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Mechanized tree planting in Nordic forestry: simulating a machine concept for continuously advancing site preparation and planting

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Abstract: As labour for manual tree planting becomes scarcer, regeneration costs are steadily increasing in Nordic forestry. Today's intermittently advancing tree planting machines provide excellent silvicultural results, but are expensive to operate because of poor productivity. In contrast, continuously advancing planting machines, thanks to high productivities, are increasingly being regarded as a solution to these runaway regeneration costs. The Silva Nova was a historical, continuously advancing tree planting machine with high productivity. However, Silva Nova's weaknesses included high labour costs (it required two operators) and the random nature of how it chose planting spots. In contrast, SuperSilva, a purely conceptual modernisation of Silva Nova, involves both automation and microsite identification to make the machine more efficient. We used discrete-event simulation to analyse the stocking rate and spatial distribution of tree planting with SuperSilva. The simulation results showed that introducing sensors for identifying suitable microsites will allow continuously advancing planting machines (like SuperSilva) to plant seedlings in a numerically and spatially adequate manner on moraine soils. Hence, these sensors will increase the competitiveness and versatility of tree planting machines. Unfortunately, such reliable and robust sensor technology (unaffected by a wide variety of operating conditions) is not yet commercially available.

Keywords: tree planting machine; disc trenching; discrete-event simulation; reforestation; silviculture; microsite

Boom-tip mounted planting devices are currently the only fully mechanized systems commercially available for tree planting in the Nordic countries. These devices prepare the soil and then plant a seedling. These devices provide excellent silvicultural results, but their productivity is poor (Ersson 2014). Consequently, their share of tree planting is < 1% in the Nordic countries, while the most common practice is mechanized soil preparation (Figure 1 top) followed by manual planting (Ersson et al. 2018; Ramantswana et al. 2020).

However, a few decades ago in Sweden, there was an exception: a fully mechanised tree planting machine called Silva Nova (Figure 1, bottom). The 1980–1990s were the golden era of Silva Nova, and in 1997 it planted 9–12% of all trees in northern and central Sweden (Lindholm, Berg 2005). The original Silva Nova was operated by two operators, one drove the base machine while the other operated the planting unit. At its best, Silva Nova planted > 2 000 seedlings per productive machine hour (PMh) (Ersson 2010).

Although poor mechanical availability and complicated workplace organization led to the high operating costs that prevented Silva Nova from surviving (Ersson 2010), it is still the only mechanized tree planting system that has ever challenged manual planting in terms of the share of planted area in northern Europe. Hence, one might ask if the basic concept of Silva Nova is too good to be completely ignored. That being said, the Swedish state-owned tree nursery company Svenska Skogsplantor has built a prototype machine, PlantmaX, which basically is a reinvented, modernized Silva

Photo: Bracke Forest AB

Photo: Henrik von Hofsten

Figure 1. Site preparation with a 2-row disc trencher (top), and with the Midas disc trencher on the Silva Nova planting machine of the 1990s (bottom)

Nova (Ramantswana et al. 2020). However, in our view, certain improvements like planting spot detection and autonomous route finding are required to make continuously advancing tree planting machines (such as PlantmaX) more competitive.

We used the program packages ExtendSim AT (Version 9.2, 2019) and SAS (Version 9.4, 2019) to conduct a discrete-event simulation, in which a conceptual machine called SuperSilva was used to analyse the improvement potential of the "basic Silva Nova concept". To decrease operational costs, SuperSilva's planting unit was conceived to be fully automated and the whole machine to be operated by a single person. Further in the future, SuperSilva might even operate completely autonomously, e.g. following a given path (Ringdahl et al. 2011). Similarly to the original Silva Nova, SuperSilva is also equipped with chassis-mounted scarification arms for inverse soil preparation (Figure 1). The scarification discs invert the humus, which is then compacted by the rear tyres. Lastly, the planting arms plant seedlings in the newly inverted and compacted soil. Thus, the SuperSilva's basic configuration is similar to that of the original Silva Nova.

