Possible Concepts for Mechanized Tree Planting in Southern Sweden

-An Introductory Essay on Forest Technology

by

Back Tomas Ersson

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1. Introduction: Why mechanize?

Today, the vast majority of all harvesting work within the Swedish forestry sector is mechanized. In contrast, the vast majority of today's silvicultural work in Sweden, including tree planting, is done manually. Consequently, the relative cost of stand regeneration has increased compared to stand harvesting when comparing year 1970 to 2007 (Berg 1993, Brunberg 2008). This cost increase lowers the profitability of the forestry industry and lessens the desire of forest owners to invest in silvicultural activities (Berg 1993). All in all, the Swedish forestry sector seeks to increase the mechanization of tree planting so as to reduce:

- the total cost of stand regeneration (Bäckström 1978)
- the mortality of seedlings caused by poor quality regeneration work (Bäckström 1978, Malmberg 1990)
- the dependency on manual labour and foreign workers (Malmberg 1990, Hallonborg et al. 1997)
- the monotony and physical labour involved in regeneration work (Bäckström 1978)
- the cost of planting large seedlings (Thorsén et al 1984, Berg 1985, Hallonborg et al. 1997)
- the overhead costs associated with educating new, inexperienced tree planters year after year (Bäckström 1978)
- unnecessary scarification thereby adjusting soil disturbance according to the needs of different land owners and demands of interest groups (Hallonborg 1997, Frank 2006)

To help facilitate this transition, the following essay aims to describe the various conditions that influence mechanized tree planting in southern Sweden, summarize past research and development on mechanized tree planting, and to identify potential solutions and challenges that should be addressed during future development work on tree planting machines. This essay is the first output from the PhD project "Concepts for mechanized tree planting that meets the needs of small forest owners in southern Sweden" which is part of the Swedish-Finnish collaboration called FIRST (Forest Industry Research School on Technology).

2. Forestry in southern Sweden – an overview

In general forestry terms, southern Sweden can be defined as the region of Götaland which has 4.995 million ha of productive forests (Anon. 2008). Götaland is the region south of the black line in Figure 1. Throughout this essay, southern Sweden will be referred to as Götaland.

Figure 1. Götaland, south of the black line.

2.1 Biological conditions

Compared to the rest of Sweden, Götaland's forests are generally characterized by warmer temperatures, more precipitation, more nitrogen deposition, more fertile sites and, consequently, shorter rotational periods (Skogsstyrelsen 1975). The mean site productivity in Götaland is 8.6 m^3sk/ha/year as compared to the national average of 5.3 m^3sk/ha/year (Anon. 2008). As a rule, main stem density after stand regeneration reflects the productivity potential of the site. The mean main stem density after stand regeneration is higher in Götaland compared to the rest of Sweden, with 2462 and 2207 main stems per ha respectively (Anon. 2007). Likewise, main stem density has historically been higher in Götaland compared to the rest of Sweden. Between 1953 and 1968, over 50% of the regenerated clearcuts in Götaland had more than 3000 main stems per ha, whereas in the rest of Sweden, this percentage was less than 10% (Skogsstyrelsen 1975).

To make the most of this high site productivity and to lessen the damage caused by ungulate browsing, the Swedish forest sector tends to favour the planting of *Picea abies* in Götaland. Indeed, 68% of the forested area in Götaland is classified as suitable for *P. abies* (Anon. 2008). Nevertheless, *Pinus sylvestris, Betula spp.* and other deciduous trees (e.g. *Fagus sylvatica, Quercus robur*) still constitute almost 50% of the standing volume in Götaland (Anon. 2008).

In 2007, 63% of the 367 million seedlings used by the Swedish forestry sector for the whole of Sweden were *P. abies* (Anon. 2008). This percentage is much higher in Götaland. For example, more than 90% of the 3 million seedlings ordered by the Alvesta-Växjö district of Södra Skog in the year 2009 were *P. abies* (Grape, Pers. Comm.). Even during the 1980s, *P. abies* was by far the most frequently planted species in southern Sweden's forests (Nilsson 1990). Therefore, forestry, including mechanized tree planting, in Götaland is heavily oriented towards the cultivation of *P. abies*.

There are a number of particular factors that cause difficulties during stand regeneration in Götaland. The first and foremost is predation by *Hylobius abietis* (Örlander & Nilsson 1999). The abundance of this weevil has greatly increased with the rise of clearcut forestry (Eidmann & Klingström 1976, Håkansson 2000), especially in Götaland (Eidmann et al 1996). *H. abietis* feeds on the cambium of a seedling's stem, with loss of vitality and growth as a result of moderate predation or mortality if the feeding girdles the seedling (Eidmann & Klingström 1976). Predation from *H. abietis* can be averted by (see e.g. Eidmann & Klingström 1976, Örlander & Nilsson 1999, Wallertz 2005):

- treating the seedlings with insecticides
- planting seedlings with mechanical barriers
- planting large seedlings
- scarifying the stand and creating patches with bare mineral soil
- planting under shelterwood
- leaving the clearcuts dormant at least 2 growing seasons
- sowing instead of planting
- planting *P. abies* rather than *P. sylvestris*
- leaving large amounts of freshly harvested branches as an alternative food source to the planted seedlings (at least while the branches are fresh).

The second factor is vegetative competition. Vegetative competition from grass is commonly a very serious constraint during stand regeneration (Davies 1985). Field vegetation competes for resources with planted seedlings, and competition from grass vegetation is probably more severe than that from herbs (Nilsson & Örlander 1999). Because of soil acidification, nitrogen deposition (Nilsson & Örlander 1999) and the generally high fertility of sites in this part of Sweden, a clearcut in Götaland is often thoroughly covered by *Deschampsia flexuosa*, *Rubus spp.* and ferns already two growing seasons post-harvest (Grape, Pers. Comm.). Bergquist (1998) noted that *Deschampsia flexuosa, Betula spp., Rubus idaeus,* and *Calluna vulgaris* together made up more than 95% of the biomass on 20 clearcuts in Götaland. On some of these clearcuts, *Deschampsia flexuosa* accounted for circa 75% of plant biomass in the field layer (Bergquist 1998). It seems that field vegetation biomass increases with the age of a clearcut. Not surprisingly, seedlings planted on clearcuts older than 3 to 4 years are negatively affected by competition from ground vegetation (Nilsson & Örlander 1999). Indeed, a clearcut on one of Götaland's most fertile sites may be completely covered by vegetation 1 to 2 years after harvest (Lindell & Sundin 1981).

Grass vegetation may adversely affect seedlings by lowering the soil temperature (Hogg & Lieffers 1991) or affecting the risk for summer frost (Örlander et al. 1990). Still, vegetative competition impedes seedling survival mainly through competition for nutrients, moisture and through allelopathy (Nilsson & Örlander 1999). The competition for light, however, is not considered a problem for *P. abies* seedlings in grassy vegetation (Örlander et al. 1996). Thus, mowing the vegetation often has no positive effect on seedling growth since it does not lessen the degree of root competition (Nilsson et al. 1996). Highly fertile forested land is found on 2.6 million ha in Götaland (Bäcke et al. 1983). These highly fertile lands tend to be the most difficult sites in Götaland to regenerate (Berg 1983), especially when located in areas that are prone to spring drought

(Lindell & Sundin 1981).Vegetative competition can be reduced through (e.g. Skogsstyrelsen 1975, Nilsson & Örlander 1999):

- herbicide use
- scarification of the stand
- shelterwood forestry
- planting large seedlings
- planting directly in the LF horizon (not scarifying).

The third factor causing stand regeneration difficulties is spring drought. Drought reduces seedling survival, tree growth and disease resistance. The lack of precipitation during the start of the growth season seems to be a major problem during stand regeneration and for seedling survival (Eidmann & Klingström 1976, Nilsson & Örlander, 1995). Spring drought is especially prevalent along the eastern coast of Götaland where, based on data from 1931-1960, precipitation varies in the month of May between 10-40 mm (SMHI, in Skogsstyrelsen 1975). According to Lindell & Sundin (1981), this means that 20% of Götaland's forested area is vulnerable to spring drought. In 1974, however, no precipitation fell on parts of Västergötland over 65 days from March 22 to May 26. In addition, no precipitation fell between May 13 and July 11 along the coast of south-eastern Götaland in 1992 (SMHI 2003a). Climate models predict that global warming will lead to drier vegetation period in Götaland. In fact, several climate models from 2002 suggest that precipitation from June to August in Götaland will decrease 20-25% by the year 2100 compared to 1961-1990 (SMHI 2003b). The negative effects of spring drought can be reduced by (e.g. Skogsstyrelsen 1975, Lindell & Sundin 1981):

- scarifying by mounding
- planting directly in the LF horizon (not scarifying; this is common practice by Södra in Blekinge)
- shelterwood forestry.

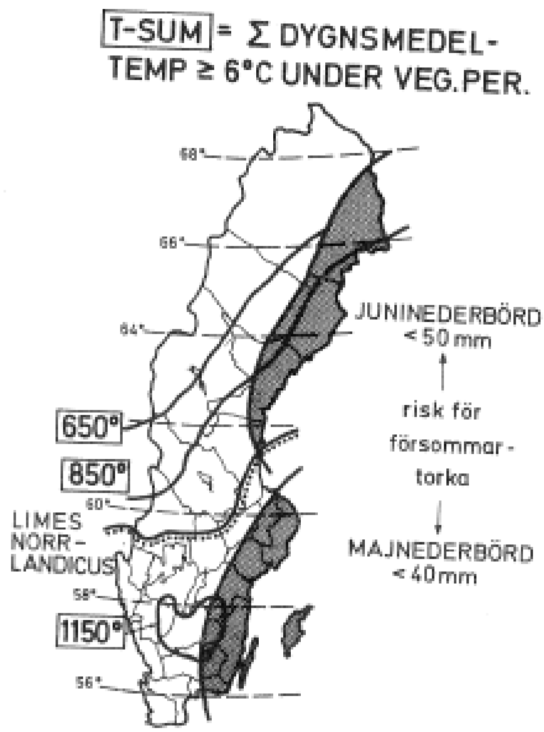

Figure 2. The temperature-sums of Sweden organized into three main regions. The shaded areas along the eastern coastline are especially susceptible to spring drought – i.e. <40 mm of precipitation in May in the southern half and <50 mm of precipitation in June in the northern half (from Bäcke et al. 1983).

The fourth factor causing stand regeneration difficulties is frost heaving. Frost heaving occurs on soils with a large silt content, in some types of clay and on some organic soils with a high moisture content (Bergsten et al 2001). Newly planted and yet-to-be-rooted seedlings are then pushed or heaved out of the ground when the ground freezes (Goulet 2000). Alternatively, seedlings may remain in the soil but their roots may be broken by the heaving process (de Chantal et al. 2007). The incidence of frost heaving is lessened by snow cover and amplified by a repeated freeze-thaw cycle (Holmes & Robertson 1960). Frost heaving may greatly reduce growth and survival of seedlings in regions where freezing and thawing are accompanied by high soil moisture (Goulet 2000). However, the deeper the snow, the less chance there is of frost heaving damage to seedlings (Goulet 2000). Today, snow cover is rare in Götaland and the temperature fluctuates around the freezing point for much of the winter months (SMHI 2005). Also, the incidence of frost heaving is linked to the silvicultural system used, i.e. the more stems left after harvest, the less risk of frost heaving (de Chantal et al. 2007). Moreover, scarification can increase frost heaving damage on soils susceptible to frost heaving as a result of the removal of the humus layer which otherwise dampens the diurnal fluctuation in soil surface temperature and moisture content (Söderström 1973). Intensive or deep soil preparation increases frost heaving and seedling mortality when compared to shallower soil preparation (de Chantal et al. 2006). Thus, frost heaving is a factor throughout Götaland during tree planting on susceptible soils where standard site scarification has occurred. According to Bäcke et al (1983), frost-heaving-susceptible soils are found on 700 000 ha of forested land south of Limes Norrlandicus (Götaland and eastern Svealand). The risk of frost heaving on susceptible soils can be reduced by (e.g. Goulet 2000, de Chantal et al. 2007 & 2009):

- the shade provided by (dense) shelterwoods
- planting directly in the LF horizon (not scarifying)
- scarifying by mounding (mounds placed on the humus layer)
- mulching (or leaving the surrounding field vegetation intact)
- planting deeply (root collar being 5-10 cm under the soil surface)
- fertilizing the seedlings to promote rapid root growth
- sowing instead of planting
- planting large seedlings.

The fifth factor causing stand regeneration difficulties is ungulate browsing. There are large populations of ungulates, especially *Capreolus capreolus* and *Alces alces*, and few predators in Götaland (Bergquist 1998). Therefore, new shoots on seedlings and younger trees are often browsed upon, sometimes very heavily. Browsing lowers the growth rate of trees, reduces wood quality and can lead to seedling mortality or change the tree species composition at stand level (Gill 1992). The dramatic increase in ungulate populations in Götaland since the 1970s (Cederlund & Markgren 1987) has affected which tree species that can successfully be planted on clearcuts without fencing. Today, many forest owners in Götaland hesitate to plant *Pinus sylvestris* and deciduous tree species on forested land without fencing (Rosenquist 2003). Nevertheless, *C. capreolus* can also cause major damage to *P. abies* by browsing new shoots or uprooting newly planted seedlings (Bergquist 1998). Browsing damage to *P. abies* seedlings can be reduced by (Kullberg 2000, Grape, Pers. Comm.):

- applying repellents to leading shoots
- applying additional hunting pressure on ungulates
- introducing predators to Götaland
- planting large seedlings
- fencing.

