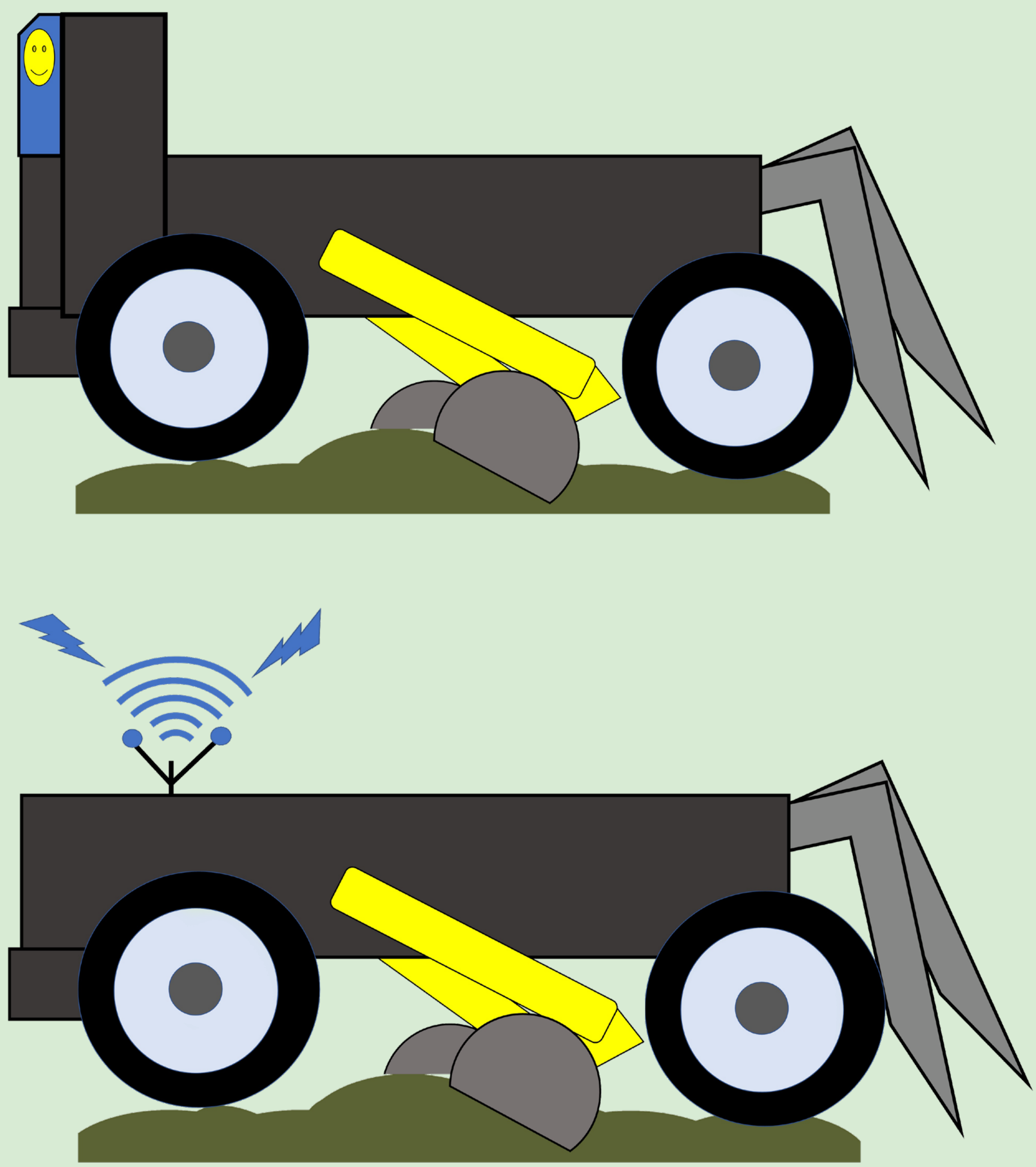
ARBETSRAPPORT 1024-2019

Simulating concepts for fully mechanized stand regeneration

Simulering av maskinkoncept för helmekaniserad plantering



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Sammanfattning

Olika typer av kranspetsmonterade planteringsaggregat är idag de enda alternativen till maskinell plantering i Norden. Dessa så kallade riktade system skapar en hög och planterar strax därefter en planta i högen, allt detta under samma krancykel. De högläggande planteringsaggregaten möjliggör ett mycket bra föryngringsresultat, men till en hög kostnad som sällan är konkurrenskraftig jämfört med manuell plantering. Den höga kostnaden beror på låg prestation och låg teknisk utnyttjandegrad.