Moreover, we added a traditional 2-row disc trencher (hereafter "TradTrencher") as a reference system in our simulation model. Although TradTrencher's output is not directly comparable with SuperSilva's output, TradTrencher provides our simulation model with a reference and connects the simulation outcomes better with current silvicultural practices. The objectives of this study were to analyse (*i*) the silvicultural potential and (*ii*) the productivity potential of the conceptual SuperSilva tree planting machine. The hypothesis of the study was that SuperSilva is capable of adequately planting seedlings according to Swedish forest regulations.

MATERIAL AND METHODS

Simulation model. Because SuperSilva is completely conceptual and no direct data was available, we were required to determine its functionality in an often simplified manner. Based on Hallonborg et al. (1995), we set SuperSilva's top travelling speed under completely obstacle-free conditions to 10, 15 or 20 m·min^{-1} depending on a productivity scenario (low, basic and high). Because SuperSilva does not have an extra operator commanding the planting arms, combined with the ambition to increase the planting quality compared to that of the original Silva Nova, SuperSilva's top travelling speed was set below the level of the original Silva Nova. Based on Ersson et al. (2017), TradTrencher was simulated with only one travelling speed of 55 m·min^{-1}.

A 0.15-m impulse was the basic unit of our simulation model. For SuperSilva, an obstacle-free impulse took 0.45, 0.6 or 0.9 s, and for TradTrencher it took ~ 0.164 s. The distance travelled during one impulse was consistently 0.15 m irrespective of the system. Hence, the time consumed (in seconds) during a given period was expressed as $0.45n$, $0.6n$, $0.9n$ (SuperSilva) and ~ $0.164n$ (TradTrencher), where n is the number of impulses in that period. Similarly, the total distance travelled (in metres) during a given period depended on the number of impulses, i.e. generally $0.15n$.

Having defined the distance travelled and the time required to travel that distance, we established the travelling speed as a relationship between distance and time. For SuperSilva, the travelling

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speeds (from low to high productivity scenarios) were 0.15 m × (0.9 s)$^{-1}$, 0.15 m × (0.6 s)$^{-1}$, and 0.15 m × (0.45 s)$^{-1}$, or interchangeably 10 m·min^{-1}, 15 m·min^{-1} and 20 m·min^{-1}, respectively. Meanwhile, the travelling speed of TradTrencher was 0.15 m × (0.164 s)$^{-1}$ or correspondingly 55 m·min^{-1}.

To make the simulation more realistic, a random number generator, based on the sampling by Larsson (1976), defined some of the impulses as obstacles. Obstacles could be either stones or stumps. Each obstacle was the same size and covered the whole furrow laterally. The probability of each impulse being obstacle-free was 0.7. Obstacles affected work in different ways. Each time a trenching disc hit an obstacle, a time penalty was added on the regular impulse time. For SuperSilva, the penalty was 0.2 s·impulse^{-1}, and for TradTrencher, it was 0.1 s·impulse^{-1}. Thus, we considered SuperSilva to be more sensitive to obstacles than TradTrencher. Because of the time penalties, obstacles decreased travelling speed. Obstacles also affected the silvicultural results (more precisely, the length of the microsites and the distance between the planting spots or planted seedlings).

An acceptable microsite required that a minimum number of obstacle-free impulses would be generated. Based on the authoritative simulation models of Andersson et al. (1977), we assumed that the minimum number of impulses for SuperSilva was 5, giving a minimum microsite length of 0.75 m (5 × 0.15 m). Meanwhile, for TradTrencher, the assumed corresponding length was 0.45 m (3 × 0.15 m). Each microsite length included a constant gap of 0.3 m (2 × 0.15 m) which was the distance necessary before the discs could start producing the next planting spot. Moreover, the probability of 5 subsequent impulses being obstacle-free was 0.7^5, and for 3 impulses 0.7^3. The criteria between the systems differed because we considered manual tree planters to be more efficient than automated planting units at locating planting spots. Finally, to avoid successive seedlings being planted too close to each other, some additional criteria were applied. Based on Hallonborg et al. (1995), the minimum distance between the centre points of successive planting spots for SuperSilva was assumed to be 1.35 m (9 × 0.15 m). Meanwhile, for TradTrencher, the corresponding minimum distance was assumed to be 1.2 m (8 × 0.15 m).