The sixth factor causing stand regeneration difficulties is large sized seedlings. The planting of large seedlings reduces seedling mortality as a result of frost heaving, vegetative competition (Skogsstyrelsen 1975) and predation from *H. abietis* (Eidmann & Klingström 1976). Due to prevalence of the last two factors listed above, seedlings taller than 20 cm are standard when planting *P. abies* throughout most of Götaland (Grape, Pers. Comm.). When compared to the averaged 12 cm seedlings used in the rest of Sweden, the planting of large sized seedlings increases the cost of stand regeneration through more expensive logistics (Thorsén et al. 1984, Berg 1993b), more difficult storage and handling (Berg 1993b), less productivity during planting (Thorsén et al. 1984, Berg 1993b) and a higher seedling purchasing costs (Häggström 1957, Berg 1993b).

The seventh factor causing stand regeneration difficulties is the logging residues produced after harvesting, which are also termed harvesting residues, slash or brash. Slash is the branches and tops of trees, and these can either be left on the clearcut or harvested for primarily bioenergy purposes (Sikström 2004). Slash generally reduces the temperature of the underlying soil (Proe et al. 1994) but can have both positive and negative effects on seedling predation by *H. abietis* and plant species diversity on clearcuts (Sikström 2004). When slash is removed, seedling survival rates (for both *P. abies* and especially *P. sylvestris*) generally improve while seedling growth rates may decline (Egnell et al. 1998). This is primarily because of reductions in the shelter effect of the slash, increased weed competition and reductions in soil nitrogen availability (Proe et al. 1994). Studies have shown that growth rates decline between 0-30% in the 10-15 years after harvest, with 5-15% reductions being most common (Sikström 2004). Nonetheless, the removal of slash on clearcuts in Norway and Finland has been shown to (Sönsteby & Kohmann 2003, Saarinen 2006):

- increase the work quality and productivity during mounding, manual planting and mechanized planting
- generally reduce regeneration costs.

In Sweden, slash removal is less common in Götaland than in the country as a whole. Based on the applications for clearcutting received by Skogsstyrelsen (the Swedish Forest Agency) in 2006, slash was removed from 33% of all clearcuts in Götaland. In contrast, this percentage was 37% for the rest of Sweden. But private forest owners in Götaland are more prone to remove slash from clearcuts than their counterparts in the rest of Sweden given that slash was removed from 27% of privately owned clearcuts in Götaland compared to 22% for the whole of Sweden (Anon. 2007). Nevertheless, slash removal is presently becoming more common, especially in Götaland and Svealand, due to the rapid development of the Swedish bioenergy sector (Matisons, Pers. Comm.).

The final factor that causes difficulties for stand regeneration in Götaland is shelterwood systems. Shelterwoods lessen predation by *H. abietis* and dampen the effects of spring drought, water stagnation, vegetative competition and frost heaving on seedlings, but impede the use of silvicultural machines in a rational manner (Håkansson 1994), and can usually cause unevenly distributed regeneration at stand level. In Götaland, shelterwood systems in the form of seed tree establishment or uniform high shelterwoods are, relative to the rest of Sweden, uncommon (Anon. 2007). Still, shelterwoods are used for stand regeneration on circa 20% of the harvested area per year (Hallonborg et al. 1995, Anon. 2007). This area is therefore not suitable for mechanized stand regeneration, unless the machine can work intermittently (Hallonborg et al 1995, Åhlund 1995). One negative aspect of shelterwood systems in Götaland is the high risk of wind throws, just as the January storms of 2005 and 2007 have shown. Even without hurricanes, practical experience has shown that up to one third of all shelter trees are blown over during the first years after the establishment of the shelterwood (Håkansson 1994). What's more, seed tree regeneration in Götaland is often impeded by poor seedling establishment caused by vegetative competition owing to the generally high fertility of soils (Örlander, Pers. Comm.).

2.2 Terrain characteristics

Terrain characteristics are thought to be the most significant factor when determining which sites can be replanted mechanically (Bäckström 1978). In Sweden, the terrain of the average stand is much more technically challenging than in those parts of the world where mechanized tree planting is common (Berg 1991). This is especially true for Götaland (Örlander, Pers. Comm.) because population growth and a climate relatively advantageous for agriculture turned most of the tillable land into agricultural fields during the 1800s; thereby leaving forests only on land too marshy, rocky or steep to cultivate. That said, more than one million hectares of poorer quality agricultural fields in Sweden have been reforested since the First World War (Svensson 1998), and these sites have much gentler terrain characteristics.

According to the Swedish Terrain Classification System of Skogsarbeten (1982), forest terrain can be rated on a scale of 1–5 within the following three categories:

Bearing capacity (G, or ground condition) is determined by the soil type, soil humidity and ground reinforcement in the form of rocks, boulders, stumps, tree residues etc. Rocks and boulders provide long-term reinforcement while stumps and tree residues only reinforce temporarily.

Surface structure (Y, or ground roughness) describes the height and number of obstacles that impede machine advancement. By definition, obstacles are rocks, boulders, holes, mounds etc. that reach at least 10 cm above or below mean ground level.

Inclination (L, or slope) describes the dominating steepness of the terrain in all directions.

Forest stands with a rated bearing capacity above 3 are not suitable for wheeled forest machines unless the ground is frozen. Because tree planting and scarification must be carried out on unfrozen ground, stands with a bearing capacity of 4 or 5 must be treated with light weight / tracked machines or not scarified at all.

In Bäckström (1978), continuously advancing mechanized tree planters were considered limited to $G \leq 4$, $Y \leq 3$ and $L \leq 2$. However, Adelsköld et al. (1983) suggested that mechanized planting machines should be limited to work on $Y \leq 2$ and $L \leq 2$. In Hallonborg (1987), the terrain limitations for the Silva Nova continuously advancing tree planting machine were adjusted to $G \leq 3$, $Y \leq 3$ and $L \leq 3$ but the sum of these ratings could not exceed 6 (e.g. sites rated G=2, Y=3, L=2 were not suitable for mechanized planting).

Based on data from Riksskogstaxeringen (the Swedish National Forest Inventory) of 1970-72, Berg & Lindberg (1974) divided Götaland's forested area into a number of different terrain classes. This analysis was in turn used by Hallonborg et al. (1995) to state that 50% of all of Götaland's regeneration sites have a terrain rating sum greater than 6. Even when the allowable terrain rating sum is increased to 8 (where $G \leq 3$, $Y \leq 3$ and $L \leq 2$), 30% of Götaland's forests are unsuitable for mechanized planting (Berg

1983). By contrast, only 36% of the forested areas in the southern and western parts of Götaland have a terrain rating sum greater than 6 (Berg & Lindberg 1974).

The following three terrain factors, rated on a scale of 1-5, from the Swedish Terrain Classification System are also useful when describing forest terrain before scarification or mechanized planting (Skogsarbeten 1982):

Treatment resistance of the ground surface (M, or surface treatment resistance) describes how the ground cover, including the soil type, field and bottom vegetation, and the thickness of the forest litter and humus layer affects site preparation (scarification).

Boulder quota (B) indicates how many boulders and large rocks are present in the surface layer down to a depth of 20 cm. This factor is useful when planning site preparation or choice of regeneration method.

Slash and stumps (T, or harvesting residues) increase the soil treatment resistance but also reinforce the ground's bearing capacity. Slash thickness, spatial extent and the number of stumps are measured. This factor is never static because of the constant change in moisture content and the decomposition of the slash and stumps.

According to Berg (1991), 50% of the Sweden's forested area that was to be harvested during the 1990s was classified as M=2-3 (humus layer 5-30 cm thick), B=3-4 (20-60% of all probing attempts strike a rock), and T=3-4 (60-100% of the stand is covered by slash layers circa 20-30 cm thick and 400-800 stumps/ha).

2.3 Stand characteristics

Along with terrain characteristics, stand size is the second most significant factor when determining which sites are suitable for mechanized planting (Bäckström 1978). The size (area) of the stand is significant because it (Skogsstyrelsen 1975, Hallonborg et al. 1995):

- determines how often the machine must be moved (transportation and set-up/start-up costs)
- affects the ratio of effective work hours versus total hours worked (machine utilization degree, also termed technical availability or simply TU)
- affects seedling transportation, both to and at the clearcut.

Stand size affects the productivity and costs of stand regeneration for both manual and mechanized planting systems but is especially significant for the mechanized system (Bäckström 1978).

The total clearcut area in Götaland in 2006 (a year without major storms) was 60 185 ha. Private forests accounted for 50 787 ha (or 84%) of this area (Anon. 2007). Bäckström (1978) assumed that by 1990, the smallest sized clearcut suitable for efficient mechanized tree planting would be 3 ha. That said, 54% of the clearcuts in southern Sweden (Götaland and eastern Svealand) were less than 2 ha in size in 1979 (Berg 1983). Similarly, the mean clearcut area in Götaland was 3 ha in 1992-93, but only 2 ha for private forest owners (Anon.

1994). In 2006, these figures were 2.7 ha and 2.5 ha respectively (Anon. 2007). However, the statistics from 1992-93 and 2006 only consider stands larger than 0.5 ha that were reported to the Swedish Forest Agency before clear cutting. Thus, the mean clearcut is in reality smaller than what the official statistics from the Swedish Forest Agency say. Because of the above-listed productivity effects that clearcut size has on forest machines, small clearcuts call for small (less costly) machines. Consequently, tree planting machines working in Götaland on private land should ideally be small, easily transported and have a low hourly cost (Figure 3).

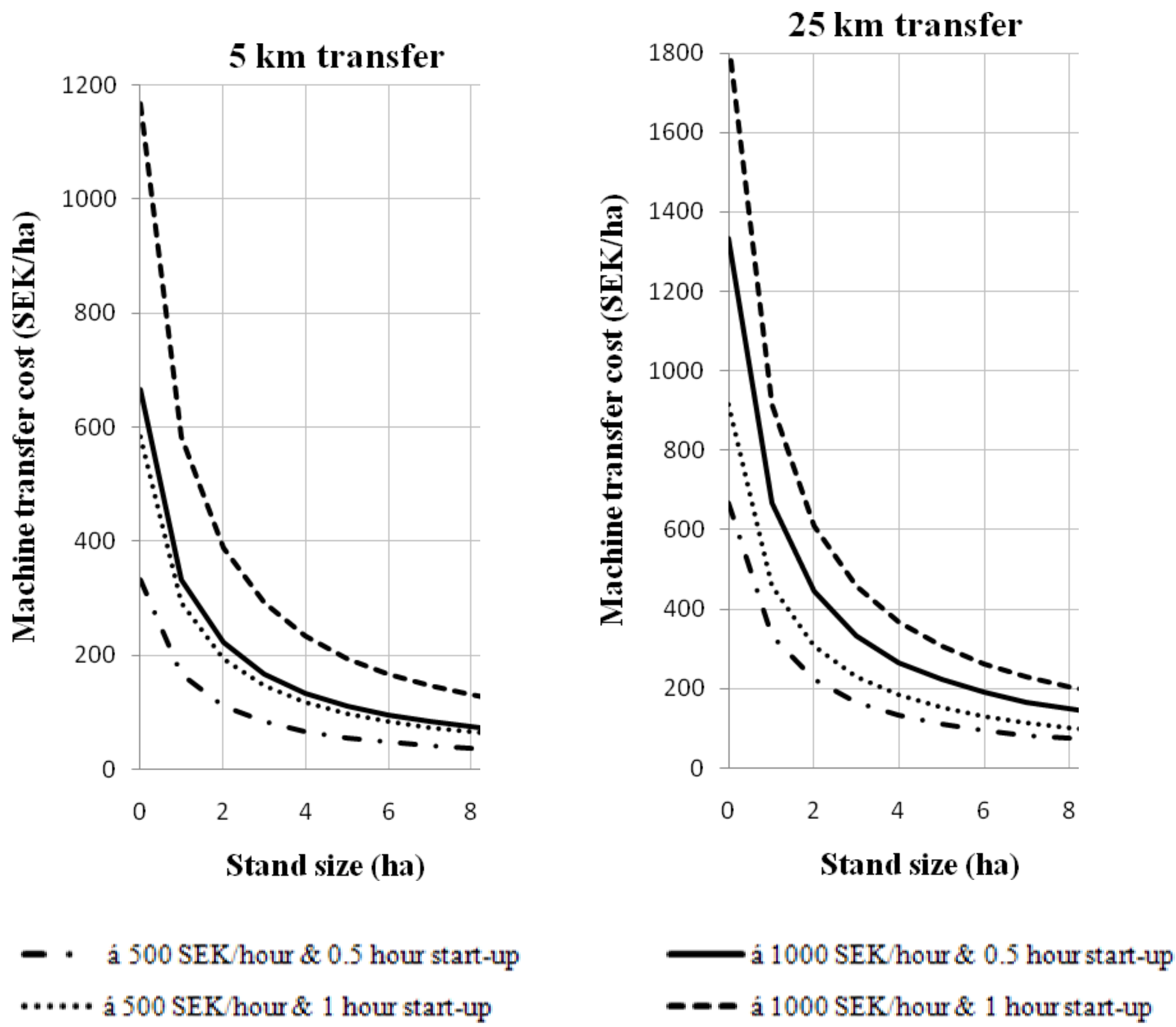

Figure 3. The cost per ha of 5 and 25 km machine transfers under own power as a function of stand size – assuming mean transport velocity of 30 km/h and with two different hourly machine costs and start-up time requirements.

