-armed (1a) and two-armed (2a) tracked excavators, on which one- (1h) or two-headed (2h) planting devices were mounted (Figure 17). Article III used only one-armed base machines but modelled one- to four-headed planting devices (Figure 18).

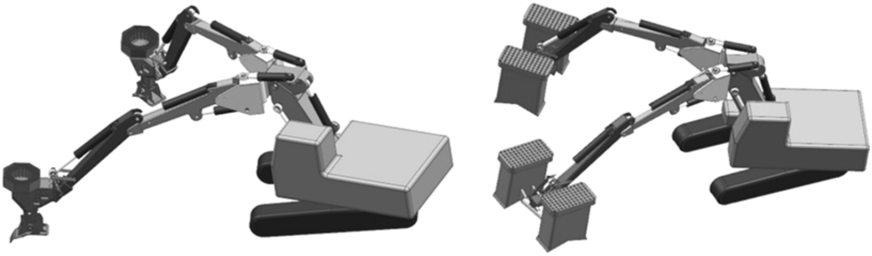

Figure 17. Conceptual two-armed excavators with one-headed (left, named 2a2h in article II) and two-headed (right, named 2a4h in article II) crane-mounted planting devices. Drawings by Rikard Wennberg.

We assumed the two-armed base machines to be fully achievable to build today because they could have two sets of standard outer booms and dippersticks from 14 tonne excavators mounted via an attachment plate on the crane pillar of a 21 tonne tracked excavator. The attachment plate would allow both cranes to move vertically and laterally independent of another. Moreover, rotators mounted between the planting devices and the dippersticks would allow the base machine to slew and each 2a-crane to move while the other is working.

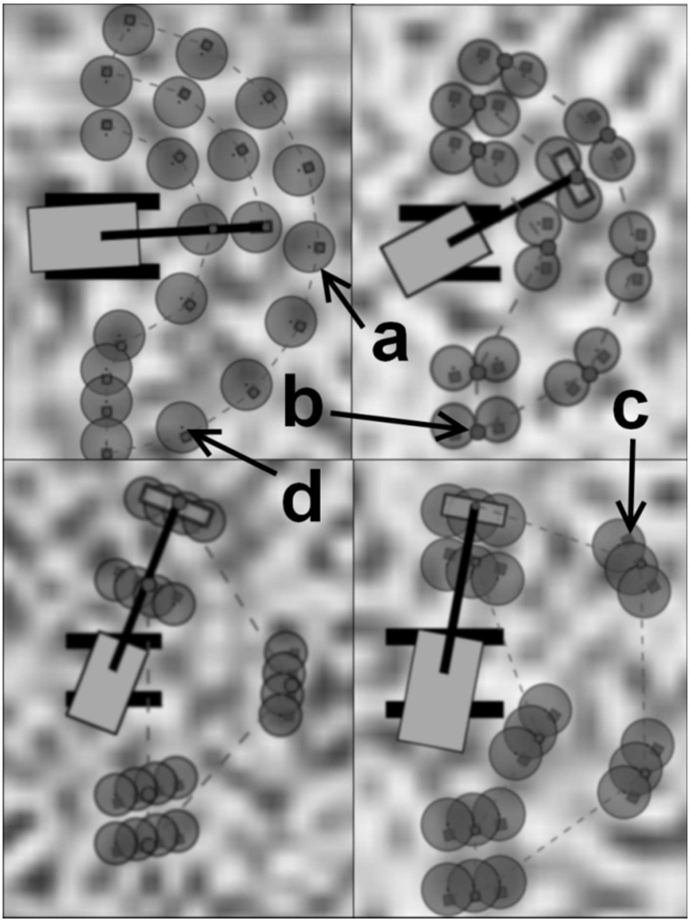

Figure 18. The ideal work patterns of the (clockwise from upper left) one-, two-, three, and four-headed planting device models (abbreviated 1h-4h) on humus-covered, obstacle-free terrain in article III. The dashed lines illustrate the crane motion; the radius of the large, lightly shaded circles (a) is the minimum seedling spacing; the small darker circles (b) show each crane stop; the dark squares (c) illustrate the scoops; and the tiny dots close to the scoop (d) are successfully planted seedlings.

The one- and two-headed planting devices were assumed to be the Bracke Planter and M-Planter respectively, while the three- (3h) and four-headed (4h) devices were conceptual versions with the planting heads linearly oriented perpendicular to the crane (Figure 18). The distance between planting dibbles for 3h and 4h was set to 1 m. This dibble distance is half of the M-Planter's (2h) but is in accordance with the minimum seedling spacing criteria of Sveaskog and SCA, Sweden's largest two forest owners.

When reforesting the terrain model, the planting machine models executed four main tasks (moving crane, choosing microsite, mounding and planting) and two secondary tasks (moving base machine and reloading seedlings). Because today's planting machines are intermittently advancing, the main tasks were performed recurrently at machine stationary points while the secondary tasks were performed when the stationary point was reforested (sufficient number of seedlings planted or no suitable microsites remaining) or when the planting devices needed to be refilled with seedlings. In article III, a fifth main task, termed inverting, was added when the devices prepared the soil using the inverting method.

3.2.3 Simulation models

The simulation models governed the interaction of the planting machine models with the terrain models. Simulating was done at the level of machine stationary points meaning that the base machine was stationary and only the cranes moved during simulation runs (Figure 19). We assumed the following: that the planting machine always worked in a semicircle; that the number of ideal crane stops per stationary point decreased with more planting heads per device; and that each simulation run consisted of minimum 50 stationary points, the exact number depending on when the planting devices had to be reloaded with seedlings. Each stationary point was randomly allocated over the terrain model.

Acceptable microsites for the planting device were rectangles free from visible obstacles. The rectangles measured 1m × W_{MB} and 1m × W_{Total} for 1h- and multi-headed planting devices respectively, where W_{MB} is the mounding blade width and W_{Total} is the device's total width. We assigned a time penalty for multi-headed planting devices to reflect operators' greater difficulty in finding obstacle-free microsites with two-headed crane-mounted mounding devices (von Hofsten & Petersson, 1991). Also, in article II, 2a-machines were assigned a time penalty whenever the operator switched focus between arms.

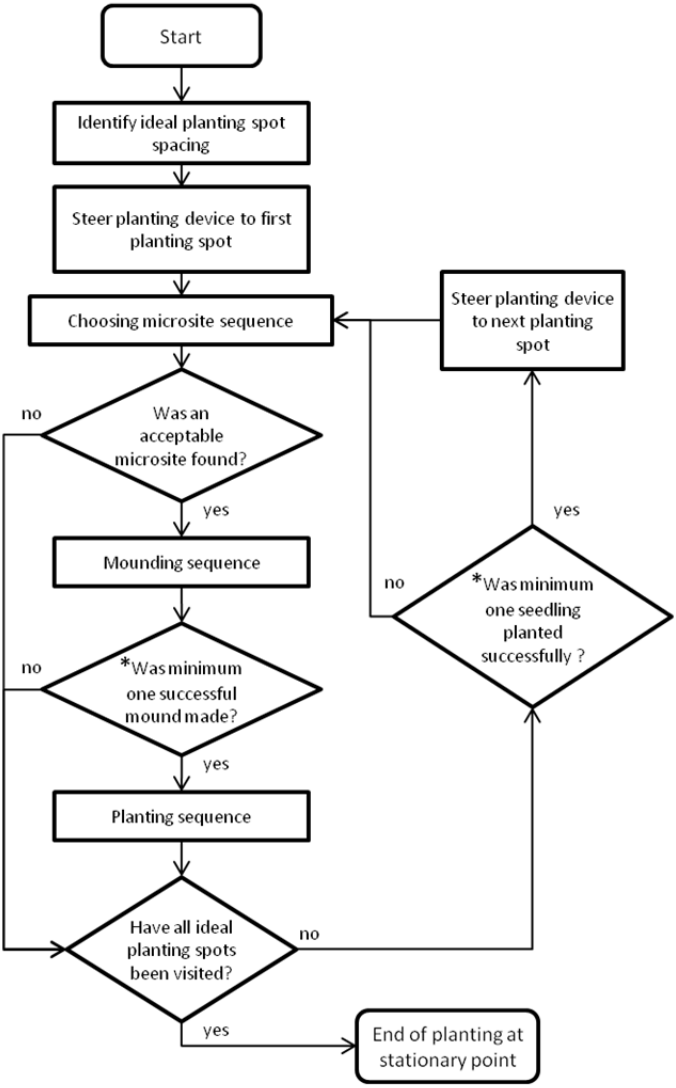

Figure 19. Flowchart for determining the planting machine models' work pattern per machine stationary point (* only relevant for multi-headed planting devices).