RESULTS AND DISCUSSION

When studying our time consumption and silvicultural results, readers should remember that SuperSilva both prepares the soil and plants seedlings. In contrast, TradTrencher only prepares the soil, with the actual regeneration occurring later on, either naturally (seed fall), through sowing (direct seeding), or by manual tree planting.

SuperSilva's average travelling speed was 60–78% slower than TradTrencher's speed depending on a productivity scenario (Table 1). Similarly, SuperSilva needed 147–345% more time to treat a hectare than TradTrencher did. SuperSilva planted on average 362–650 seedlings·PMh^{-1}, while TradTrencher created 2 903 planting spots·PMh^{-1} (which is 347–703% more). Indeed, TradTrencher created > 3 000 acceptable planting spots per hectare. Slightly over 60% of these planting spots were 1.2–1.5 m from their closest row-wise neighbour, and ca 30% were 1.65–2.4 m (Figure 2). This practically means that manual planters can choose the best planting spots among several ones, allowing for a relatively even seedling distribution without any empty (seedling-free) areas.

Table 1. Simulation results

System	Productivity scenario	Average travelling speed (m·min^{-1})	Average time consumption (h·ha^{-1}) [a]	Average number of seedlings planted and/or planting spots created		Median distance between the seedlings or planting spots within a row (*m*) [b]
				(*n*·ha^{-1})	(*n*·h^{-1})	
SuperSilva	low	8.9	4.70	1 699	362	2.33 (1.35; 5.10)
	basic	12.6	3.31		514	
	high	15.9	2.61		650	
TradTrencher	basic	39.5	1.06[c]	3 065	2 903	1.35 (1.2; 2.25)

[a]Calculated with 2 m row spacing, i.e. 4 m working width; [b]10th and 90th percentiles in parentheses; [c]TradTrencher only prepares the soil; the time consumption of manual tree planting is ca 10 h·ha^{-1} (Hallongren et al. 2014)

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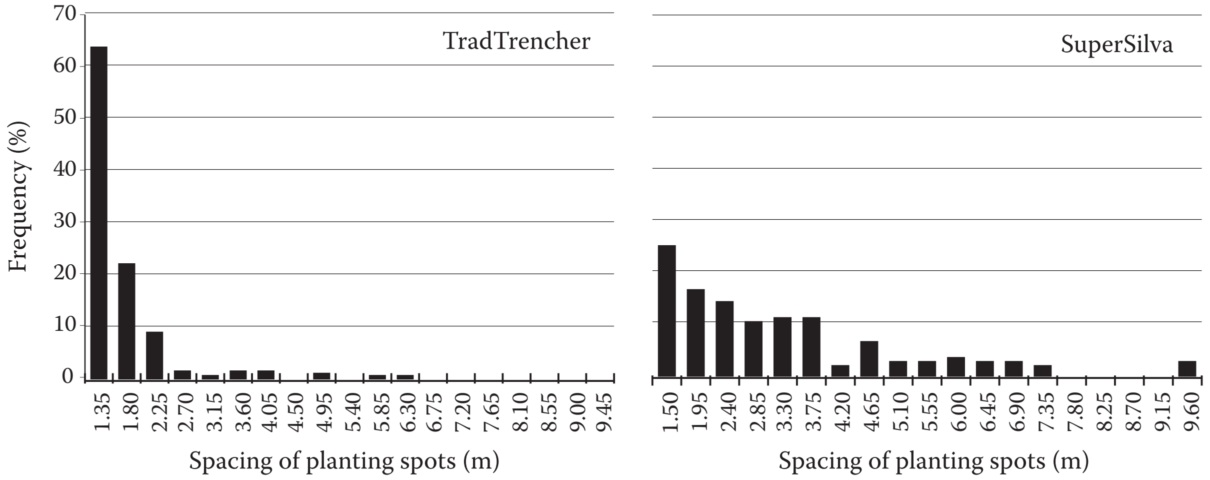