The <u>stand shape</u> is also significant because it (Hallonborg et al. 1995):

- determines the time needed for turnarounds, which is especially important for continuously advancing machines
- affects the driving pattern of the machine at the clearcut
- affects seedling transportation at the clearcut.

An irregular shaped stand can cause productivity losses and make machine work more complicated. For example, the turnarounds' share of the work time increases if the length of the average machine passage decreases (Hallonborg et al. 1995). The length of the average machine passage can be assumed to be short on irregular shaped stands and small sized stands. Even with a turnaround time of 30 seconds and a driving speed of 25 m/min, turnarounds account for 12% of the machine work time on a 1 square ha if the machine is driven back and forth straight across the stand (Hallonborg et al. 1995). Structural retention, riparian zones, dead wood left on the clearcut, etc. also causes irregular stand shape. According to Hallonborg et al. (1995), the irregularity of a stand can be characterized by a winding coefficient. This winding coefficient is the difference between the irregular stand's circumference and the circumference of a stand with the same area but with the shape of a square. Hence, the higher the winding coefficient is, the more irregular the stand is and the more manoeuvring time the machine needs to reach all the areas within the stand.

Because of the windthrow caused by the January storms of 2005 and 2007, clearcuts in large parts of central Götaland tend today to be very irregular in shape when compared to the rest of Sweden. Moreover, climate models predict that the negative consequences of severe storms will become more common for forests in Götaland in the future (SMHI 2003b), chiefly because mature stands of *P. abies* are susceptible to windthrow (Karlsson & Lönnstedt 2006) and most stands in Götaland are *P. abies* stands. Hence, because of windthrow and the increasing focus on leaving structural retention, dead wood and riparian zones, clearcuts are apt to remain irregularly shaped in the near future. This, in turn, will make manoeuvrability important for future tree planting machines working in Götaland. As experience from the Silva Nova (see page 25) has shown, irregularly shaped stands are much more problematic for continuously advancing machines compared to intermittently advancing planting machines with crane-tip mounted planting heads.

The spatial distribution of clearcuts is another important factor affecting mechanized tree planting in Götaland because it (Skogsstyrelsen 1975):

- determines the mean transport distance between stands
- affects the cost of seedling transportation to the stand
- affects overhead and costs for operative planning (e.g. road maintenance).

The spatial distribution of clearcuts is influenced by the:

- size of the clearcuts
- arrangement of the road network
- size and shape of forest estates.

Linked to spatial distribution is also the stand's proximity to the nearest road, termed the average forwarding distance of a stand. This strongly affects the start-up costs and the technical degree of utilization of forest machines at a stand (von Segebaden 1969). Using data from Swedish National Forest Inventory 1957-1963, von Segebaden (1969) calculated the average forwarding distance to be 0.2 km in the southernmost county (municipal district) and 2.4 km in the northernmost county. Notwithstanding, many of the roads in southern Sweden were of poorer standard than in the north, which helped even out the difference (von Segebaden 1969). Based on data from Swedish National Forest Inventory, the average forwarding distance in Götaland today is circa 215 m which is 135 m shorter than the average for the whole of Sweden (Athanassiadis, Pers. Comm.). Shorter forwarding distances allow for use of more expensive machines because then the machine's degree of technical utilization is higher (i.e. less work time is spent commuting between the forest road and the clearcut).

2.4 Ownership and Land Use aspects

As mentioned above, both the size and shape of forest estates and the road network affect the cost of mechanized forestry work. Both of these factors are strongly influenced by how land ownership is structured within a parish (arronderingen). The mean forest estate in Götaland has 49 ha of productive forested land, whereas this number is 40 ha for Götaland's privately owned forest estates (Anon. 2008). This number is small when compared to the rest of Sweden where the corresponding estate sizes are 95 ha and 50 ha respectively (Anon. 2008).

Small private forest owners dominate in Götaland; 78% of the forested land in Götaland is owned by small-scale private forest owners (Anon 2008). Historically, small-scale forest owners have been less interested in experimentation with new forestry technology and much slower to embrace it (Larsson, M. Pers. Comm.). This is logical because many forest owners have emotional bonds, often inherited, to their forest estate and do not share the forest companies' rational view on silviculture. To let machines plant fragile (and sometimes expensive) seedlings in a manner which entails circa 5-20% of the seedlings (von Hofsten 1997a) lying on the ground or sticking halfway out of the soil – clearly doomed – is unthinkable for many small forest owners. These forest owners are beforehand negatively inclined towards planting machines, even when the terrain and circumstances on their clearcut are suitable for mechanized planting (Larsson, M. Pers. Comm.).

Historical remnants left by previous generations can be found all over Sweden and forested land is no exception. Kulturminneslagen (the Swedish Heritage Conservation Act) protects ancient and historical sites and monuments ("fasta fornlämningar" Langhammer, Pers. Comm.). Furthermore, Skogsvårdslagen (the Swedish Forestry Act) and Miljöbalken (the Swedish Environmental Code) stipulate that all physical traces of past human activities which have effectively been abandoned – hereafter termed ancient remains or "fornminnen" (Strömberg & Aronsson 2001) – and all other physical traces of past human activities (historical remains or "kulturminnen", Langhammer, Pers. Comm.) including rock walls, cabin foundations, old trails, charcoal beds, etc. must also be protected. Therefore, a land owner must, by law, protect all types of historical remnants from damage. Effectively, this means that forestry activities like scarification and tree planting are not allowed on historical remains (or within 5-10 m of ancient remains) (www.skogforsk.se). Today, however, field studies have shown that forestry activities damage 36 – 80% of all ancient remains found on regenerated clearcuts – with scarification causing most damage (Anon. 2006). Besides being illegal, the damaging of historical remains – and especially ancient remains – can lead to more restrictive government regulations if the damage reaches critical proportions.

Historical remnants are common on forested land in Sweden. In fact, 89% of all historical remnants found by the Swedish Forest Agency during regeneration controls on clearcuts are classified as "kulturminnen" (historical remains) and 11% as "fornminnen" (ancient remains). The corresponding percentage for Götaland is 96% "kulturminnen" and 4% "fornminnen". As is shown in Figure 4, some type of historical remnant (historical remains or ancient remains) is found on at least every third clearcut in Götaland (Eriksson, Pers. Comm.). These remains complicate the work of mechanical scarifiers and continuously advancing planting machines because of the additional manoeuvring needed to avoid the remains. However, historical remnants pose less of a problem for intermittently advancing scarifiers and planting machines because of their ability to be more accurate when choosing treatment spots (Strömberg & Aronsson 2001, Torstensdotter Åhlin 2001, www.skogforsk.se).

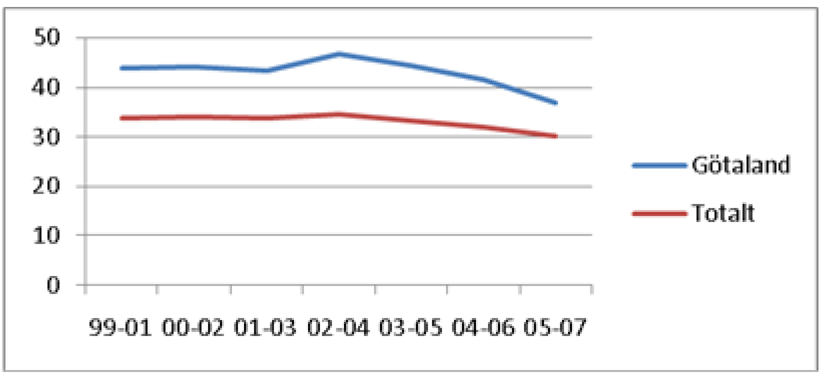

Figure 4. The percentage of all clearcuts where at least one historical remain (fornminne and kulturminne) was found during the Swedish Forest Agency's regeneration surveys. "Totalt" refers to the whole of Sweden (from Eriksson, Pers. Comm.).

According to the Swedish Forest Agency, 200 000 sites with ancient remains (about half of all these sites are various types of graves or burial grounds) cover 120 000 ha of forested land throughout all of Sweden, totalling circa 0.5% of Sweden's forested area (www.skogforsk.se). The Swedish Forest Agency has found that 0.1% of the total area of clearcuts in both Götaland and the rest of Sweden are covered by historical remnants and their buffer zones. This last number of 0.l% is less than the aforementioned 0.5% because most of the larger areas with ancient remains are never exposed to any type of harvesting and are therefore not included in the Swedish Forest Agency's statistics from regenerated clearcuts (Eriksson, Pers. Comm.).

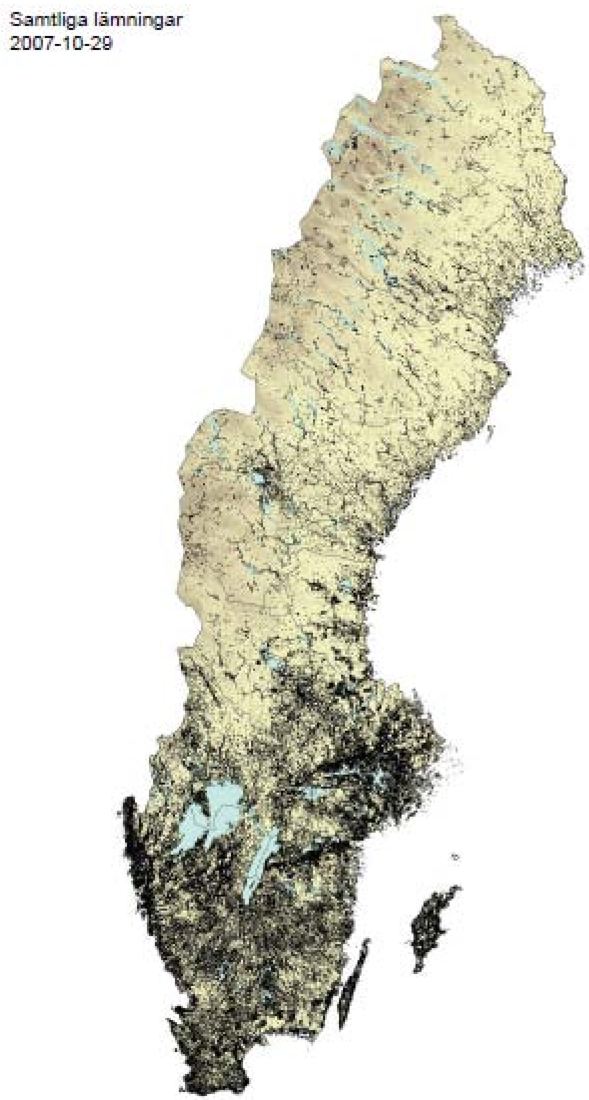

Figure 5. The distribution as of October 2007 of historical remnants in Sweden (ancient remains and historical remains, both types are symbolized by a black dot). These are clearly concentrated to Götaland and eastern Svealand (from Riksantikvarieämbetet 2008).

Silvicultural treatments that involve heavy machinery in urban forests, including forests on the periphery of cities and towns, are often controversial or subject to increasing criticism. This is because these treatments can be scrutinized by more people with a wider range of viewpoints as compared to forests in more remote locations. This criticism, or potential for criticism, hinders the use of scarifiers and even harvesters in a "normal" manner (Strandh, Pers. Comm.). 1% of the forested area in Sweden is within 1 km of a town of 3000 or more inhabitants (Rydberg & Falck, 1999). However, by using the latest data (from 2005) and definition of localities (towns and cities with 200 or more inhabitants) from SCB (Statistics Sweden), 5% of all forests in Sweden are within 1 km of localities. In comparison, this number is 10% for Götaland (Birkne, Pers. Comm.). Urban forests are therefore a dilemma – especially in Götaland – for mechanical scarifiers and some continuously advancing planting machines (i.e. Silva Nova, see page 25) but much less so for intermittently advancing planting machines owing to the latter's ability to scarify the soil in a less extensive manner (Åhlund 1995).

3. Mechanized tree planting – a short history

3.1 Planting machine basics

A mechanization wave swept over the Swedish forestry sector in the 1960's and brought with it a fear of future shortages of labour available for silvicultural work (Sirén 1967, Malmberg 1990). This concern was based on the fact that workers who manually harvested wood during the winter also supplied the labour force needed for silvicultural work during the summer. This fear, together with the wish to improve the working conditions for silvicultural workers and a generally optimistic attitude towards technological improvements, prompted Sirén et al. to start "Operation Machine Planting" at Skogshögskolan (the Swedish College of Forestry) in 1965. This operation was the first dedicated research program for tree planting machines in the Nordic countries (Bäckström 1978).