During mounding, a half-cylinder (W_{MB} wide) of soil was removed from the ground and inverted in front of the scoop towards the machine (Figure 20). During inverting in article III, the mound was either pushed back into the scoop (termed on-ground inverting) or placed directly in it without touching the ground (termed bucket inverting). Devices could be impeded by underground roots or stones during mounding. Mounding had to be aborted when stones over the immobile limit (8 dm^3) were present and when an impeding root was more perpendicular than parallel to the mounding blade. Contrariwise, when impeding roots were more parallel than perpendicular, the mounding task was assumed to be successful as long as more soil was gathered via remounding. Striking obstacles with multi-headed devices resulted in delays for one or all of the planting heads. In article III, humus layers thicker than ten cm increased the time consumption during mounding, while humus layers ≥ 20 cm thick made underground stones irrelevant (compare scoop depth in Figure 20).

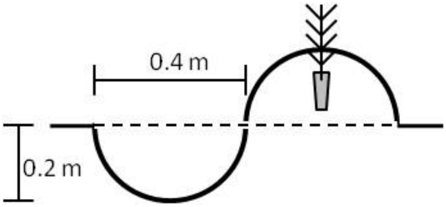

Figure 20. The dimensions of the simulated scoops and mounds (the dashed line represents ground level)in article II and III. The seedlings were assumed to be cultivated in Hiko v93 and have standard root plug lengths of 9 cm.

During the planting phase, planting was not allowed in mounds with aggregate numbers of stones whose total volume surpassed 8 dm^3. Alternatively, planting could be delayed if there were individual stones >1 dm^3 in the mound, although, as during mounding, we assumed that remounding would add enough soil to the mound that planting ultimately succeeded. Consequently, individual planting heads on multi-headed planting devices ran the risk of queuing also during planting.

3.3 Seedling reloading (IV)

This study consisted of two parts, a time study and a cost analysis. The time study was a comparative study with continuous timing (Bergstrand, 1987), and measured the time consumed when reloading seedlings on a tray-wise-loaded carousel test-rig named MagMat versus today’s standard seedling-wise-loaded carousel (Figure 21). The reason why MagMat could be loaded tray-wise was that it automatically deplugged seedlings from the cultivation trays (Safrani & Lideskog, 2011). The standard and MagMat carousels were refilled with 70 and 320 seedlings per reload respectively. Both carousels fed a Bracke Planter

P11.a mounted on a 23 tonne tracked excavator. Hiko v93 cultivation trays, holding 40 seedlings per tray, comprised the seedling packaging (cf. article I). The seedling reloading task with both carousels involved several work elements, some shared and some exclusive to each carousel (Figure 22).

Figure 21. Left: tray-wise loading of a Hiko cultivation tray onto one of MagMat's eight frames (Photo: Rikard Wennberg). Right: seedling-wise loading of today's standard Bracke Planter carousel (note: the right-hand picture was not taken during the time studies).

The time study was conducted on a flat and obstacle-free landing. Since reloading is most often performed on clearcuts, a nearby clearcut was used to validate the landing time study. Three operators with varying experience levels were timed: operator 1 had no previous planting machine experience whatsoever but had considerable experience handling seedlings; operator 2 had one season planting machine experience; and operator 3 had nearly three seasons of mechanized planting experience. Before being timed, all three operators practiced any unfamiliar work element until they were satisfied with their performance. Each replication/reload comprised work elements B-D in Figure 22. Reloading was reiterated until no learning effect could be discerned, and the replications judged to be influenced by this effect were excluded from the results.

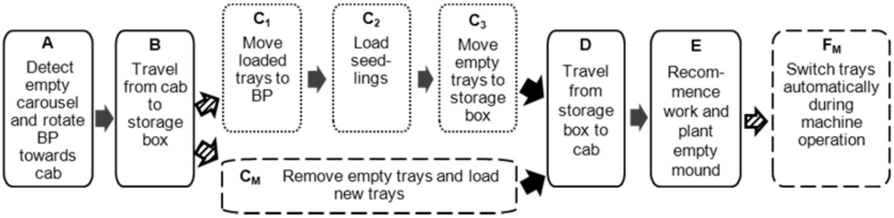

Figure 22. **.** Flowchart of the work elements involved in reloading the Bracke Planter (BP) with seedlings. Dotted- and dashed-border boxes represent work elements exclusive to the standard and MagMat carousels respectively, while elements common to both carousels have a solid border.

Analysis of variance (ANOVA) was used to test if there were significant differences in TC between operators per work element and carousel type in the landing study, and if there were significant differences in TC between operator 3 at the landing and on the clearcut. The tests were compared pairwise in the Minitab 16 statistical package using Tukey's HSD test at the 95% confidence level.

The cost analysis compared the cost-efficiency of mechanized tree planting with excavator-mounted one-headed Bracke Planter and two-headed M-Planter planting devices using the MagMat versus existing carousels. For the Bracke Planter planting machine, the assumed annual productive work time, productivity level, and total hourly cost was 1000 PWh/year, 200 pl/PWh, and 78.5 Euro/PWh, respectively, while the corresponding values for the M-Planter planting machine was 984 PWh/year, 236 pl/PWh, and 81.8 Euro/PWh, respectively.

4 Results and Discussion

4.1 Seedling packaging (I)

Article I showed that cultivation trays (s1) was the most cost-efficient packaging system to deliver seedlings to the planting tube of today's intermittently advancing tree planting machines. Under the basic assumptions (two contracted excavator-mounted Bracke Planter planting machines and 100 km average trucking distance, among others), seedlings in cultivation trays were 12%, 16% and 23% less costly than seedlings in cardboard boxes (s2), paper bands (s3), and container modules (s4), respectively (Figure 23, left, 0.4 million mechanically planted seedlings per year). It was the lack of additional investment costs for the cultivation tray system that made it the least expensive packaging system. Having only two relatively inexpensive and unproductive planting machines did not generate enough yearly demand for seedlings in machine-specific packaging to offset the paper band and container module systems' added investment costs.

Cultivation trays remained the most cost-efficient system throughout the sensitivity analysis except when trucking distances exceeded 500 km one-way (then cardboard boxes were most cost-efficient, compare s1 and s2 in Figure 23, right). Such long one-way trucking distances do not exist in southern Sweden, however, and are also not common as average trucking distances in Finland (Rantala, 2005). Alternatively, one-way trucking distances over 1000 km and average distances of 400 km do exist in northern Sweden (Peter Engblom, Transport Manager, Norrplant, pers. comm. 2014). Similarly long distances tend to be used in analyses of seedling logistics in Canada (Stjernberg, 1989) and USA (Colby & Lewis, 1973 in Mattsson, 1983), and these distances might become more common in the future as nurseries amalgamate and become bigger and fewer (c.f. Rantala, 2005). The competitiveness of both cardboard boxes and band-mounted seedlings increased with longer trucking distances because these two systems did not need to return any packaging from the contractor depot to the nursery.

Of the two machine-specific packaging systems, band-mounted seedlings were consistently more cost-efficient than container modules in all scenarios. Only when planting machine productivity exceeded 350 pl/PWh with ≤100 km average trucking distances were container modules more cost-efficient than band-mounted seedlings. This result is logical when considering the historical use of the linked (PLS) cells. The PLS system was invented so to increase the cost-efficiency of the Silva Nova (whose average productivity could exceed 2000 pl/PWh excluding delays; Mats-Åke Lantz, SCA Skog, pers. comm. 2009). The PLS cells were hooked together to form long belts and loaded into large containers at roadside landings, thereby, in essence, being a system without any trucking distance whatsoever (Ersson, 2010). Thus, container modules might be useful in the future together with highly productive planting machines as long as the container modules do not have to travel far to be reloaded with seedlings.