Figure 2. Frequency distribution of row-wise distances (spacing, in m) between successive planting spots for TradTrencher (left) and between successive planted seedlings for SuperSilva (right)

SuperSilva planted ca 1 700 seedlings·ha^{-1}, which is somewhat less than the standard Swedish practice of planting ca 2 000 seedlings·ha^{-1} (Table 1). Nevertheless, this result is completely in line with the latest research which has found that the economically optimal number of planted seedlings is 1 000–1 500 per ha depending on the site fertility (Krekula et al. 2018). That being said, most blocks reached the traditional target of ca 2 000 seedlings·ha^{-1}. As indicated by the median distance between successive seedlings together with the corresponding 10th and 90th percentiles, SuperSilva's seedling distribution was positively skewed (Figure 2). Indeed, slightly over 50% of the seedlings were planted within the range of 1.35–2.55 m from their closest row-wise neighbour, ca 30% within the range of 2.7–3.9 m, and ca 15% within the range of 4.05–7.50 m (Figure 2). The 10th percentile (1.35 m), which also equalled the minimum distance of this study, is shorter than the traditional spacing of ca 2 m (Table 1). But the minimum distance of this study was chosen based on scientific literature. According to Salminen and Varmola (1993), Davidsson (2002) and Lundqvist and Elfving (2010), seedlings can be planted relatively close to one another (ca 1 m) without any significant growth losses.

However, SuperSilva tended to leave notable large gaps, up to ~ 35 m^2, without any planted seedlings at all (no data shown). In Fennoscandia, particularly after soil preparation, these gaps will be regenerated naturally with especially deciduous trees, creating mixed forests. Despite the fact that mixed forests are preferable for many reasons over monocultures (Jonsson et al. 2019), the interaction of seedling density and spatial distribution must not be ignored. Even if neither low seedling density nor irregular seedling distribution alone pose a risk, combined together they might produce poor quality regenerations. Hence, the simulated seedling distribution of SuperSilva might be relatively sensitive to various threats (e.g. browsing, insect predation, or frost injuries) which occasionally affect planted stands. Basically, a stand with relatively few, unevenly distributed seedlings withstands seedling losses poorly because there are fewer "extra" seedlings nearby benefiting from lower competition as the stand thins out. Row spacing is a way of addressing this issue. *Ceteris paribus*, reducing the row spacing (from the currently applied 2 m) enables increasing distances between the seedlings within rows, or alternatively increasing seedling density and generally reducing the occurrence of gaps without seedlings. However, one major disadvantage of decreasing the inter-row spacing is that it increases the time consumption of soil preparation and planting (Bjurulf, Westerberg 1992).

We consciously chose relatively easy working conditions because it is a sound presumption that the mechanization of tree planting starts on sites with relatively low stoniness. That was the case with today's intermittently advancing planting machines like the Bracke Planter (von Hofsten 1993) and M-Planter (Rantala et al. 2009). In the future, if more advanced sensor technology is available, mechanized planting might also be a feasible alternative on more stony sites.

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Of course, our chosen input parameters dictated the simulated productivities of the two systems. However, since the sources for these parameter values were realistic (and our assumed values were slanted to err on the conservative side), we are confident that our productivity outcomes are not overly optimistic.

The simulation model, despite its simplicity, generated realistic results that are in line with current literature; traditional disc trenching can efficiently create many planting spots per hectare (Ersson et al. 2017; Wallertz et al. 2018). Moreover, the simulation supported the hypothesis: introducing sensor technology will enable continuously advancing, partly automated tree planting machines to plant seedlings with adequate spacing. But to get to that stage, abundant research work is required.

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