Operation Machine Planting lasted until 1970 and produced four prototype machines, all of which did not scarify the soil but only planted the seedling; two of these worked continuously and two worked intermittently (Figure 6) (Malmberg 1990).

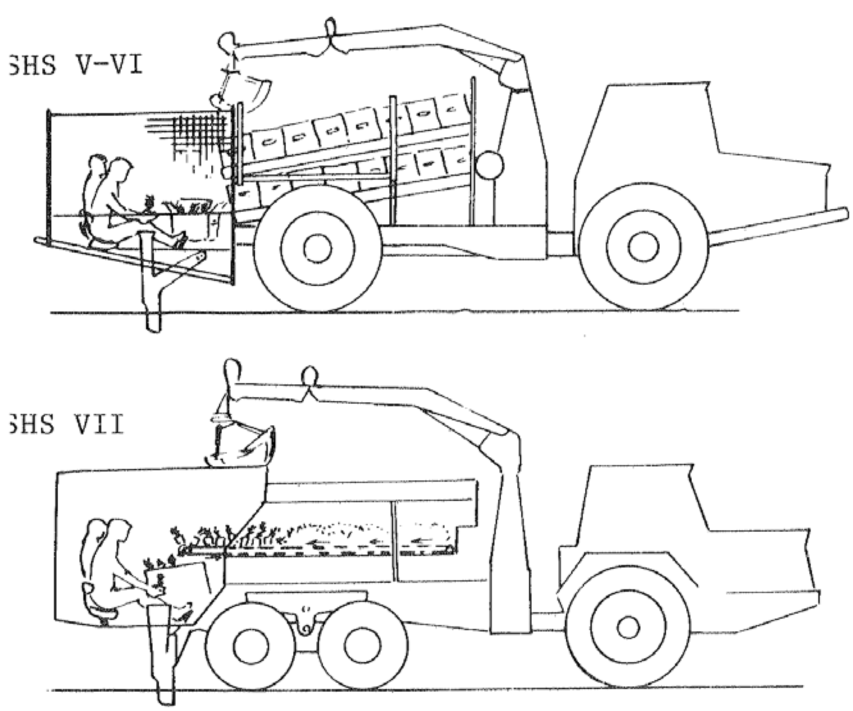

Figure 6. Sketches of the two intermittently working prototypes developed at Skogshögskolan (from Bäckström 1978).

At this point in time, however, intermittently working machines meant that they were continuously advancing but working with a planting head that moved up and down, in and out of the soil (Malmberg 1990). Nonetheless, these were the first intermittently working tree planting heads created. All previous machines made in either the Soviet Union, USA or Germany were ploughs combined with some sort of continuously advancing planting head (Bäckström 1978) and were limited to prairie land, abandoned agricultural fields or similar flat terrain free from obstacles (Bäckström 1978, Malmberg 1990). Indeed, mechanized planting was relatively common outside of the Nordic countries (Bäckström 1977). Both a shortage of labour and extensive areas of smooth, easy terrain had led to the development of tree planting machines in those countries (Berg 1991). Then in 1973, hole-making planting heads were introduced thereby ushering in the third generation of planting heads on continuously advancing planting machines as summarized by Bäckström (1978) below:

- First generation, from 1885 and onwards: continuously ploughing planting heads
- Second generation, from 1965 and onwards: intermittently ploughing planting heads
- Third generation, from 1973 and onwards: hole-making planting heads.

As the research progressed, it was established that planting machines on forested terrain should (Malmberg 1990):

- carry the planting heads rather than drag them behind the machine
- use intermittently working rather than continuously ploughing planting heads (so that obstacles like stumps and boulders can be avoided)
- perform any necessary scarification concurrently with planting rather than having two machines scarify and plant separately.

In 1971, Forskningsstiftelsen Skogsarbeten (the Forest Operations Institute of Sweden, today called Skogforsk) took over after Skogshögskolan and started research on tree planting machines through “Project Mechanized Planting”. To begin with, Skogsarbeten established that planting machines operating on forested land with moraine soils should preferably be able to work according to the following flowchart:

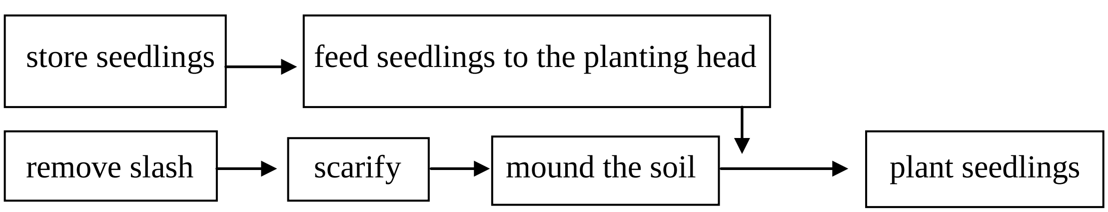

Figure 7. The ideal working method of a planting machine according to Skogsarbeten (from Bäckström 1978)

All of the above steps should be completed as autonomously and quickly as possible. The seedling storage and feeding parts of the process can be solved in various ways and are illustrated below in Figure 8:

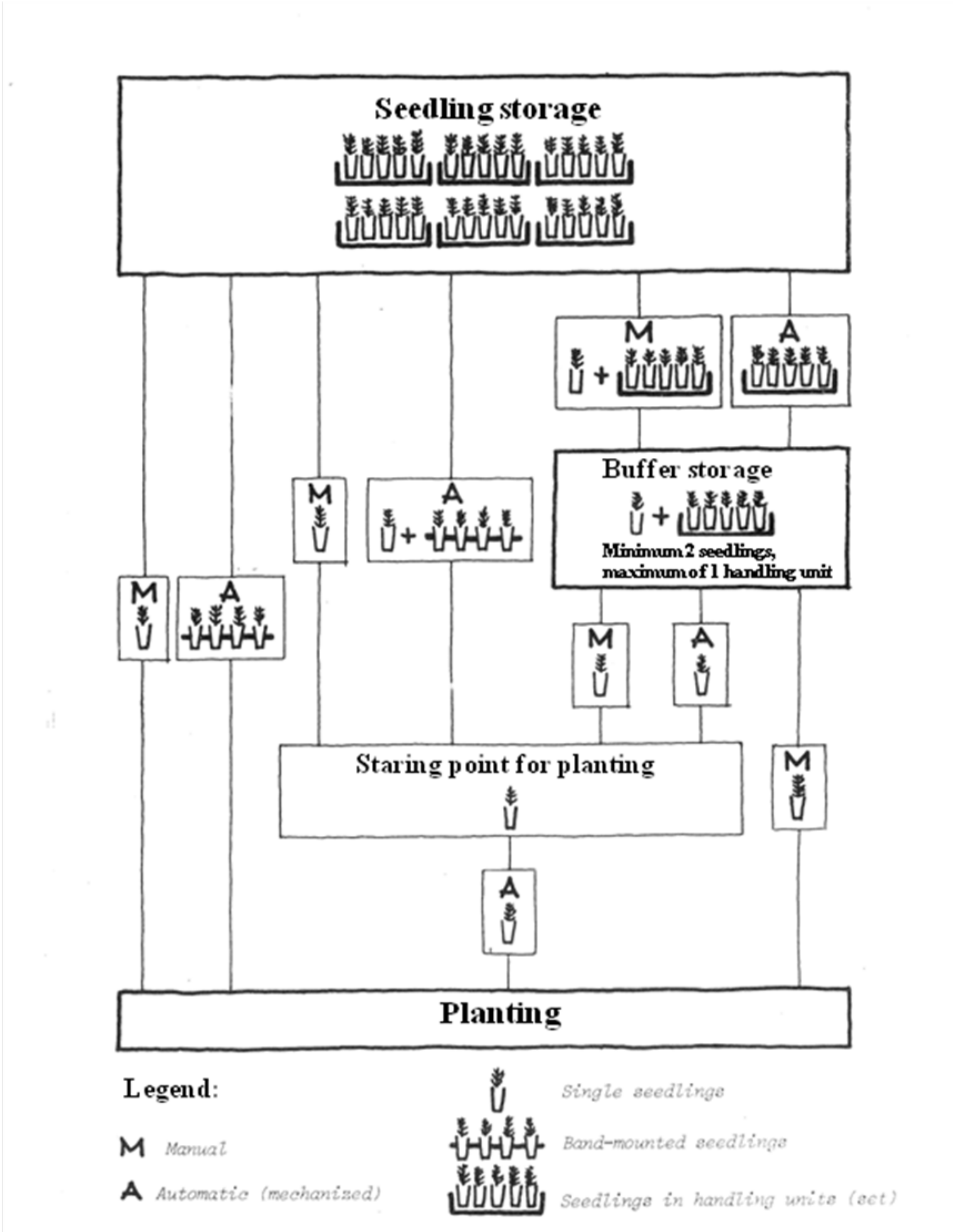

Figure 8.The principles of feeding seedlings from the seedling storage to the planting head on a planting machine (from Bäckström 1978).

Initially, all the feeding, internal transport and planting of seedlings on the first planting machines were performed manually, as is still common in agriculture today (Figure 9).

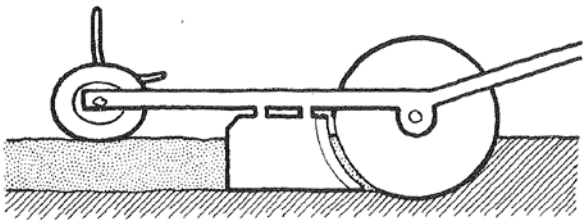

Figure 9. The most basic planting machine with manual feeding and planting of seedlings (from Bäckström 1978).

Thereafter, machines were developed where seedlings were fed manually to buffer storage and then planted mechanically (Figure 10). Even though the machines in question were first generation planting machines, today's planting machines still use this same seedling feeding concept.

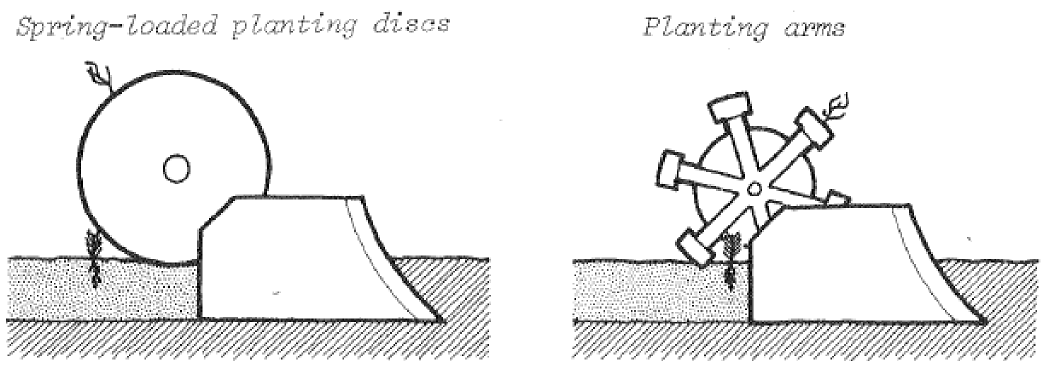

Figure 10. Manual feeding of seedlings to buffer storage followed by mechanical planting (from Bäckström 1978).

As the second generation tree planting machines (with intermittently ploughing planting heads) were invented in the 1960s and 1970s, manual feeding of individual seedlings to the starting point for mechanical planting (Figure 11) was used.

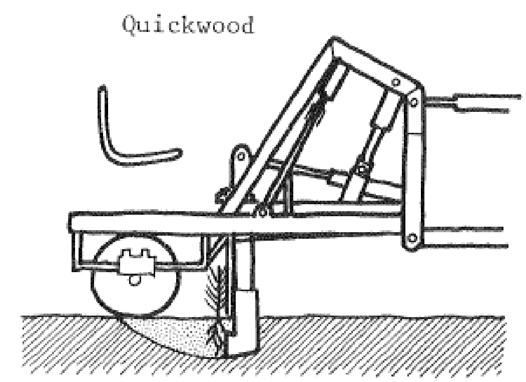

Figure 11. The manual feeding of seedlings to the starting point for mechanical planting (from Bäckström 1978).

From a productivity point-of-view, the ideal planting machine should be able to internally transport the seedlings as automatically as possible.

The most critical challenge for planting machines is how to insert the seedling into the ground in a biologically correct manner (Bäckström 1978). The seedlings are fragile and cannot tolerate careless handling, and the consequences of how they were handled might only be discernible years after planting (Malmberg 1990). Historically, the first planting machines created furrows where the soil is returned overtop of the bare-root seedling's roots once the seedling is placed within the furrow. Nowadays, planting machines use some sort of hole-making planting head and plant containerized stock in the ground, but during the 1970s-80s creative minds invented planting machines which placed the seedling on top of the ground (so called surface planting). These machines "planted" seedlings either grown within a pillar (R-O-plantan) or pillow (Odlingsplattan) of peat, or used normal containerized stock with extra-added soil placed around the seedling (Malmberg 1990).