Syftet med studien var att konstruera ett antal konceptuella system för helmekaniserad markberedning och plantering. Med hjälp av händelsestyrd simulering analyserades hur dessa konceptuella system kan konkurrera mot maskinell harvning med efterföljande manuell plantering. Analysen bestod av fyra system, varav de två första (1 och 2) är befintliga existerande system medan de två sistnämnda (3 och 4) är helt konceptuella:

System 1: Maskinell markberedning med 3-radig harv + manuell plantering

System 2: Helmekaniserad plantering med högläggande kranspetsmonterat aggregat Bracke P11.

System 3: Helmekaniserad markberedning och plantering med Silva Nova 2.0.

System 4: Helmekaniserad markberedning och plantering med förarlös Silva Super Nova.

System 3 och 4 är uppgraderade versioner av en före detta existerande Silva Nova-planteringsmaskin. Precis som den ursprungliga Silva Novan är också de nya konceptuella Silva Nova-systemen utrustade med midjemonterade markberedningstallrikar. Den markberedda tiltan körs över och kompakteras av maskinens bakre boggi. Planteringsarmar planterar plantor i den kompakterade tiltan. Men för att de nya Silva Nova-varianterna kan tänkas konkurrera med befintliga föryngringssystem krävs markanta ändringar. Den ursprungliga Silva Novan framfördes av två personer. Silva Nova 2.0 körs av en person, då planteringen är helautomatiserad. Silva Super Nova är helt förarlös och antas följa en i förväg programmerad rutt. Som en ytterligare skillnad till den ursprungliga Silva Novan ska planteringsarmarna på de konceptuella varianterna stoppa in en planta i marken endast om en acceptabel planteringspunkt har skapats.

Simuleringsresultatet bekräftade i stort sett befintlig kunskap; maskinell harvning kan mycket effektivt skapa ett stort antal planteringspunkter, vilket gjorde *System 1* till det billigaste alternativet. *System 2*, planteringsmaskin med kranspetsmonterat aggregat (Bracke P11), var det dyraste alternativet. Silva Nova 2.0 (*System 3*) var dyrare än *System 1*, men billigare än *System 2*. Föryngringskostnaden med förarlös Silva Super Nova (*System 4*) var ungefär på samma nivå som System 1. Simuleringarna visade att Silva Nova-systemen kan ha utvecklingspotential. Men likaså visade de att Silva Nova-systemen har en tendens att lämna ganska stora luckor utan plantor.

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Foreword

EFFORTE is a research and innovation project aimed at increasing and disseminating knowledge regarding efficient and sustainable forestry in the European forest sector. EFFORTE is a collaborative project involving research organisations and practical forestry actors in Sweden, Finland, France, Scotland and Switzerland.

The project is divided into three main focus areas: 1) Minimise the impact of forestry on soils; 2) Efficient and value-generating silviculture; and 3) Precision forestry with new areas of application for 'Big Data' relating to forest.

This report is part of Work Package 2 - Efficient Silviculture.

Thanks are extended to Tomas Johannesson and Lars Eliasson (both from Skogforsk) who provided important input from practical forestry that formed a basis for system analysis and simulation.