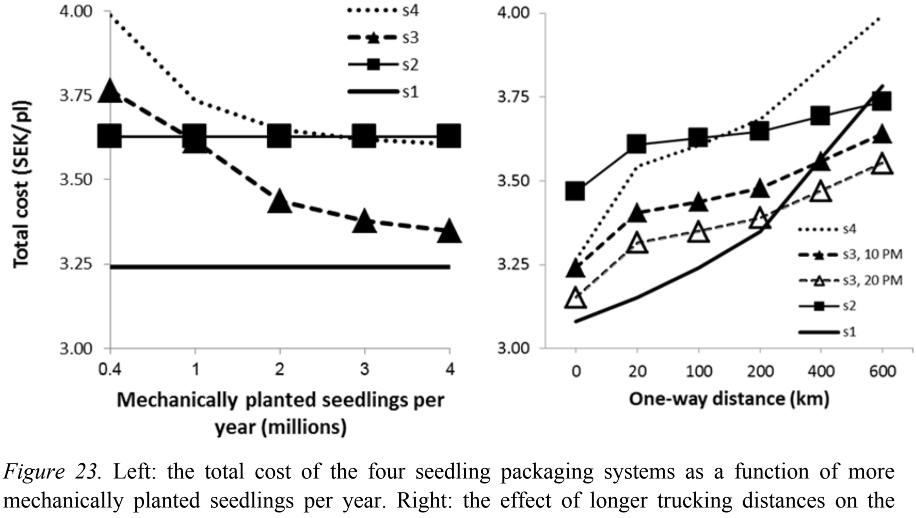

Figure 23. Left: the total cost of the four seedling packaging systems as a function of more mechanically planted seedlings per year. Right: the effect of longer trucking distances on the packaging systems' total cost. s1 is cultivation trays; s2 is cardboard boxes; s3 is band-mounted seedlings; s3, 10 PM is band-mounted seedlings with ten contracted planting machines (planting two million seedlings per year); s3, 20 PM is band-mounted seedlings with 20 contracted planting machines (planting four million seedlings per year); and s4 is seedlings in container modules. Note: the y-axes have been truncated. Reworked from article I.

Band-mounted seedlings (s3) were nearly as cost-efficient as cultivation trays with 20 contracted planting machines (demanding in total 4 million band-mounted seedlings per year, Figure 23, left). Moreover, compared to cultivation trays, the cost-efficiency of band-mounted seedlings increased with increased planting machine productivity and fixed costs, and longer average trucking distances. The latter only had to triple to 300 km with 20 contracted planting machines, or quadruple to 400 km with ten contracted planting machines, for band-mounted seedlings to outcompete cultivation trays (Figure 23, right).

The fixed costs of planting machines are directly dependant on their annual use (termed total utilisation; NSR, 1978). Hence, all else equal, the longer the planting season, the lower the cost per mechanically planted seedling (Bäckström & Wahlqvist, 1972; Rantala *et al.*, 2009). But planting trees in e.g. September calls for seedlings in another growth phase than those planted in e.g. April or July (Nilsson *et al.*, 2010). Indeed, seedlings planted in the spring should preferably be dormant (i.e. frozen-stored; Luoranen *et al.*, 2005), be actively growing when planted during summer, and be short-day treated when planted in the autumn (Luoranen *et al.*, 2006). Unfortunately, both the cultivation tray and container module packaging systems do not allow for frozen-stored seedlings unless relatively costly repacking is done at the nursery. Granted, there would not be any problems to switch between the cultivation tray and cardboard box systems when needed (e.g. delivering seedlings to the planting machine in cardboard boxes during springtime and in cultivation trays during summer and autumn). In contrast, the costly contractor investments in container module handling equipment would become even more expensive if they were to be unused during springtime. One advantage the machine-specific packaging has over the existing packaging systems, however, is that the paper bands and the linked pots can protect the seedlings from detrimental root plug abrasion. For example, today’s standard Bracke Planter carousel causes abrasion which in turn causes root plugs to fall apart, leading to root damage and missed planting actions (Drake-Brockman, 1998). Consequently, when reloading seedlings from trays or boxes, seedlings with loose root plugs have to be culled, and this increases seedling reloading time and stocking costs.

All things considered, I judge that band-mounted seedlings have the greatest potential of the four packaging concepts to lower the cost of tree planting with today’s crane-mounted devices in Fennoscandia. Band-mounted seedlings can be graded wintertime; frozen-stored; shipped long distances relatively economically; loaded fast onto the planting device; are protected from detrimental abrasion in the planting device carousel; and minimize the time spent handling seedlings by the contractor. Despite southern Sweden's relatively short trucking distances, band-mounted seedlings would probably be especially suitable there because Södra suspends seedling delivery and planting during July. This means that Södra's nurseries can avoid shipping actively growing seedlings. In the spring time (April-midsummer), Södra delivers only frozen-stored seedlings while delivering cooler-stored, short-day treated seedlings in the autumn (August-November, or however long the planting machines' season lasts). Both of these seedling types are graded by automatic grading lines before storage and shipment. Frozen-stored seedlings do not need watering, and the cooler-stored short-day treated seedlings are dormant enough to not require watering within one week (Johan Henriksson, Södra Skogsplantor, pers. comm. 2014). And because Södra currently delivers weekly shipments of seedlings to their contractors, planting machine contractors receiving band-mounted seedlings would probably not have to do any seedling watering at all. In any case, the bands and boxes could be designed to allow for seedling watering (just as Södra's cardboard boxes do today), thus making the tending of band-mounted seedlings comparable to seedlings in today's cardboard boxes.

That said, a fifth seedling packaging system, seedlings cultivated in peat pots/cells or pellets, has previously been tested with the Bracke Planter (Nieuwenhuis & Egan, 2002), EcoPlanter (Sønsteby & Kohmann, 2003) and Serlachius planting machine (Adelsköld, 1983; Stjernberg, 1985) with good biological and technical results. Because this type of seedling packaging is planted together with the seedling, no returns are necessary (in contrast to plastic cultivation trays) and it allows for robust seedling feeding solutions on the planting machine. However, since the seedling must be cultivated in these specific peat pots/cells (or other types of biodegradable materials, c.f. Domeij & Olofsson, 2000) and not in reusable plastic trays, there would probably be unjustifiably high nursery investment costs and inefficiencies associated with introducing this packaging system at existing nurseries.

4.2 Base machine and planting device design (II & III)

As expected, the simulated productivity of all four machine models in article II decreased with increasing number of clearcut obstacles (Figure 24, compare terrain models 1-4). 1a1h (Bracke Planter on a one-armed excavator) was the least sensitive to more obstacles while 2a4h (two M-Planters on a two-armed excavator) was the most sensitive, productivity decreased by 14% and 35% respectively from terrain model 0 to 4. 1a2h (M-Planter on a one-armed excavator) was the most productive machine model on terrain model 4, the most obstacle-rich clearcut. Moreover, mean productivity was consistently higher with 1a2h than 2a2h (two Bracke Planters on a two-armed excavator) on all types of clearcuts. Despite having four planting heads, 2a4h only increased productivity by 87% and 71% compared to 1a1h on the obstacle-free (terrain model 0) and moderate terrain (terrain model 5) respectively.

The simulation results from article II showed that two-armed excavators do not improve planting machine productivity on clearcuts with underlying moraine soils (compare 1a2h with 2a2h in Figure 24). Moreover, the productivity figures revealed that the two-armed planting machines' cost-efficiency would be poor, especially when accounting for the added necessary investment costs. Simply put, 2a4h's higher productivity compared to 1a2h was not enough on any terrain model to compensate for the added costs of an extra M-Planter device, the base machine modification costs, the added fuel consumption of the heavier base machine, the added repair and maintenance costs of a more complex machine (Mellgren, 1989), and the reduction in productivity because of more frequent relocations (Rantala *et al.*, 2009).