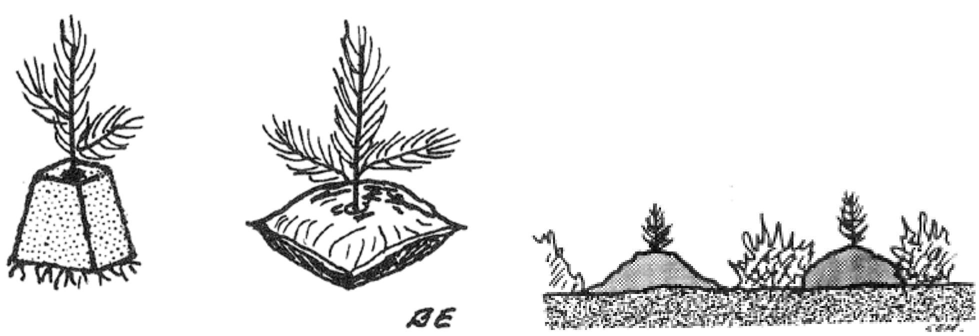

Figure 12. From left to right: R-O-plantan, Odlingsplattan, and seedlings planted using extra-added soil (from Malmberg 1990).

Similarly, Walters (1961) and Bäckström (1978) theorized that a planting machine could plant seedlings using bullet-plug or hard-nosed seedlings, thus eliminating the need for hole-making planting heads (Figure 13).

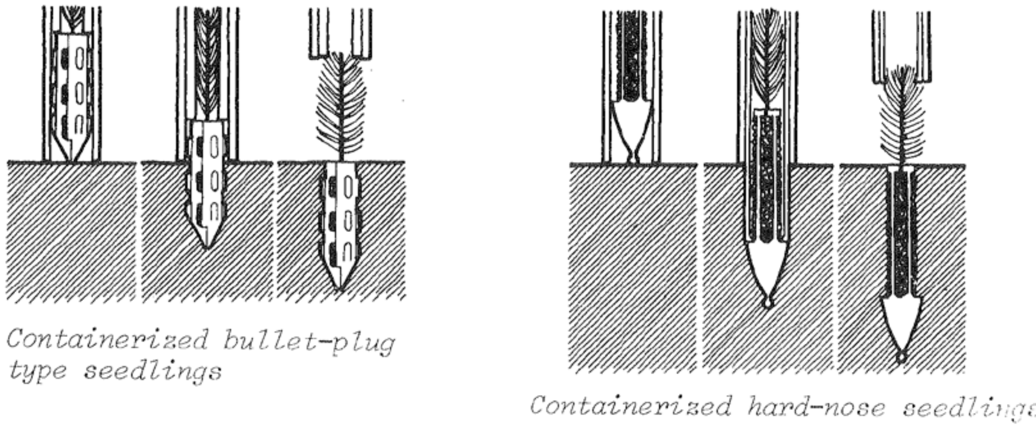

Figure 13. Concepts for planting seedlings without needing hole-making planting heads (from Bäckström 1978).

In his dissertation, Bäckström (1978) finds it most logical to classify planting machines according to how they:

- advance (continuously or intermittently)
- plant the seedling (with a continuously-ploughing planting head, an intermittently-ploughing planting head or a hole-making planting head)
- are constructed (either being a custom-built planting machine or being a planting device that is carried or towed by a base machine).

Alternatively, Lawyer and Fridley (1981) classified North American and European planting machine development as follows:

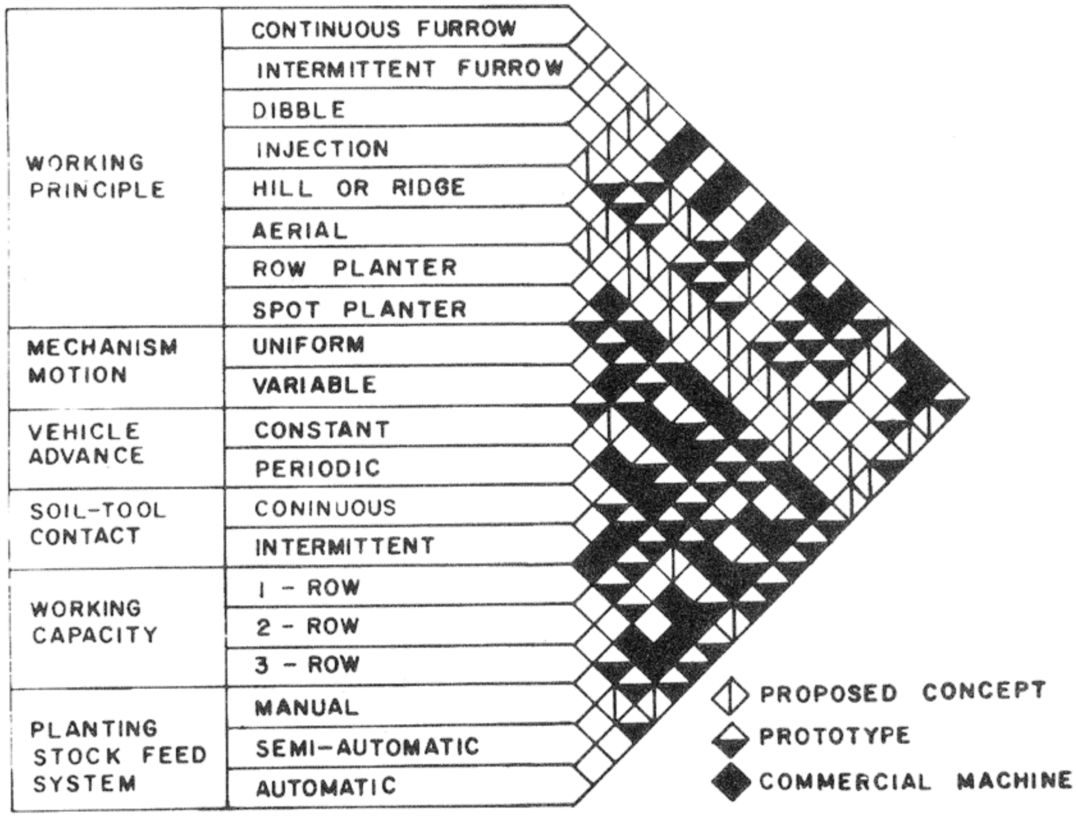

Figure 14. Categories of planting machine concepts. The diagram shows which concepts were proposed, which existed as prototypes and which were in commercial development in the early 1980s (from Lawyer and Fridley 1981).

In this essay, however, planting machines will be classified only according to how they advance and their level of mechanization (fully or partially mechanized).

3.2 Continuously advancing machines

During the early development stages of mechanized planting, continuously advancing planting machines were thought to be much better than intermittently advancing machines in competing economically with manual planting (Bäckström 1978). This was logical because early tree planting machines tended to work on flat, obstacle free terrains which lead to continuously advancing machines having approximately twice the productivity of intermittently advancing machines. (Adelsköld et al. 1983, Berg 1983).

The Doroplanter and MoDo Mekan were the first two commercially developed prototypes in Sweden. They were developed in the mid 1970s, scarified intermittently, planted with a hole-making planting head, were operated by two operators and were marketed towards Sweden’s large forest companies (Berg 1991). The Doroplanter (Figure 15) was a separate unit towed behind a forwarder while the MoDo Mekan (Figure 16) was carried by a forwarder (Myhrman & Zylberstein 1983, Berg 1991).

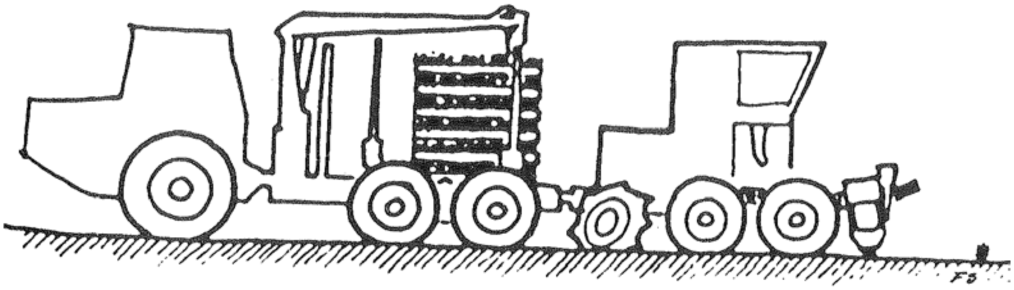

Figure 15. The Doroplanter (from Malmberg 1990).

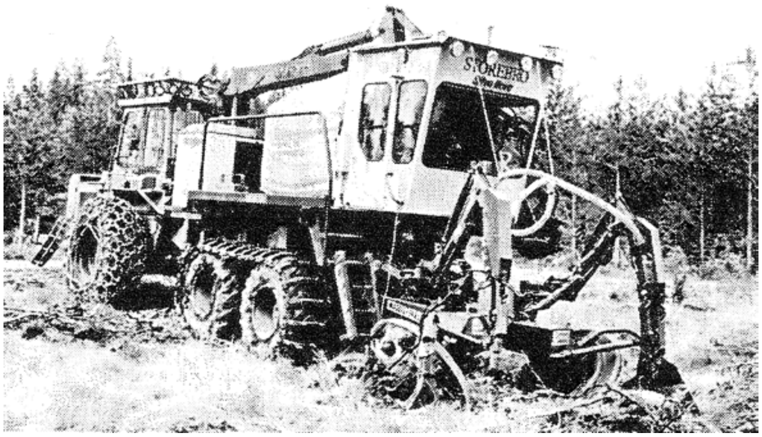

Figure 16. The MoDo Mekan planting machine (from Malmberg 1990).

Thereafter, two more continuously advancing planting machines were developed near the end of the 1970s: the Serlachius and the FIAB YPM 30 planting machines (Adelsköld et al. 1983, Berg 1983, Myhrman & Zylberstein 1983, Berg 1991). The Serlachius machine (Figure 17) was quite advanced (Malmberg 1990). It was also carried by a forwarder but required only one operator, planted specially designed seedlings, used an automatic seedling feeding system that could handle several types of seedlings, and scarified according to the inverse-turf concept (Stjernberg 1985). During one Swedish study, productivity reached 1100 adequately planted seedlings per effective hour but concerns were expressed over the quality of scarification (Adelsköld 1983). The Serlachius machine planted seedlings at the right depth and with good soil packing above the ground level on upturned sod and, thus, allowed for good local drainage (Adelsköld 1983, Stjernberg 1985). Details of the Serlachius machine´s capabilities and attributes are well described by Kohonen (1981) and Stjernberg (1985).

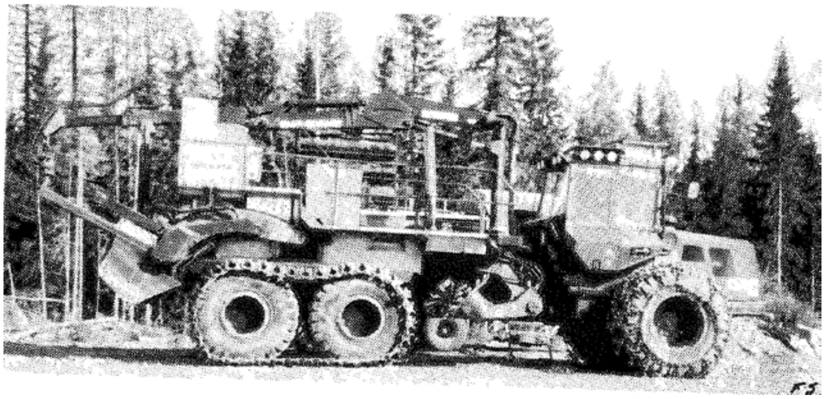

Figure 17. The Serlachius planting machine (from Malmberg 1990).

In one sense, the FIAB YPM 30 planting machine (Figure 18) was more a scarifier and carrier of seedlings than a planting machine because it scarified the soil and then portioned out within the furrows seedlings grown inside pillows of peat (Myhrman & Zylberstein 1983). The whole apparatus was carried by a forwarder and the seedling feeding system was automatic. However, since the seedlings were only placed on the soil, at least one man was needed to walk behind the machine and turn seedlings right-side up, adjust the seedling position etc. More importantly, these seedlings were very vulnerable to being overturned once again after being correctly repositioned, this time by browsing deer, moose, crows etc. (Malmberg 1990).

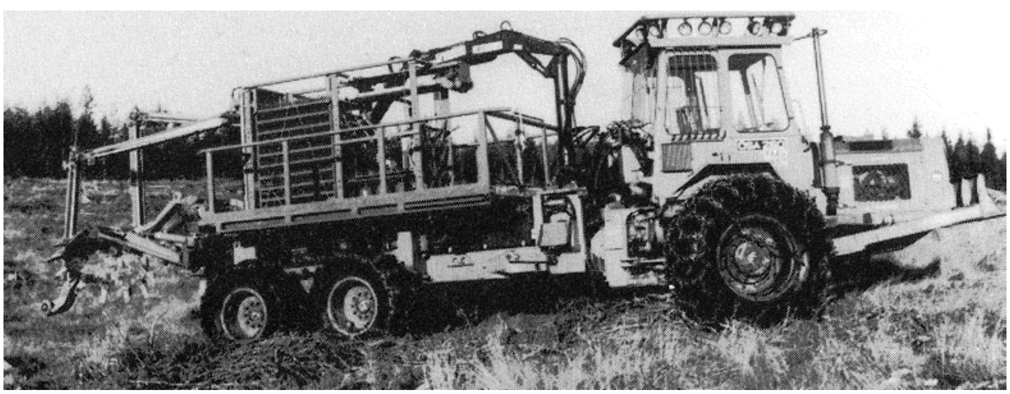

Figure 18. The FIAB YPM 30 planting machine (from Berg 1991).