Uppsala, 28 August 2019

Isabelle Bergkvist

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Contents

Summary

Boom-tip mounted planting devices are currently the only fully mechanized systems available commercially for tree planting in the Nordic countries. These devices prepare the soil (generally via spot mounding) and plant a seedling, both during the same work cycle. Bracke P11 and M-planter are the most common devices on the market. When mounted on excavators, these systems provide excellent silvicultural results, but their productivity is poor. Consequently, today's tree planting machines generally cannot compete economically with today's most common reforestation system, i.e. mechanized scarification followed by manual planting.

The objective of the present study was to investigate novel conceptual systems for fully mechanized stand regeneration that could possibly compete with mechanized scarification and manual planting. We created four alternative systems using discrete-event simulation. The systems were as follows:

System 1: Mechanized scarification (disc trenching, continuously advancing machines) and manual planting.

System 2: M-planter or Bracke P11, i.e. mounding with planting (fully mechanized, intermittently advancing machines).

System 3: Silva Nova 2.0 (fully mechanized, continuously advancing machines).

System 4: Silva Super Nova (fully mechanized, continuously advancing machines).

Hence, *System 1* and *System 2* already exist, whereas *System 3* and *System 4* are purely conceptual. *System 3* and *System 4* are upgraded versions of the old Silva Nova planting machine which was large, expensive and mounted on a forwarder's load-space. The original Silva Nova was operated by two operators, one drove the base machine while the other operated the planting unit. Moreover, later versions of the Silva Nova were equipped with MIDAS trenching units (which were mounted in front of the rear bogie so that it immediately compacted the berm, effectively inverting the soil and humus). To improve competitiveness, we assumed the planting unit of *System 3* (Silva Nova 2.0) to be fully automated and the whole machine to be operated by a single person. Meanwhile, *System 4* (Silva Super Nova) is assumed to be completely autonomous following a beforehand programmed path.

The simulation results confirmed current knowledge: mechanized scarification can efficiently create many planting spots per hectare making *System 1* the most cost-efficient, non-autonomous alternative. Meanwhile, *System 2*, mounding with planting, was the most expensive alternative. Silva Nova 2.0 (*System 3)* was more expensive than *System 1*, but cheaper than *System 2*. And finally, the cost-efficiency of autonomous Silva Super Nova (*System 4*) was approximately on the same level with *System 1*. Thus, the simulations showed that Silva Nova 2.0 and Silva Super Nova probably have some development potential. But equally important, the simulation showed that the silvicultural results, in terms of occurrence of empty areas lacking seedlings, are a relative weakness of these conceptual machine configurations.

Introduction

TREE PLANTING IN SWEDEN

Boom-tip mounted planting devices are currently the only fully mechanized systems available commercially for tree planting in the Nordic countries. These devices prepare the soil (generally via spot mounding) and plant a seedling, both work elements during the same work cycle. Bracke P11 and M-planter are the most common devices on the market (Figure 1). When mounted on excavators, these systems provide excellent silvicultural results, but their productivity, and first of all technical availability, is poor (Ersson 2014). Consequently, today's tree planting machines generally cannot compete economically with today's most common reforestation system, i.e. mechanized scarification followed by manual tree planting (Figure 2). Despite many attempts, mechanized planting has not made a large scale breakthrough in Swedish forestry, with one exception called Silva Nova.

ORIGINAL SILVA NOVA 1970s – 2001

The golden era of mechanised planting in Sweden (1980s-1990s) culminated in the Silva Nova (Figure 3: Panel: A). The original Silva Nova was operated by two operators, one drove the base machine while the other operated the planting unit. Several generations of the Silva Nova were built. At its best, the Silva Nova could sustain a productivity of over 2000 seedlings per productive machine hour (PMh) (Hallonborg et al. 1995). For instance, in 1997, the Silva Nova stood for 9-12% of all tree planting in north and central Sweden (Lindholm & Berg 2005).

Although the Silva Nova did not sustain its prevalence because of high operation costs, it still is the only mechanised tree planting system that has ever seriously challenged mechanized scarification and manual planting (in terms of share of planted area). For instance, today's commercially available Bracke P11 is used on ca 1 % of planted area in southern Sweden, while being more or less absent in the northern parts of the country (Ersson 2014). Thus, one might state that: maybe the basic concept of the Silva Nova is too good to be completely rejected?