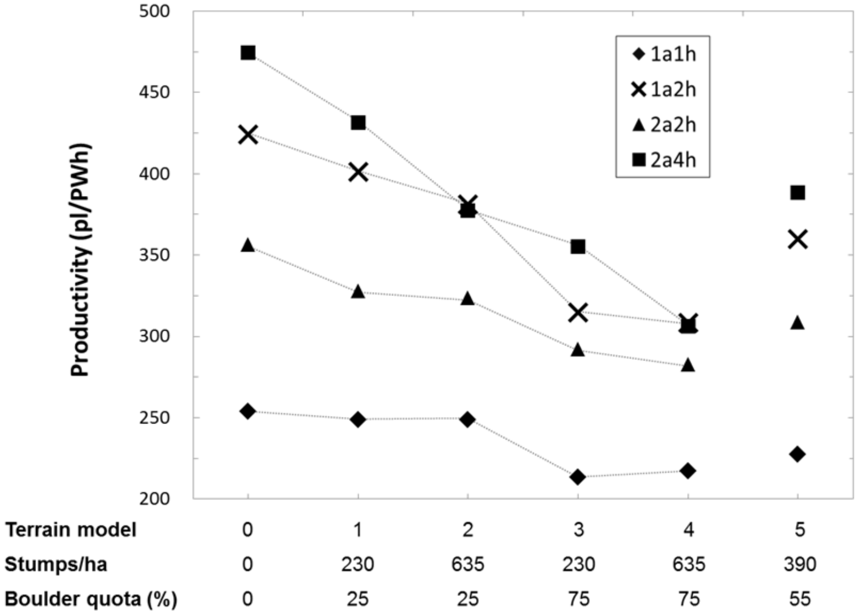

Figure 24. Mean productivity (planted seedlings per productive work hour including seedling reloading) per machine and terrain model. 1a1h = one-headed planting device on one-armed excavator; 1a2h = two-headed planting device on one-armed excavator; 2a2h = two one-headed devices on two-armed excavator; 2a4h = two two-headed devices on two-armed excavator. Terrain model 5 was meant to closely resemble typical southern Swedish clearcuts. Note: the y-axis has been truncated. From article II.

Granted, even though our chosen model was judged most realistic and cost-efficient, a two-armed planting machine could be designed differently than ours. For example, the attachment plate could be located further out at the end of the boom, or further in at the crane pillar or on the opposite side from the cab. Having the attachment further in would result in more flexibility but more expensive and heavier base machines, while having the attachment plate further out would mean less flexible but cheaper and lighter base machines. But as the sensitivity analysis demonstrated, moving the attachment plate even 1 m further out decreased productivity enough that 2a4h became less productive than 1a2h on moderate terrain. Thus, I am confident that analyses with other designs of two-armed planting machines with crane-mounted planting devices would reach similar negative conclusions regarding the feasibility of two-armed base machines.

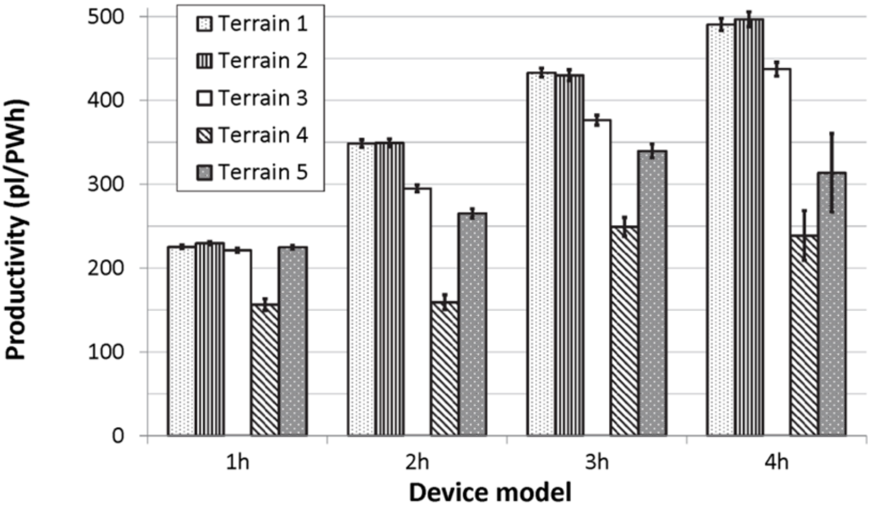

Figure 25. The mean productivity (planted seedlings per productive work hour) of one- to four-headed planting devices (1h-4h) on the five terrain models of article III when mounding. The vertical bars are the 95% confidence intervals. Terrain model 1 and 2 = obstacle-sparse terrain with thin and thick humus layers respectively; terrain model 3 = moderate terrain; terrain model 4 and 5 = obstacle-rich terrain with thin and thick humus layers respectively.

In contrast, the simulation results of article III pointed to a more promising concept than multi-armed planting machines, namely multi-headed tree planting devices. On obstacle-sparse and moderate terrain, productivity increased significantly with increasing number of planting heads (Figure 25). However, on obstacle-rich terrain, three-headed planting devices were more productive than four-headed. On terrain model 4 (many obstacles and thin humus layers), one-headed devices were as equally productive as two-headed devices. Many obstacles slowed down the task of finding acceptably large microsites for the two- to four-headed devices, and also caused frequent queuing delays.

Being over 3 m wide in the basic scenario, four-headed devices were especially impeded by many obstacles. Indeed, the largeness of the four-headed devices sometimes inhibited the model from finding a large enough microsite to plant even one seedling at a machine stationary point. Meanwhile, on the same obstacle-rich terrain, three-headed devices planted significantly more seedlings per ha than both four- and two-headed devices (Figure 26). This difference was the result of the four-headed devices being so large and that the two-headed devices were modelled as being today's M-Planter. The M-Planter is a relatively large planting device with the same total width as our three-headed device model had.

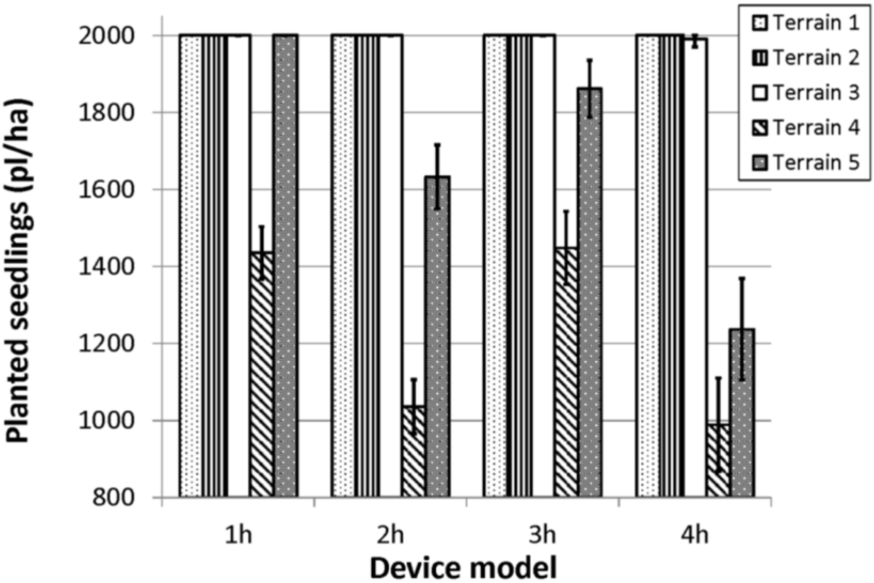

Figure 26. The mean number of planted seedlings per ha by the one- to four-headed planting devices (1h-4h) on the five terrain models of article III. The vertical bars are the 95% confidence intervals. See Figure 25 for terrain model clarification. Note: the y-axis has been truncated

All in all, article III's simulation results pointed to significant productivity gains for crane-mounted planting devices when they have more heads than today's devices. The overall high performance of three-headed devices and their comparative insensitivity to obstacle-rich terrain suggests that three heads per planting device is the most feasible option to increase the planting devices' productivity. Obstacle-rich terrain is of such interest because crane-mounted planting devices perform directed mechanical site preparation (cf. Löf *et al.*, 2012), which is a more effective and cost-efficient way of site preparation on obstacle-rich terrain compared to using continuously advancing machines (Arvidsson *et al.*, 1988; von der Gönna, 1992). Hence, it can be argued that obstacle-rich terrain is the domain of directed mechanical site preparation, which makes it important that crane-mounted planting devices are designed to also work satisfactorily on obstacle-rich terrain. Given the questionable silvicultural result of four-headed devices on obstacle-rich terrain, I conclude that even more heads per device, e.g. five or six heads, are not relevant.