The concept of planting bullets led to a prototype machine being built in British Columbia called the ReForester (Figure 19). This prototype, which was field tested in 1978, was a converted armoured personnel carrier operated by three planting-gun operators and one driver. The machine did not, however, meet specified planting rates (Walters & Silversides 1979). What's more, there were concerns regarding the bullet-seedlings' root egress and field performance (Klinka & von Hahn 1978).

Figure 19. The ReForester prototype automatic injection planting machine (from Walters & Silversides 1979).

The beginning of the 1980s was certainly the climax of mechanized tree planting research and development in both North America and the Nordic countries. Several symposia on the mechanization of forest regeneration were held in North America (e.g. the ASAE Symposium on Engineering Systems for Forest Regeneration, March 1981, and the Canadian Containerized Tree Seedling Symposium, September 1981), and no less than 16 varieties of tree planting had either been developed, were in development or were commercially available in Canada at that time (for a comprehensive list, see Stjernberg 1985).

In the early 1980s, the MoDo Mekan machine concept was overtaken by the Silva Nova project. Backed by the four largest Swedish forest companies (Berg 1991, Hallonborg et al. 1995), the Silva Nova effectively terminated development work on the other three planting machines. Thereafter, 15 years of development and improvements followed for the Silva Nova (Figure 20), culminating in 1994 with at least six Silva Nova machines working on clearcuts in mostly Svealand and Norrland (Hallonborg et al. 1995). The Silva Nova was operated by two operators, scarified using a disc trencher, planted using two sophisticated planting arms and sometimes included an automatic seedling feeding system (Malmberg 1990, Hallonborg et al. 1995). According to a number of studies summarized in Hallonborg et al. (1997), between 60-66% of the seedlings planted by the Silva Nova were planted correctly, i.e. at the right depth, with acceptable packing and above ground level in scarified soil.

In the economic analysis of Hallonborg et al. (1995), the Silva Nova's productivity was assumed to be 1367 seedlings per productive hour. In October 1998, SCA's Silva Nova using the PLS automatic seedling feeding system averaged a monthly productivity of 1770 seedlings per effective hour, which in this case translated to circa 1100 seedlings per productive hour (Lantz, Pers. Comm.).

Figure 20. The final version of the Silva Nova planting machine (from Åhlund 1995).

The Silva Nova project represented the culmination of development work on continuously advancing planting machines. The project lasted until the beginning of the new millennium and is well documented by Malmberg 1990 and Hallonborg et al. 1995. In 1997, the implementation of mechanized planting peaked when 9 and 12% of the total regeneration area of Norrland and Svealand respectively was planted mechanically (Lindholm & Berg 2005). Some of the reasons why, however, the Silva Nova concept was abandoned include:

- complicated workplace organization which led to high administration costs and high wage costs (Hallonborg et al. 1995)
- high investment costs (circa 4.5 million SEK per machine in 1995) that could not be offset by productivity improvements versus manual planting, (Hallonborg et al. 1995)
- low acceptance by private owners of the Silva Nova's quality of work mainly because of the many seedlings that were found lying on the ground, uprooted, buried, poorly placed etc. in the wake of the Silva Nova (Malmberg 1990)
- resistance from local district foresters who resented the special treatment given to the Silva Nova during regeneration planning, "the creaming of the best clearcuts" by the Silva Nova and the stealing of well paid, summer work otherwise destined for local teenagers (Berg 1985, Hallonborg et al. 1995)
- lower survival rates compared to manual planting; a 10% lower survival rate after three years was generally the silvicultural result with the Silva Nova (von Hofsten 1997a)
- a since-the-1970s-steadily-decreasing mean clearcut size that, unfortunately for the Silva Nova, reduces its competitiveness because of the higher share of the planting cost caused by machine relocation and machine turn-around time (Hallonborg et al. 1995, Anon. 2007)
- poor ergonomic conditions, especially for the rear operator feeding the seedlings (Hallonborg et al. 1995)

- a shift towards piece-rate pay rather than hourly wages for manual tree planters which raised the motivation and productivity of manual tree planting, the main alternative to the Silva Nova (Hallonborg et al. 1995).

3.3 Intermittently advancing machines

Despite having lower productivity compared to continuously advancing planting machines (Bäckström 1978), intermittently advancing machines have some distinct advantages including (Berg 1983, Hallonborg et al. 1997):

- simpler construction thereby increasing the TU
- lower investment costs and, consequently, reduced requirements for productivity, utilization, planning and organization
- more flexibility in choosing planting spots and in accessing rougher terrain
- less extensive scarification thereby leaving more of the ground cover intact.

According to Bäckström (1978), intermittently advancing machines can either work with the scarifier and planting arms attached to the chassis or by having these mounted on the boom tip.

The first commercially developed intermittently advancing planting machine in Sweden was the Hilleshög (Malmberg 1990) or HIKO planting machine (Figure 21) (Myhrman & Zylberstein 1983, Berg 1991). It was mounted on a smaller forwarder, used relatively simple and inexpensive technology, was operated by one operator, was relatively nimble and manoeuvrable, fed seedlings manually or automatically and had 3 planting arms which also did the scarifying (Malmberg 1990, Berg 1991). Despite being competitive on smaller clearcuts and allowing for a more flexible planning and organization compared to the Silva Nova, the HIKO concept was abandoned in the mid 1980s mainly because of the low productivity, poor scarification which caused seedlings to be planted in depressions and the limited flexibility in the placement of the planting arms (Malmberg 1990).

Figure 21. The HIKO intermittently advancing planting machine (from Berg 1983).

In the meantime, forestry companies also searched for technical solutions for rocky sites where hole-making planting heads were ineffective (Malmberg 1990). The idea was to surface plant seedlings surrounded by extra-added soil, soil that the machine carried with it. In the end, two machines were constructed, the first being Panth's planting machine and the last and most advanced being Doppingen (Figure 22) (Malmberg 1990). The Doppingen used a boom-tip planting head to plant shortened seedlings using 2 L of fine-grained sand per seedling; its productivity reached 150-200 seedlings per productive hour by the mid-1980s. However, this productivity was too low and the seedling survival rate after planting was often poor because (Malmberg 1990):

- the added soil dried out too quickly, especially if it was not compacted around the seedling properly
- the soil often flowed away from the seedling exposing the root plug, especially when planting on slopes
- the seedlings' short root plug made the seedlings less robust and vigorous
- the seedlings were not anchored in the ground and were, therefore, vulnerable to trampling and browsing by ungulates.

Much research was conducted on properties of the extra-added soil during these projects, and is well documented by Malmberg (1990). All soil fractions and organic materials had both advantages and disadvantages from a biological and technological point-of-view, and heterogeneous mixes tended to separate into different layers because of vibrations and bumps during the planting work. In the end, fine-grained sand with a 0-8 mm fraction size was the best compromise, but then it also required extra logistics, planning and incurred added costs as it had to be purchased and delivered from gravel pits (Malmberg 1990).

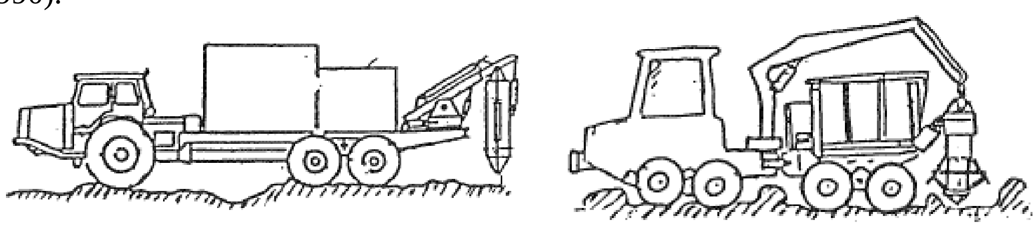

Figure 22. Panth's planting machine (left) and Doppingen planting machine (from Malmberg 1990).

During the late 1980s, the first successful boom-tip scarifying and planting head was developed – the Öje-planter. This head (today called the Bracke Planter) is either mounted on a tracked excavator or a harvester, creates a mound and then plants a seedling on top of the mound (von Hofsten 1993, Hallonborg et al 1997). The Bracke Planter is relatively robust, is well-suited for moist sites, can plant a wide range of seedling types, has a seedling magazine holding up to 85 seedlings that is reloaded manually, and has a productivity of 180-250 seedlings per effective hour (Hallonborg et al. 1997, Drake-Brockman 1998). Experience with commercially working Bracke Planters has shown average productivities of 170-240 seedlings per productive hour dependent on terrain (Hallonborg et al. 1997). The Bracke Planter is well documented by Hallonborg et al. (1997) and plants seedlings with good biological results (von Hofsten 1997b). Indeed, according to five studies summarized in Hallonborg et al. (1997), between 89-96% of the seedlings planted by the Bracke Planter were planted correctly. Nevertheless, some of the disadvantages of the Bracke Planter include (von Hofsten 1996):

- low productivity, mainly because the machine only plants one seedling at a time, but also because the seedling magazine is small and must be reloaded manually
- lower productivity and silvicultural quality on rocky sites or sites with many stumps or much slash
- productivity is very much dependant on the operator.

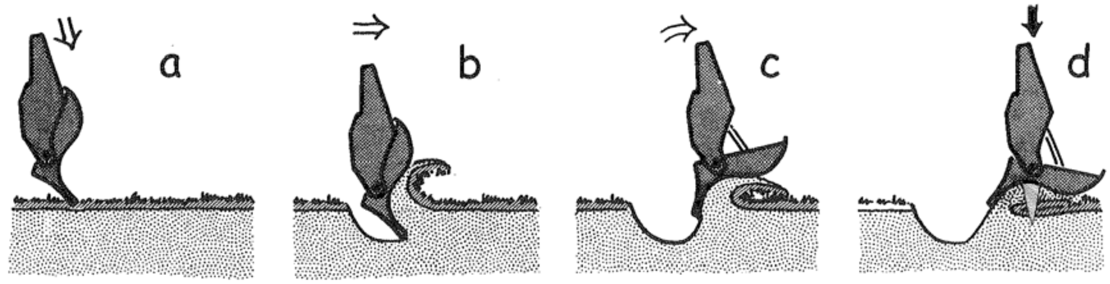

Figure 23. The Bracke Planter's working method (from Hallonborg et al. 1997)

In the beginning of the 1990s, a second boom-tip planting machine was developed called the EcoPlanter (Figure 24) (Åhlund 1995). This machine is meant to be mounted on harvesters, uses two rotavators to create mounds of humus and soil mixed together, plants two seedlings at a time, can efficiently apply insecticides while planting, has a seedling magazine that is reloaded manually and holds up to 240 seedlings, and has productivity around 200-600 seedlings per productive hour (Hallonborg et al. 1997, Mattsson 1997, Halonen 2002, Normark & Norr 2002, Sönsteby & Kohmann 2003, Tolblad 2007) – the highest being reported in 2002 on sites with smooth surface structure in eastern Sweden (Normark & Norr 2002). The EcoPlanter is well documented by Normark & Norr (2002). According to numerous studies by ForeCare (1999) and Sönsteby & Kohmann (2003), circa 80-85% of seedlings planted by the EcoPlanter survive after four growing seasons. Some of the disadvantages with the EcoPlanter include (Mattsson 1997, Normark & Norr 2002, Tolblad 2007):

- low productivity, mainly because the seedling magazine must be reloaded manually (manual reloading accounts for up to 29% of the effective machine time)
- relatively low TU compared to the Bracke Planter
- productivity is very much dependant on the operator
- relatively time-consuming scarification
- the mounds, a mixture of humus and soil, may not protect the seedling well enough against *H. abietis* if the mound is not covered by mineral soil
- poorer silvicultural results on sloping terrain.

Figure 24. The EcoPlanter planting head (from Normark & Norr 2002)

In the mid 1990s, the Bracke concept was further developed by a prototype named SwePlant (Figure 25) (Hallonborg et al. 1997). This prototype was mounted on either a large or small excavator (Drake-Brockman 1998) and included a seedling magazine, an automatic feeding system, and a mounder/planting head. The prototype’s seedling magazine could store up to 1680 seedlings, used a mechanical claw to move seedlings one at a time from the cassettes to the hose feeding the planting head, and mounded using the inverse-turf concept (Hallonborg et al. 1997, Drake-Brockman 1998).