Beyond factors like mechanical availability (von Hofsten, 1993; Arnkil & Hämäläinen, 1995), device purchase price, and faster seedling reloading systems like tray-wise loaded carousels (Rantala *et al.*, 2009), the cost-efficiency of real-life three-headed planting devices will also depend on the configuration (geometric design) of the planting heads, the distance between planting dibbles, and the device's mass. Article III's device models assumed linearly arranged planting heads, but arranging them in a triangle would reduce the area required per microsite plus produce more evenly dispersed planting patterns (Figure 27). For example, 3h Triangle and 4h Square in Figure 27 would require less microsite area than article III's linearly arranged three- and four-headed models and give each seedling more growing space compared to the innermost seedlings planted by the three- and four-headed models (cf. the Voronoi polygons of Lundqvist & Elfving, 2010). One potential disadvantage with 4h Square is that it would probably prevent the operator from seeing all planting heads during the on-ground work. 3h Triangle could be designed to allow full view of the planting heads by arranging the triangle so that an apex points towards the cab.

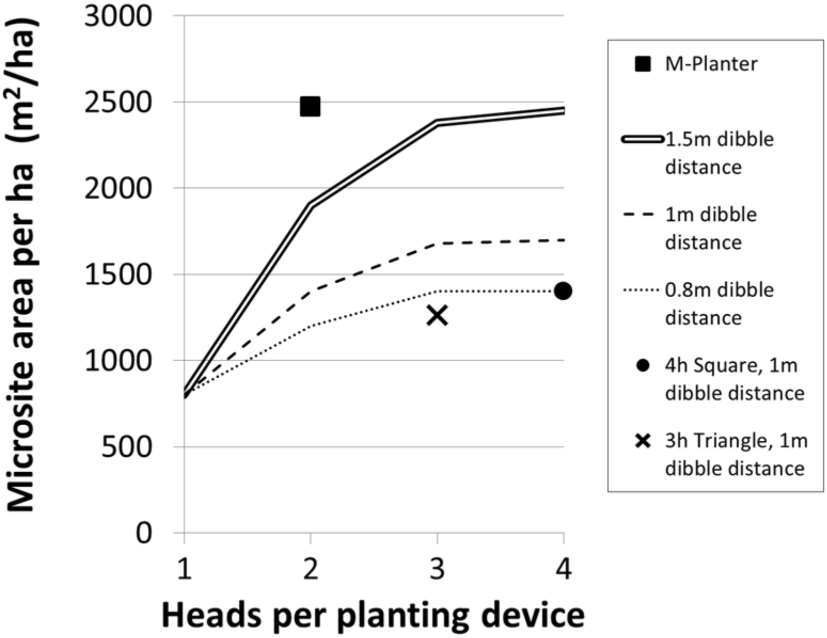

Figure 27. The area required to find 2000 acceptable microsites per ha as a function of the number of planting heads per planting device. The calculations assumed 40 cm wide mounding blades (except for the M-Planter which assumed 45 cm wide mounding blades). Note: 3h Triangle, 4h Square, and two-headed configurations other than the M-Planter were not simulated. Reworked from article III.

The distance between planting dibbles directly affects the planting device's total width, size, and mass. The simulations assumed a 1 m dibble distance for three- and four-headed devices because this is the minimum seedling spacing accepted by Sveaskog (Mattsson & Larsson-Stern, 2009) and SCA (SCA, 2013), Sweden's largest forest owners. Alternatively, Södra Skog and Bergvik Skog have 1.5 m as their minimum seedling spacing (Petersson & Lindén, 2010b; Åke Granqvist, Bergvik Skog, pers. comm. 2014), and Salminen and Varmola (1993) have shown that conifer growth is unaffected by a 0.8 m spacing. The three-headed model became significantly larger and less productive with the 1.5 m dibble distance, while 0.8 m did not significantly improve productivity. Although the legal minimum seedling spacing in Sweden is lower yet (0.6 m; Skogsstyrelsen, 2014), other studies of stem spacing have reported growth losses when trees are excessively clumped together (Stiell, 1982; Pretzsch, 1995; Tiedemann, 2014). Still, the narrowest biologically acceptable dibble distance probably allows for the lightest possible device, which in turn allows for smaller and more cost-efficient base machines to carry the device.

Since the conclusions from article II and III are drawn from discrete-event simulations, it is most important to examine the validity of the simulation results (Asikainen, 1995). In article II, the one-headed device model's average productivity ranged from 4% below to 6% above reported maximum productivities from Bracke Planter time studies on moderate and obstacle-sparse terrain (Engqvist & Moretoft, 1993; von Hofsten, 1993; Rantala *et al.*, 2009). In article III, these average productivity values were 1% above to 15% below reported maximum productivities from Bracke Planter time studies on moderate, obstacle-sparse, and obstacle-rich terrain (Engqvist & Moretoft, 1993; von Hofsten, 1993; Saarinen, 2006; Rantala *et al.*, 2009). For the two-headed device, compared to the maximum reported productivities from M-Planter time studies on obstacle-sparse terrain, the results from article II overestimated productivity by 8.5%, while article III's results only differed by 1-3% (Rantala *et al.*, 2009; Laine & Rantala, 2013). The main reason why the productivity figures for one- and two-headed devices were lower in article III than in article II was probably the addition of surface boulders. The surface boulders were visible obstacles and mainly affected the multi-headed devices. For example, the average time needed to choose microsites with the two-headed device on moderate terrain more than quintupled in article III versus article II. Nevertheless, I judge that these differences between the simulated and time studied productivities do not affect the validity of the inter-machine and inter-device model comparisons of article II and III respectively.

4.3 Seedling reloading (IV)

Seedling reloading was significantly faster with the MagMat tray carousel than the standard Bracke Planter seedling carousel ($p<0.001$); mean total TC per loaded seedling was 57% lower and the range was also narrower (Figure 28). There were no significant differences between the landing and clearcut time studies for any work element or interaction effect of operator 3 ($p \geq 0.122$).

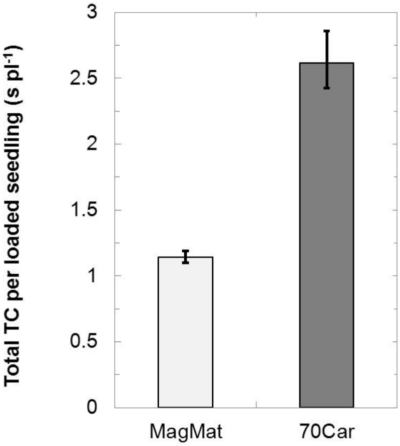

Figure 28. The mean total time consumption (TC) per loaded seedling for the MagMat tray carousel and standard Bracke Planter seedling carousel (70Car). MagMat's TC includes an assumed 10 s per reload for opening/closing a protective barrier. Vertical bars delineate the range of means for the landing time study's three operators. From article IV.

In the cost-analysis, compared to manual seedling-wise reloading, the faster tray-wise reloading increased the assumed average planting machine productivity by 9% (from 200 to 218 pl/PWh) and by 8% (from 236 to 255 pl/PWh) for the Bracke Planter and M-Planter respectively. Consequently, the assumed annual production for the MagMat-equipped planting machines rose by 8% (from 200 000 to 215 965 pl/year) and 7% (from 232 224 to 248 282 pl/year) for the Bracke Planter and M-Planter respectively.

MagMat's total time consumption per loaded seedling included the time needed to automatically switch trays, which averaged 25 s per tray or 200 s per reload. This was the most time consuming task when reloading the MagMat carousel. The sensitivity analysis showed that if this tray-switching task only took half as long, then the assumed average planting machine productivity could increase to 223 and 262 pl/PWh for the Bracke Planter and M-Planter respectively.

Today's standard Bracke Planter carousel comprises only two moving parts and essentially has 100% mechanical availability (MA). A tray-wise-loaded carousel will invariably be more complex than today's standard carousel, thereby potentially creating series-parts reliability dilemmas (Bowen, 1981) which reduces the whole planting machine's mechanical availability (Mellgren, 1989). Nevertheless, the cost analysis showed that a commercial version of MagMat having at least 97% MA could incur added investment cost up to 16 000 Euro and still be profitable. Indeed, the importance of the MA for MagMat's cost-efficiency has prompted engineering students to redesign the carousel with focus on improving its reliability (Almquist & Brandt, 2014).