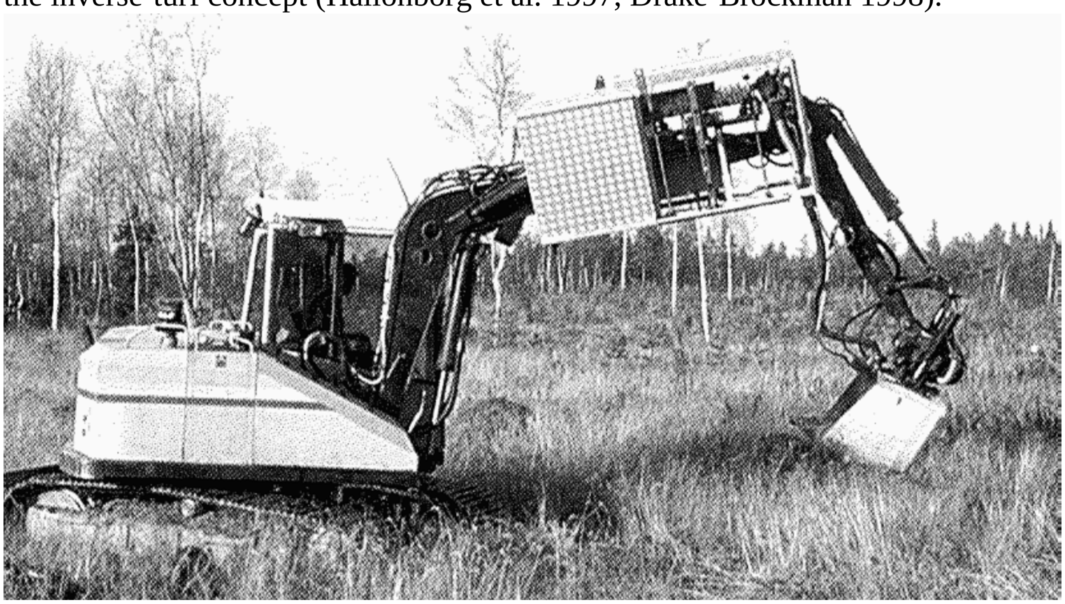

Figure 25. The SwePlant prototype mounted on a medium-sized excavator (from Hallonborg et al. 1997)

Yet another planting machine has further developed the Bracke Planter concept. The M-Planter (Figure 26), developed in 2006 in Finland, has a seedling magazine that can hold 162 seedlings, mounds and plants two seedlings simultaneously and can be mounted on an excavator (Johansson 2007). Based on an unpublished productivity study in which the M-Planter planted 236 seedlings per effective hour (Rantala et al. 2009), stand regeneration in Finland is on average 23% less expensive with the M-Planter compared to the Bracke Planter (Harstela et al. 2007). The same study concluded that this productivity gap between the Bracke Planter and the M-Planter widened with increasing slash coverage and narrowed with an increasing rockiness or number of stumps.

Figure 26. The M-Planter mounted on an excavator (from Johansson 2007)

3.4 Partially mechanized planting machines

Hallonborg et al. (1997) identified partially mechanized planting machines as the third type of planting machine. Being small, inexpensive, easily manoeuvrable and relocated, these machines are especially useful for small clearcuts distributed in close proximity to one another within a landscape and where large seedlings are planted or when fill planting (von Hofsten 1996, Hallonborg et al. 1997). Indeed, the smaller the clearcuts, the simpler the machine should be to relocate and organize, and the lower the fixed costs should be. Partial mechanization means that while the operator carries out the most complicated tasks like planting the seedling, choosing the planting spot and determining stem density, the machine aids the operator with the most arduous tasks, i.e. carrying the seedlings and making the hole (see Figure 27 and 28). These tasks are especially laborious when planting large seedlings (Thorsén et al. 1984).

The Hevotrac (Figure 27) was a self-propelled 8-wheeled carrier of seedlings with two manually operated drills, mounted fore and aft of the machine, each operated by one operator (von Hofsten 1996, Hallonborg et al. 1997). The machine could not, however, scarify the soil. Moreover, because two operators seldom work equally fast, up to 6% of the effective work time was spent waiting for the other operator to finish planting so that the machine could move on. Nevertheless, the Hevotrac was used in commercial production during the 1990s and could plant up to 300 seedlings per effective hour using two operators despite having a weak engine and sub-optimal drills (von Hofsten 1996).

Figure 27. The Hevotrac partially mechanized planting machine (from Hallonborg et al. 1997)

The Silviplant (Figure 28) was another partially mechanized planting machine that was developed as a prototype. This machine used a self-propelled 8-wheeled carrier of seedlings as well, but used just one single crane-mounted hydraulic planting tube instead of the Hevotrac's two drills; thereby operating with only one operator (Hallonborg et al 1997). Even so, the Silviplant, just like the Hevotrac, could not scarify the soil.

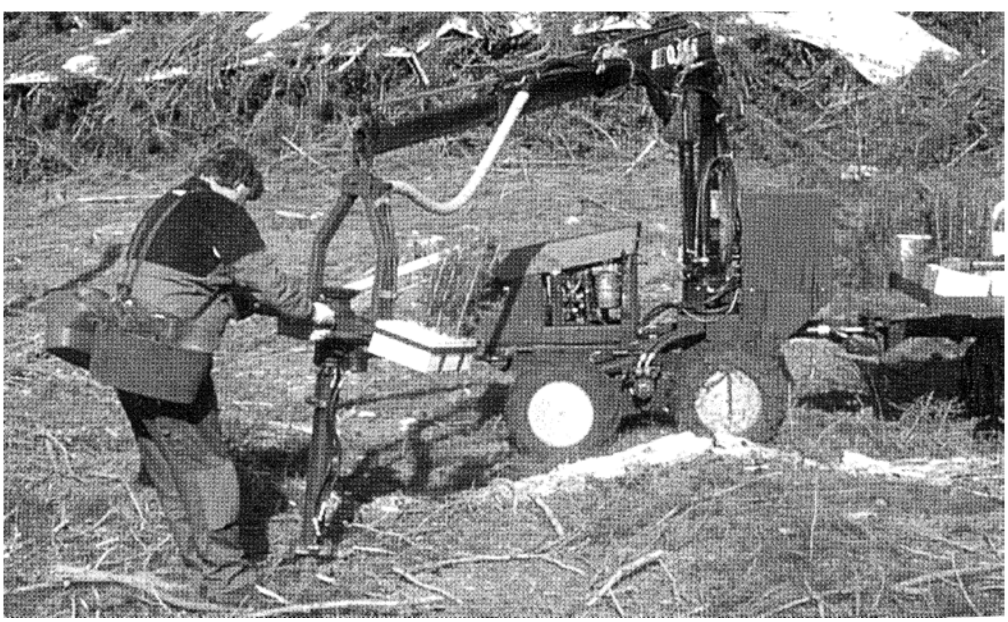

Figure 28. The Silviplant partially mechanized planting machine (from Hallonborg et al. 1997)

3.5 Seedling logistics systems

One of the most important factors allowing for the mechanization of tree planting was the development of the containerized seedling (Malmberg 1990). Containerized seedlings, i.e. seedlings with a covered root plug as opposed to bare root seedlings whose roots hang unprotected, allowed for a more rational and rougher handling because of their more uniform size and their ability to protect the seedlings' roots (Malmberg 1990, Landis et al. 2009). From 1960s to 1980s, techniques were even invented in some countries to "convert" bare root seedlings into containerized seedlings before being shipped from the nursery; thereby opening up for mechanized planting operations in the field (Bušs 1981, Maw 1981) During handling, shipping and storage outside of the nursery, seedlings may be exposed to many damaging stresses including extreme temperatures, desiccation, mechanical injuries, and storage moulds; the most common among these being desiccation (Landis et al. 2009). This is also the period of greatest financial risk because nursery seedlings have reached their maximum value right before shipping (Landis et al. 2009). From a biological, economical and technological point-of-view, root plugs made of peat have shown to be the best material for seedlings planted mechanically (Malmberg 1990). Indeed, peat is by far the most superior media for today's containerized forestry seedlings (Landis 1990).

Seedlings are grown in a wide variety of containers, often termed trays (Landis 1990). Seedlings can remain in these trays (the growth container) until planting or be removed and placed in cardboard boxes to be delivered to the clearcut (Landis et al. 2009). When compared to trays, the advantages of shipping seedlings in cardboard boxes include (Landis et al. 2009):

- less storage space required
- lighter weight
- physical protection for the seedlings
- the ability to stack the boxes resulting in more efficient shipping
- no equipment must be returned to the nursery
- the ability to cull poor quality seedlings before shipping.

Therefore, cardboard boxes are usually used when shipping seedlings long distances, albeit often placed on racks so that the underlying boxes are not crushed (Landis et al. 2009).

Alternatively, the advantages of shipping the seedlings in their growth containers (trays) include (Malmberg 1990, Landis et al. 2009):

- less packing and unpacking of seedlings resulting in more efficient handling
- the ability to develop efficient large-scale handling systems within the nursery and for delivery
- allows for easier development of automated seedling feeding systems on machines
- protection for the roots and the ability to irrigate seedlings if needed
- no need for extra packaging costs
- more air volume for the seedlings during shipping thus reducing the chance of storage mould or heat stress.

Therefore, trays are usually used when shipping distances are relatively short and the roads are not overly rough. Nevertheless, trays can also be loaded into boxes for added protection and more efficient shipping (Landis et al. 2009).

In addition to trays and boxes was the RO-plant system developed in the 1980s (Malmberg 1990). The RO-plant system entailed seedlings being grown in pyramid-shaped pots of peat which were linked together and could be rolled up into rolls (hence, roll-on and roll-off). This system was designed to allow for very efficient mechanized seedling production at the nursery and for mechanized seedling handling and feeding on planting machines. However, since the seedlings were also meant to be surface planted, the concept was never realized beyond experimentation at the nursery (Malmberg 1990).

In the mid to late 1990s, SCA used the Pot Link System (PLS) on one of the Silva Nova planting machines (Hallonborg et al. 1995, Lantz, Pers. Comm.). Like the RO-plant system, the PLS consisted of pots linked together lengthwise but instead used single plastic pots that could be arranged in a belt or even into trays. Seedlings were meant to be cultivated in either the PLS pots or in other trays, and then transferred to the PLS pots before shipping (Hallonborg et al. 1995). SCA, however, found both the cultivation and the distribution of PLS pots too expensive and instead settled on normal shipping of standard seedlings to the roadside landing where a portable robot loaded the seedlings into PLS pots (Figure 29, Lantz, Pers. Comm.). About 70 pots were linked together into one belt and then the robot filled the pots with seedlings. There were more than 100 belts which were thereafter automatically loaded into a large container carried by the Silva Nova. There were two of these containers, and they were rotated so that one was always being loaded while the Silva Nova was planting. While on the machine, the PLS belts were then automatically coupled together and fed to the planting arms in two long continuous belts. This feeding system was rather complex, and the harsh operating environment caused frequent jams and breakdowns in the PLS system. The plastic linking arms were especially prone to breaking off when two belts were coupled together. For example, in 1998, the last year that SCA used the Silva Nova, the PLS system averaged 2.4 stops per working hour and stood for 53% of the Silva Nova's total repair time (Lantz, Pers. Comm.). Nevertheless, the PLS system had the following advantages compared to manual feeding of seedlings in the Silva Nova:

- better ergonomics and working environment for the rear operator
- gentler handling of seedlings
- higher seedling feeding capacity
- increased free time so the rear operator could supervise the planting arms' quality of work instead of just feeding seedlings.

Equally important, the PLS system allowed the Silva Nova on some days in 1998 to average a daily productivity level of over 2000 planted seedlings per effective hour (Lantz, Pers. Comm.).

Figure 29. The portable loading robot at a roadside landing in 1998. The nursery trays were fed in by a conveyor belt (at right of the operator), and the loaded PLS belts were automatically arranged into separate slots within the white coloured container at left (from Lantz, Pers. Comm.).

Just as SCA was ending the PLS venture on the Silva Nova, a concept was developed allowing for an automatic seedling feeding system on the EcoPlanter (Normark & Norr 2002). This concept, called the EcoBandPak, used standard containerized seedlings that were linked together in a belt using two long strips of paper glued together. This belt of seedlings was meant to reduce the EcoPlanter's reloading time but the cost of the extra work needed at the nursery was too high. Likewise, no development of an automatic feeding device for the planting head took place. Altogether, this meant that the concept was not deemed cost-competitive (Normark & Norr 2002).

Figure 30. The EcoBandPak packaging machine (from Normark & Norr 2002)

All in all, it seems that only the EcoBandPak, PLS and Serlachius automatic feeding systems survived past the first experimentation stage. These latter two systems, some planting machine history and much more seedling feeding theory – including experiments with pneumatic feeding of seedlings – are described in Hallonborg's dissertation (1997).

3.6 Workplace organization

In the 1980s, when the first commercial planting machines were introduced in Sweden, further rationalization of the forestry work force was seen as one of the major benefits of planting machines (Berg 1985). Conversely, one of the major challenges with mechanized planting in the 1980s was deemed to be the need for more qualified personnel because the machines were expensive and complicated (Adelsköld et al. 1983). Today, however, this requirement of qualified personnel is considered an asset when recruiting potential operators because higher qualified jobs are considered more attractive by young people choosing occupational fields (Anon. 1998).