Since the time study involved inexperienced, somewhat experienced, and experienced planting machine operators, I am confident that this study's results accurately reflect the potential time-savings of using tray-wise loading on crane-mounted planting devices. As opposed to seedling-wise loading (seedlings loaded one-by-one), tray-wise loading could be categorized as loading seedlings unit-wise (termed bundle-wise in article IV). Unit-wise handling is widely recognized within the field of logistics as a way of saving time and costs when handling products (Lumsden, 2006). Indeed, Bäckström and Wahlqvist (1972) assumed unit-wise loading of planting machines in their system analysis from the early 1970s. Thus, unless there is willingness in the future to invest in machine-specific seedling packaging, tray-wise loading of seedling feeding systems will most certainly be necessary for highly productive planting machines to be cost-efficient.

Assuming tray-wise loaded seedling feeding systems, the seedlings have to be extracted from the cavities once the cultivation trays have been loaded onto the planting machine. On most past planting machines designed for planting on moraine soils, this extraction was done manually. However, both Serlachius machines (Stjernberg, 1985) and two versions of the Silva Nova (Hallonborg, 1997) extracted seedlings automatically, either via deplugging from rigid-walled cultivation trays, lifting from linked/PLS pots, or singulating seedlings by sawing them from blocks of peat pots. Automatic extraction is necessary for highly productive planting machines that advance continuously with only one operator (Hallonborg *et al.*, 1995) or that advance intermittently and use crane-mounted planting devices (Malmberg, 1990). Singulation disqualifies re-usable packaging and lifting can sometimes damage seedlings (Hallonborg, 1997). As shown during the end of the 1990s by the PLS-equipped Silva Nova and by Finnish tests with a tray-wise-loaded Bracke Planter carousel, lifting is also prone to being unreliable in shaky environments (Mats-Åke Lantz, SCA Skog, pers. comm. 2009; Jukka Alakorpi, Bracke Forest, pers. comm. 2009).

According to article IV's field tests, deplugging, MagMat's method of seedling extraction, seems to be a very reliable extraction method. During field tests in both June 2012 and 2013, circa 15 trays (>550 seedlings) were deplugged with >98% success rate. When a seedling was not extracted from the tray, it was mainly because of an error in the test-rig's control system when the power of the base machine was switched off. If seedlings can be extracted so reliably even at the boom-tip of an excavator, I conclude that deplugging can probably be performed reliably anywhere on any type of tree planting machine as long as suitable cultivation trays are involved. Suitable cultivation trays are rigid-walled, copper-painted, and with drainage holes wide enough to permit a push rod (Figure 29). Highly reliable seedling-feed systems are especially necessary for highly productive, continuously advancing planting machines (Hallonborg, 1996).

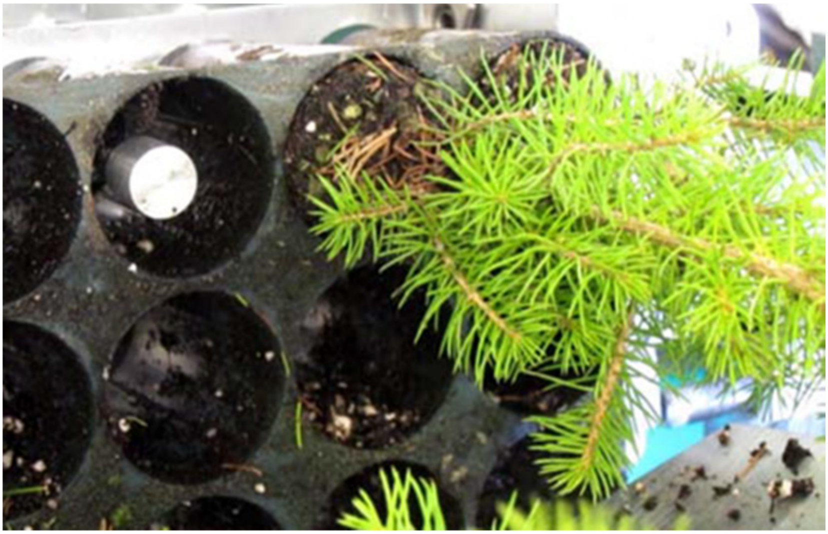

Figure 29. Deplugging *Picea abies* seedlings from a rigid-walled, copper-painted, Hiko v93 cultivation tray. Note the extended push rod in the upper-left cavity/cell. Photo: Rikard Wennberg.

4.4 Potential improvements to Fennoscandian tree planting machines

In the short-term, feasible improvements to planting machines that work on moraine soils revolve around the concept of crane-mounted planting devices. However, in the medium- and long-term, continuously advancing and semi-autonomous tree planting machines are probably feasible.

4.4.1 Crane-mounted tree planting devices

As shown by article II and III's simulations plus practical experience with the EcoPlanter (Mattson, 1997) and M-Planter (Laine & Rantala, 2013), productivity is generally higher with two-headed than one-headed planting devices. Therefore, efforts to improve the productivity of crane-mounted planting devices should concentrate on multi-headed devices. For example, narrowing the M-Planter by making the distance between dibbles approximately one metre would make the device lighter and the operator's task of finding acceptable microsites easier. Alternatively, adding a third planting head between the M-Planter's existing two heads would turn today's M-Planter into a real-life version of the three-headed device simulated in article III. The heads would be linearly arranged and the dibble distance approximately one metre, thereby offering an efficient way of evaluating the simulation results. In any case, three-headed devices seem to have potential productivity levels high enough for tree planting machines to become economically competitive with manual tree planting in southern Sweden.

A more time- and resource-demanding approach to increasing the productivity of crane-mounted planting devices would be to develop a whole new device. For instance, this device (Figure 30, left) could be designed to be carried by harvester cranes (like the EcoPlanter was); have a reliable tray-wise-loaded seedling carousel similar to the recently designed AMP carousel (Almquist & Brandt, 2014); have two digging blades that move in opposite directions to balance forces; prepare soil via patch scarification, mounding or inverting (Sundblad, 2009); and have sensors to detect suitable microsites (Lideskog *et al.,* 2014). Of course, as article III's results indicate, the productivity of this new device could probably be increased even more by making it three-headed (e.g. Figure 30, right).

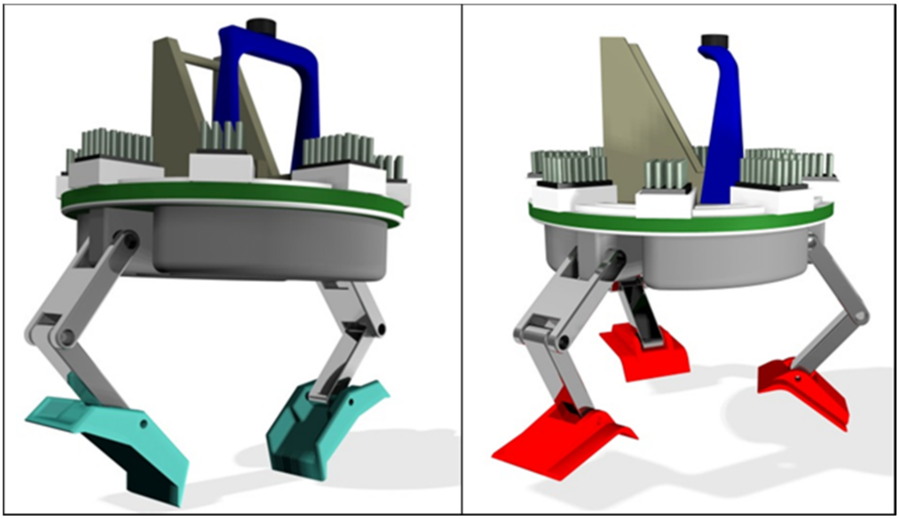

Figure 30. Conceptual drawings of a two-headed (left) and three-headed (right) planting device with tray-wise-loaded seedling carousels and attachment points for harvester cranes. The two-headed device has digging blades for mounding and inverting, and the three-headed device has the planting heads triangularly arranged. Drawings by Rikard Wennberg.