According to Adelsköld et al. (1983), continuously advancing planting machines were considered to offer a tiresome yet variable workplace full of diverse tasks. Moreover, planting machines needed more careful site selection and seasonal planning, more frequent seedling deliveries and better quality seedlings compared to manual planting. Because of the investment costs, planting during the whole summer half of the year (vegetative period) was considered a necessity (Adelsköld et al. 1983). There are, however, some biological problems associated with planting seedlings during the whole vegetative period. But according to research in Finland, the following solutions can make continuous planting from April to October achievable (Luoranen & Viiri 2005, Helenius et al. 2005, Luoranen et al. 2005, Luoranen et al. 2006):

- planting dormant or actively growing seedlings April-Midsummer
- planting actively growing seedlings Midsummer-August
- planting short-day treated seedlings August-October.

Indeed, the workplace organization of the Silva Nova was complicated. Often, the Silva Novas operated 20 hours per day and the site selection determined whether the Silva Nova was profitable or not (Hallonborg et al. 1995). Other problems for the Silva Nova included poor ergonomics, inconsistent seedling quality and motivational setbacks because of low productivity levels (Hallonborg et al. 1995).

Compared to the Silva Nova, the workplace organization of the intermittently advancing EcoPlanter and Bracke Planter was much less complicated. These intermittently advancing planting machines used only one operator, had lower productivity, could access more varied terrain and were mounted on older base machines thereby reducing investment costs (Hallonborg et al. 1997). Also, these machines could plant seedlings of varying quality and could run only one shift per day without dire economic consequences (Hallonborg et al. 1997, Tolblad 2005).

Ideally, the organizational and administrative work around a planting machine should be simple and flexible. In theory, it should even be simpler than with manual planting since the planting machine does the job of both the scarifier and the manual planting crews (Berg 1983). Therefore, the machine concept should be flexible, manoeuvrable and inexpensive enough that it can handle deviations in site selection and seedling logistics without causing economic ruin. Preferably, the machine investment should also be low enough to allow for seasonal stops (e.g. no planting between midsummer and august) and one-shift operation. Also, the machine should be organized so that the operators are able to regenerate a clearcut completely, thus planting by hand those areas unsuitable for mechanized planting and only leaving finished jobs behind them.

3.7 Today's machines and technology

As of spring 2009, only one planting machine is known to be in commercial use in Sweden. This is a Bracke Planter mounted on a 16 ton excavator working for Södra Skog in southern Götaland (Alvehus & Larsson, M. Pers. Comm.), but the same company has the ambition to recruit at least one more machine in the near future because of the high-quality biological results produced by the planting machine (Frohm, Pers. Comm.). Similarly, the only planting machine in commercial use in Norway is one EcoPlanter (Kohmann, Pers. Comm.). In Finland, however, there are more than 20 Bracke Planters and several M-planters in commercial use (Harstela et al. 2007).

One important question concerning today's planting machines is which base machine, (also termed prime mover) to use. Generally, the two choices are either excavators or harvesters (Alvehus, Pers. Comm.). Forwarders are not suitable because of the machine length, the poorer visibility offered by the cabin (generally built with non-slewing cabins and unsuitable crane placement) and unsuitable crane design (Åhlund 1995). A Valmet harwarder was successfully used as a base machine together with the EcoPlanter by one contractor working for Holmen Skog in the mid-2000s (Tolblad 2005, Tolblad 2007). Excavators dominate in Finland (Petersson 2008) and the advantages of an excavator include the following (Johansson 1994, Hallonborg 1997, Alvehus, Pers. Comm.):

- lower investment costs and thus a cheaper hourly rate compared to a harvester
- the excavator's crane can apply downward pressure on the ground thereby scarifying better on hard ground
- lower ground pressure thus causing less ground damage on moist or wet sites
- the ability to multi-task (e.g. cleaning ditches, perform road work).

On the other hand, harvesters have traditionally dominated in the Swedish forests and the advantages of a harvester include (von Hofsten 1993, Åhlund 1995):

- better and faster terrain manoeuvrability because of having wheels instead of tracks
- better operator ergonomics, comfort and visibility
- the ability to relocate on its own to nearby clearcuts simply by driving on forest roads.

Today, seedlings that are destined for mechanized planting in Sweden are delivered to the clearcut either in trays or in boxes. In 2004, when the EcoPlanter was used by Holmen Skog, operators preferred receiving seedlings in boxes because then the poorest quality seedlings had already been culled, thus saving the operators from added work during reloading (Tolblad 2005).

4. Challenges to address when designing new concepts

4.1 Seedling transportation from nursery to planting machine

The following are a number of challenges needing to be addressed when designing a new logistics system meant to increase the productivity of planting machines:

- integrating the machine's requirements for seedling transportation into the standard logistical flow of seedlings for manual planting
- calculating the cost/benefit of investing in new logistics/packaging solutions or even cultivation systems
- maintaining seedling vitality; can seedlings in this new logistics system be watered in a convenient and rational manner?
- managing the movement of seedlings from one site to another (inter-stand transportation)
- identifying from the logistics point of view the most optimal type of seedling container, seedling size and packaging (e.g. should the logistics system require that trays, racks, containers etc. circulate back to the nursery?).

4.2 Handling and feeding seedlings on the planting machine

The movement of seedlings on the planting machine itself can also be vastly improved. However, the following points need to be addressed when designing a new and more productive handling and feeding system for a planting machine:

- reducing vibrations from the machine/planting head that otherwise cause root plugs to fall apart
- designing system parts (e.g. automatic claws for picking seedlings out of trays, vacuum/pneumatic tubes that neither clog up nor damage seedlings, mechanical belts for moving seedlings) to be robust enough to work commercially (i.e. do not suffer from the "series-parts reliability dilemma" described in Bowen 1981)
- using the knowledge learned from the Silva Nova, PLS and EcoBandPak projects
- designing handling and feeding systems that can be used on standard excavators
- determining where (at the nursery, roadside or on the machine) seedlings should be loaded into the seedling magazine.

4.3 Planting heads

The planting head is the most crucial part of the planting machine, and its main function is to plant the seedling correctly (at the right depth and with proper soil compression) at the best possible microsite (Malmberg 1990). However, because of the clearcut's multitude of obstacles, this is easier said than done especially since planting heads have always worked solely mechanically. If a planting head that uses sensors, electronics and computers can be designed, the planting head could help to choose better microsites and plant seedlings more appropriately. However, before such planting heads can become reality, the following issues must be addressed:

- how to mitigate the brutal environment (with vibrations, dust, slash, rocks etc.) at the crane-tip
- certifying that ground-penetrating radar, colour detection, etc. sensors really work
- establishing when or under which circumstances planting without scarification can be justifiable (e.g. compared to mechanized planting without prior scarification, Mattsson (1993) measured seedling survival to be 10-15% higher when the Silva Nova planted in scarified soil).

4.4 Combination machines

If a planting machine can perform more tasks than just scarification and planting, the cost of machine relocation and the base machine's fixed costs (e.g. investment costs) can be spread out over more work time thereby reducing the hourly cost of the machine. However, multi-tasking invariably means that the machine design must include more compromises thereby leading to added weight and fewer specialized construction solutions. Also, multi-tasking can lead to more down time and needed repairs if the machine works with tasks that it was not designed for (Malmberg 1981).

Some added functions suitable for planting machines include:

- stump removal and/or stump forwarding
- slash forwarding
- direct seeding

Stump removal has enjoyed a revival in Sweden the last five years (Egnell et al. 2008). Stumps are removed using an excavator and a specialized stump harvesting head. On average, stump removal causes ground disturbance on 75% of the stand (Egnell et al. 2008), but this disturbed area can serve as scarification before mechanized or manual planting if extra spots are scarified between the stumps. This extra scarification is needed because, in reality, only 50-70% of the stumps' basal area is harvested, meaning that some areas of the clearcut are left untouched (Larsson, A. Pers. Comm.). Therefore, it seems logical to try to combine stump removal with scarification and mechanized tree planting if the stumps then can be forwarded without damaging the newly planted seedlings.

The idea of building a tree planting machine combining planting and scarification with the task of forwarding slash is not new. In his dissertation, Bäckström (1978) wrote that intensive efforts were being made in many parts of the world to combine tree planting with soil treatment and the harvesting of slash on one machine.

The main challenge to address if designing a new combination machine is that of productivity. Can a combination machine really do two or three separate tasks better and cheaper than the specialty machines?

5. Conclusions and opportunities for future research and technical development

In conclusion, mechanized planting in Götaland mainly entails planting spruce seedlings on relatively fertile clearcuts where the following factors can cause difficulties during stand regeneration:

- *H. abietis* predation
- vegetative competition
- spring drought
- frost heaving
- ungulate browsing
- large-sized seedlings
- slash
- shelterwoods

Moreover, planting machines in Götaland will have to operate mainly on privately-owned and relatively small-sized stands where historical remains are relatively common.

Ideally, the planting machine should be able to access the same terrain and attain productivity levels equal to today's scarifiers (i.e. 1.5 to 2 productive hours/ha on terrain classified up to GYL 343 for a wheeled two-row disc trencher) (Alvehus, Pers. Comm.). It should be noted that stands on slopes steeper than 3 (L≥4) are generally not harvested in Götaland, at least not in southern Götaland (Holmberg, Pers. Comm.). Three-rowed mounders need 1 productive hour/ha on similar terrain (Holmberg, Pers. Comm.). On wetter sites with GYL classification up to 422, scarification with tracked back-hoes today generally yields 3-10 productive hours/ha at hourly costs of circa 500 to 800 SEK/working hour (Larsson, M. & Holmberg, Pers. Comm.).

All things considered, there are a number of technical features on the various tree planting machines that have worked well. The following list identifies the successful features of these machines:

Serlachius:	- an automatic feeding system that could handle numerous seedling types (Stjernberg 1985) - an inverse humus (with mineral soil on top) scarification which created an advantageous microsite for the planted seedling (Stjernberg 1985)
Silva Nova:	- highly productive and relatively robust planting arms (Lantz, Pers. Comm.) - the PLS system that allowed for automatic feeding of standard seedlings (Hallonborg 1997, Lantz, Pers. Comm.) - pneumatic feeding systems that could transport seedlings quickly over relatively long distances (Hallonborg 1997)
Bracke Planter:	- a reliable and robust planting head (Jamieson 2008) that is relatively inexpensive and can be mounted on many types of base machines (Hallonborg 1997)
EcoPlanter:	- a planting head with two simultaneously working, obstacle avoiding, scarifying and planting units that could reach productivity levels of 600 seedlings per productive hour (Normark & Norr 2002) with seedlings of different sizes - the EcoBandPak concept that could help to automate seedling feeding on boom-tip planting heads - a planting tube that can shower the seedling with insecticides or water directly as it is being planted (Normark & Norr 2002)
M-Planter:	- a planting head using the Bracke Planter concept, but with two simultaneously working scarifying and planting units.

After circa 45 years of research and development, planting machines are still not fully economically competitive versus manual planting anywhere in Sweden. Nevertheless, as experienced workers willing to plant trees manually become scarcer, the work quality of manual tree planters is decreasing. This is, at least, true for stands regenerated during 2006-2008 by contractors working for Södra Skog in Götaland (Ersson & Petersson 2009). This fact opens up a niche for planting machines to augment manual tree planting on sites with suitable stand and terrain characteristics, especially in Götaland where the use of large seedlings makes manual tree planting relatively expensive. Indeed, today's Bracke Planter working for Södra Skog has a productivity of circa 200 seedlings per productive hour and a piece-rate pay of 3.30 SEK per seedling, or a minimum of 550 SEK per productive hour on difficult sites where productivity drops (Petersson &

Alvehus, Pers. Comm.). This productivity level entails about 25% higher costs for mechanized planting compared to manual planting (Grape, Pers. Comm.); still the demand for the Bracke Planter exceeds today's single machine because of the high-quality biological results produced by the planting machine (Frohm, Pers. Comm.).

In the end, however, it is the land owners' attitude towards mechanized planting (Hallonborg et al. 1995) that determines if planting machines can play a role in the future of Götaland's forestry industry or not. Arguably, this attitude is greatly influenced by both the machine's profitability and the quality of the silvicultural work, versus the cost and quality of work of the alternative (i.e. manual planting).

Future research

Many previous studies of mechanized planting have identified the handling and feeding of seedlings as one of the major weak points in the planting machine process. Authors have expressed the need for better seedling logistics and better seedling handling and feeding systems. But many questions remain:

- should the logistics system require equipment that is returned to the nursery?
- should the logistics system be rational and large-scaled or flexible and small-scaled?
- should specially designed containers or modules be used for seedling transportation, and should they be carried on the clearcut by custom-made or run-of-the-mill base machines?

Another area with clear development potential is the planting head itself. Can planting heads be designed to automatically detect suitable planting spots, either using ground penetrating radar to detect rock-free soil or using colour detection to detect mineral soil patches between the LFH? Would potential productivity increases be enough to warrant the extra technological costs? Would the detectors be robust enough to work commercially? Can semi-automated cranes with pre-programmed routes increase the productivity of boom-tip planting machines?

Another question that has not clearly been answered is how the rise of the bioenergy sector affects the productivity of mechanized planting vs. manual planting. For example, how does less slash and stumps affect the productivity of machine vs. manual planting?

Also, with the demand for reductions in stand regeneration costs and new silvicultural strategies and goals come opportunities for diverse management schemes. These management schemes might include different species compositions, spatial distributions of main stems, rotational periods and unevenly aged forests, thereby opening up new niches for planting machines that aren't evident today.

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