By designing the planting device to do its own digging, the crane would not have to actively do the digging which would allow wheeled forest machines like harvesters to carry the device. Although being more expensive to purchase, wheeled forest machines can advance faster and more smoothly over obstacles, which makes them more suitable for forest terrain than tracked excavators (Johansson, 1997). Alternatively, intermittently advancing planting machines might increase their productivity by using all-terrain excavators as the base machine (Figure 31, upper left). By offering the flexibility to switch between the patch scarification, mounding, and inverting site preparation methods, the device could optimally prepare soil on all Fennoscandian sites regardless of soil moisture class or obstacle frequency (Sundblad, 2009). With the ability to detect obstacle-free microsites, the planting quality and productivity of mechanized planting could further increase (Rantala *et al.*, 2009). Indeed, even when aspiring to disperse microsites in square patterns on obstacle-rich clearcuts, simulations have shown that the mounding success rate can increase significantly with the help of obstacle identification (Lideskog, 2013). Recently, studies of sensors and solutions for automatic planting spot (Kemppainen & Visala, 2013) and clearcut obstacle (Björklund *et al.*, 2014) detection have been performed in both Finland and Sweden with promising results.

4.4.2 Continuously advancing tree planting machines

As theoretical calculations from the 1970s (Bäckström, 1978) and practical experiences from the 1980-90s (Hallonborg *et al.*, 1997) have shown, continuous advancement enables planting machines to be highly productive. High productivities can potentially reduce the cost per planted seedling as long as the machines have "low operating costs, good technical availability, and adequate utilization of the annual capacity" (Hallongren *et al.*, 2014). Presently, Metsätheo, Metla, and others have been planning a project to build a continuously advancing planting machine (Saarinen *et al.*, 2013; Figure 31, lower left), which might be commercially available in the medium-term. It aims to use planting spot detection and tray-wise-loaded automatic feeding of seedlings to increase planting effectiveness and productivity. The trick, of course, will be to avoid recreating a high-cost machine like the Silva Nova while simultaneously being highly productive on small, irregularly shaped clearcuts (c.f. Hallonborg *et al.*, 1995).

4.4.3 Semi-autonomous tree planting machines

Today, mechanized planting comprises integrated soil preparation and planting tasks. This integration was argued to be necessary for cost-effective planting machines already in the 1970s (Bäckström, 1978). However, it is mainly the soil preparation task, not the planting task, which necessitates large, heavy, and therefore expensive base machines. Thus, a planting machine could be made smaller, lighter and cheaper if it only planted. Since handling seedlings on today's planting machines takes many productive work hours away from the actual mounding and planting work, there is a potential to save money if the soil preparation and planting tasks can be made independent of one another (just as it is with normal mechanical site preparation and manual planting). This idea holds true if the planting-only machine can plant seedlings cheaper than what the full cost of the planting task is with the integrated planting machine. The planting task's full cost can be expressed as follows:

$$C_{PT} = (t_{Plant} \times c_{PM}) + (t_{Seedling\ handling} \times c_{FPM})$$

where C_{PT} is the total cost per seedling of the planting task with an integrated planting machine; t_{Plant} is the time to plant the seedling; c_{PM} is the total hourly cost of the planting machine; $t_{Seedling\ handling}$ is the total time needed by the planting machine operator to fetch, tend for, and load the seedling into the seedling feeding system; c_{FPM} is the fixed hourly cost of the planting machine.

An example of a planting-only machine was the Ilves planting machine. It was a rather light, crane-mounted planting device (Hallonborg *et al.*, 1997). But despite only requiring cost-efficient agricultural tractors as base machines, the productivity of Ilves was too low to be competitive with integrated planting machines (Arnkil & Hämäläinen, 1995).

But in the future, a planting-only machine could be made low in cost and highly productive. Low-cost means that the planting-only machine's planting cost is lower than C_{PT}. This cost reduction could be achieved by using small base machines lacking cabs so that the operator controls the machine remotely (e.g. by walking next to the machine as with today's Forest Ebeaver harvesting machine, Figure 31, right). Highly productive could mean that it advances continuously while simultaneously planting two or three rows of previously prepared microsites (prepared by e.g. continuously advancing machines like normal disc trenchers and mounders) and achieving the same high planting quality as today's planting machines do. With sensor development and future research on automation, these planting-only machines could be made semi-autonomous, meaning that an operator could control e.g. two machines simultaneously. Theoretically, given that each of the planting-only machine's dibbles plants a seedling as quickly as manual tree planters do, this operator is then planting seedlings up to four or six times faster than manual tree planters. Moreover, compared to manual tree planting, these machines would have the strength to plant seedlings deeply all day long, and could have the capacity to carry a shift's worth of seedlings (c.f. the section on partially mechanized planting machines in Hallonborg *et al.*, 1997). Such machines would probably be small enough to relocate relatively easily and quickly.

Figure 31. Upper left: the Menzi Muck A91 all-terrain excavator, an example of a wheeled excavator suitable for forest terrain (photo: Niklas Bodén). Lower left: Pentin Paja's modified forwarder that potentially might serve as the base machine for a continuously advancing planting machine (photo from Saarinen *et al.,* 2013). Right: the Forest Ebeaver, an example of a small, remote-controlled base machine that could serve as the prime mover for semi-autonomous planting-only machines in the future (photo from Key, 2012).

4.5 The future role of tree planting machines in southern Sweden

Tomorrow's demand for tree planting machines will most certainly be coupled the willingness of people to manually plant trees, and any added value/benefits that the planting machine can provide beyond the planting task itself. Both of these factors directly influence the planting machines' economic competitiveness compared to mechanical site preparation and manual tree planting.

Historically, urbanization has been viewed as detrimental to the supply of manual tree planters (Sirén, 1969b), and this is probably still true today. Also, forest owners who live in other municipalities than their forest estates are less inclined to work on their holdings than forest owners who live in the same municipality (Lindroos *et al.*, 2005). Since urbanization is continuing and more forest owners are increasingly living in cities (Umaerus *et al.*, 2013), the willingness to plant trees manually, at least among Swedes, will probably continue to diminish in the future. Presently, much of the labour required for manual tree planting is supplied by foreign workers, although this solution has sometimes been controversial with several high profile cases costing the Swedish forest companies involved much money and reputation (Johansson, 2008; Lefévre & Persson, 2009; Eriksson, 2013a). Because it is time-efficient compared to directed mechanical site preparation and manual planting (Hallongren *et al.*, 2014), mechanized planting can help to secure tree planting capacity even when relying on today's relatively low-productivity machines.

Beyond soil preparation, researchers have often highlighted the tree planting machines' ability to provide added value to tree plantings (e.g. Stjernberg, 1985; Malmberg, 1990). This added value can entail watering and/or fertilizing seedlings, applying herbicides and/or pesticides, vegetation removal, etc. (Bäckström & Wahlqvist, 1972). Although the above-listed services are prohibited or considered uneconomical in southern Sweden today, they can make tree planting machines economically competitive elsewhere. For example, excavator-mounted Bracke Planters planting Eucalyptus in China, Indonesia, and Brazil often water and fertilize the seedlings simultaneously (Klas-Håkan Ljungberg, Bracke Forest, pers. comm. 2014). Because low-wage regions normally call for low-tech forest machines (Nordfjell *et al.*, 2004), it is these added services which makes this Nordic planting machine economical even in these relatively low-wage countries.

Arguably, although they could be performed manually at higher costs, the added services that the excavator-mounted Bracke Planter provides in these semitropical countries could be viewed as being biological advantages of planting trees mechanically. In southern Sweden, deep-planting immediately preceded by mounding with compression are two examples of biologically advantageous services provided by crane-mounted planting devices which the combination manual tree planting with cost-efficient mechanical site preparation cannot provide. Indeed, these two services were two of the underlying assumptions in a recent analysis which suggested higher net present values for mechanized planted clearcuts than manually planted ones (Engelbrektsson & Stoltz, 2014). Saving advanced regeneration during infill planting or when reforesting back-logged windthrown stands (e.g. after hurricane Gudrun) would be other examples of advantageous services. Being permitted to reforest historical remains because of low levels of ground disturbance would be another. Moreover, the planting devices' ability to plant deeply makes them the best choice when planting expensive seedlings (e.g. seedlings grown from cuttings; Magnus Petersson, Södra Skog, pers. comm. 2013). Because the prevalence of mixed conifer-deciduous stands (Skogsdata, 2013), windthrows (Blennow *et al.*, 2010), monitoring historical remains (cf. Ulfhielm, 2014), and planting seedlings grown from cuttings (Petersson, 2008) is expected to increase in southern Sweden, I predict that reforesting with crane-mounted planting devices will grow even more common in the future.

Lastly, changes in southern Sweden's forest management regimes might increase the competitiveness mechanized tree planting compared to manual tree planting. For example, restocking clearcuts at rather low rates has sometimes been of interest in the past (Agestam, 2009). If this silvicultural regime becomes more popular in the future (because of e.g. low margins for forest owners when selling wood), the competitiveness of today's crane-mounted planting devices (because of the high seedling survival rates when planting with them) might increase. Also, if future clearcuts become even more irregular in shape than today's (because of structural retention, riparian zones, dead wood left on the clearcut, etc.), the competitiveness of crane-mounted planting devices might increase (Ersson, 2010). This holds true because tree planting machines are already today more cost-efficient in southern Sweden than the combination of directed mechanical site preparation (i.e. spot mounding with excavators) and manual tree planting. Similarly, if retention forestry (Gustafsson *et al.*, 2012) and/or selective cutting (also termed partial cutting; Forest Practices Branch, 1999) silvicultural systems become more popular in southern Sweden, then fill-planting with crane-mounted planting devices will probably be more cost-efficient than manual tree planting after mechanical site preparation. Such silvicultural systems might even open up for semi-mechanized tree planting machines (Hallonborg *et al.*, 1997) to become competitive. In any case, the trend in Swedish forestry is to leave more retention on the clearcuts after harvest (Eriksson, 2013b). Theoretically, if the trend continues, small clearcuts might become more like patches. In patch cutting management regimes, the brevity of each machine pass (strip) favours soil preparation with crane-mounted devices over continuously advancing machines (cf. Suadicani, 2003).

Meanwhile, if clearcutting remains dominant in southern Sweden, continuously advancing planting machines might still be cost-efficient in the future. Average clearcut size and stocking rates in Finland (Hallongren *et al.*, 2014) are quite similar to (or at least not larger than) the average figures in southern Sweden, so any continuously advancing planting machine suitable for Finland will probably be competitive in southern Sweden too.

4.6 Recommendations for future research

First of all, considering article III's simulation results, I recommend establishing field experiments to investigate the silvicultural effects of three-tree clumps. The focus of the experiment should be on inter- and intra-clump tree spacing. Four-tree clumps could also be investigated since Stiell's (1982) studies were performed on pine (*Pinus resinosa* Ait.) at quite low stocking rates (890 stems/ha) in Ontario, while spruce (*Picea abies*) in southern Sweden might be less sensitive to irregular spacing (Pfister *et al.*, 2007).

If no major silvicultural disadvantages can be discerned with three-tree clumps, then a three-headed planting device should be built. This device could initially be designed to be mounted on excavator cranes, and the planting heads should probably be triangularly arranged. I suggest that tests with a three-headed device focus firstly on determining its silvicultural results on various types of obstacle-rich terrain.

During the last few years, planting machines in southern Sweden have been planting seedlings as late as in December and January. If mechanized tree planting becomes more common, winter planting will probably also occur more often. Therefore, it should be of interest to study any potential difference in seedling mortality between winter and autumn planting.

Although transporting seedlings in their cultivation trays is a low investment, cost-efficient (and – if the seedlings are tray-wise reloaded– rather highly productive) packaging system, many nurseries might already be committed to cultivating seedlings in trays that aren’t as suitable for automatic deplugging as the Hiko trays are. In regions where these types of nurseries dominate, band-mounted seedlings might be an especially interesting packaging solution. Moreover, band-mounting is particularly viable when transporting dormant seedlings (see pages 44-45 for more details). Therefore, I recommend that preliminary studies be made on the choice of band material and the design of band-mounting stations. I judge these two aspects to be especially crucial for the realizability and cost-efficiency of a band-mounted seedling packaging system.

Even though the simulations of article II and III assumed otherwise, I suspect that there might be differences in how quickly mounding can be performed using the Bracke Planter’s and the M-Planter’s mounding blade design (see Figure 9 for difference in mounding work method). Since today’s Fennoscandian planting machines produce up to several hundred thousand mounds per year, being able to mound just one second faster could have a significant impact on annual production and contractor profitability. The difference in mounding work method might be especially influential on the productivity of novice operators (cf. the mean productivity of novice operators in Rantala & Laine, 2010). Time studies should be performed on various sites to evaluate this potential difference in time consumption. The results could provide valuable guidance when designing future crane-mounted planting devices.

When used as base machines for crane-mounted planting devices, I suspect that harvesters provide better working environments than excavators. In

Finland, there is at least one harvester-based planting machine (Figure 32). Considering that today's Swedish forestry industry finds it challenging to recruit skilled harvesting machinery operators (Valinger, 2009; Ager, 2014), recruiting future skilled planting machine operators might be even harder if they have to work in ergonomically inferior base machines. Therefore, studies should be made which compare the ergonomics (e.g. vibrations during on-ground work, moving the base machine on and to the clearcut) of mechanized planting with harvesters and excavators.

Figure 32. A six-wheeled Ecolog harvester with a one-headed M-Planter device and modified outer boom working as a tree planting machine in Finland (photo: Tiina Laine).

Finally, more simulations to help study forest machine design should be made. The terrain models from article II and III should be especially useful since they provide a good foundation to build detailed models of Fennoscandian forest terrain. The present terrain models could be further enhanced by adding e.g. soil characteristics, soil moisture classes, bottom/field layers, ground roughness, slope, slash, etc. Examples of tree planting machines that could be simulated are manually controlled, or semi-autonomous, continuously advancing machines with or without integrated soil preparation. Also, since operators often spend considerable time tending and fetching seedlings and maintaining equipment, it would be relevant for planting machine contractors if simulations of different organizational solutions for increasing machine uptime were made.

5 Conclusions

The following bullet list summarizes my main conclusions from this thesis:

- In southern Sweden, cultivation trays constitutes the most cost-efficient packaging system to move seedlings from the nursery to the planting tube of today's excavator-based planting machines, but band-mounted seedlings will probably be the most flexible and cost-efficient packaging system as mechanized tree planting becomes more common.

- Discrete-event simulation using detailed terrain, machine, and planting device models seems to be a resource-efficient method of evaluating tree planting machine design.

- More heads rather than more arms are better for increasing the productivity of intermittently advancing excavator-based planting machines on Fennoscandian clearcuts.

- Increasing the number of heads on crane-mounted planting devices increases the devices' productivity (up to 118% increase when going from one to four heads on obstacle-sparse terrain), although three-headed planting devices show most promise when combining the requirement of high productivity with acceptable silvicultural results on all types of Fennoscandian clearcuts.

- Tray-wise-loaded carousels make for faster seedling reloading of crane-mounted devices than today's seedling-wise-loaded carousels.

- Deplugging seedlings from suitable cultivation trays seems to be a reliable and time-efficient method of feeding seedlings on probably any type of tree planting machine.

The above list of conclusions, I believe, can be summarized as follows: there is high potential for productivity-increasing and cost-lowering technical improvements to today's tree planting machines. This observation, together with the fact that seedlings planted mechanically in southern Sweden by today's planting machines show higher survival rates than seedlings planted manually by contractors after disc trenching, points to an increased future demand for mechanized tree planting in southern Sweden. What's more, mechanized tree planting with crane-mounted devices is potentially suitable for cost-efficient regenerations in retention forestry and selective/partial cutting silvicultural systems/management regimes. Nevertheless, for mechanized tree planting to become truly competitive in southern Sweden, the machine must be productive and cost-efficient enough that planting machine contractors can make money while reforesting stands with significantly lower costs than manual tree planting after continuously advancing scarifiers.

Most likely, the main results presented in my thesis, especially those from the simulations and time studies, are also relevant for the rest of Fennoscandia and even throughout the rest of the Boreo-nemoral/Boreal forest zone.

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