SILVA NOVA 2.0 AND SILVA SUPER NOVA

The Silva Nova basic concept has lately regained some interest again. Although neither mechanical nor virtual prototypes exist (at the time of writing), a first system analysis of the next generation Silva Nova systems has already been accomplished (Table 1). Similar to later versions of the original Silva Nova, the next generation Silva Nova configurations (i.e. Silva Nova 2.0 and Silva Super Nova) are equipped with centre-mounted scarification arms for inverse soil preparation. The scarification discs invert the humus, which is immediately driven over and compacted by the bogie (or more precisely by the rear tyres; Figure 3). Lastly, the planting arms plant seedlings in the newly inverted and compacted humus. Thus, the basic principles of the next generation Silva Nova configurations are similar to the previous generations.

However, a number of changes are required to solve the main weakness of the old Silva Nova, i.e. high operational costs. The original Silva Nova was operated by two operators, one drove the base machine while the other operated the planting unit. To decrease operational costs, Silva Nova 2.0's planting unit will be fully automated and the whole machine will be operated by a single person. Meanwhile, the Silva Super Nova is assumed to be completely autonomous following a beforehand programmed path (see Ringdahl 2011).

The previous system analysis (by Isabelle Bergkvist, Skogforsk) focused mainly on costing (Table 1), while lacking an analysis of the systems' technical aspects and possible limitations and challenges. Hence, in the present study, we have mainly focused on the systems' technical performance and silvicultural results. And to keep our study concise, we have not directly included any cost analysis; instead, we have used the productivity and silvicultural figures of Table 1 as reference levels. For Silva Nova 2.0 and Silva Super Nova (hereafter collectively called as Silva Nova systems), these figures can be considered as target values.

OBJECTIVES

Thus, the objectives of the present study were to investigate whether the novel conceptual Silva Nova systems have a potential to compete with conventional scarification followed manual planting, or with today's commercially available mechanized tree planting system. Hence, the system analysis consisted of:

1) Mechanized scarification (3-row disc trencher, continuously advancing) and manual planting.
2) M-planter or Bracke P11, i.e. mounding with planting (fully mechanized, intermittently advancing).
3) Silva Nova 2.0 (fully mechanized, continuously advancing).
4) Silva Super Nova (fully mechanized, continuously advancing, autonomous).

Table 1. Summary of unpublished system analysis by Isabelle Bergkvist (Skogforsk). The number of seedlings is 2200 per ha irrespective of tree planting system. Costs are given in SEK[a)].

	3-row scarification, manual planting[b)]	**SilvaNova**[c)]	**SilvaSuperNova**[c)]	**Bracke P11**
Soil preparation, SEK/PMh (incl. relocation costs)	1349	1027	641	734
Planting, SEK/productive hour, incl. relocation costs	350	350	350	350
Effective time consumption, PMh/ha	1.7	5.4	5.6	12.5
Labour, PMh/ha	7.8	1.1	2.2	1.1
Manual planting, labour cost, SEK/seedling	1.6	0.2	0.5	0.2
Seedling cost, SEK/seedling	1.5	1.5	1.5	1.5
Regeneration costs, soil preparation & planting, SEK/ha	7533	9169	6634	14368
Relative regeneration costs in total	100 %	122 %	88 %	191 %

[a)]Average exchange rate in 2018 was: 1 Euro = 10.26 SEK (European Central Bank 2019).
[b)] Working width = 8 m [c)] Working width = 5 m

Figure 1. Some mounding-with-planting machines used in the Nordic countries.

Panel A: Double-head M-planter mounted on an excavator (photo: Heidi Hallongren).

Panel B: Single-head M-planter mounted on a harvester (photo: Tiina Laine).

Panel C: Bracke P11 mounted on an excavator (photo: Back Tomas Ersson).

Figure 2. Scarification using 3-row disc trencher. A scarification is most often followed by a manual planting (photo: Lars-Göran Sundblad).

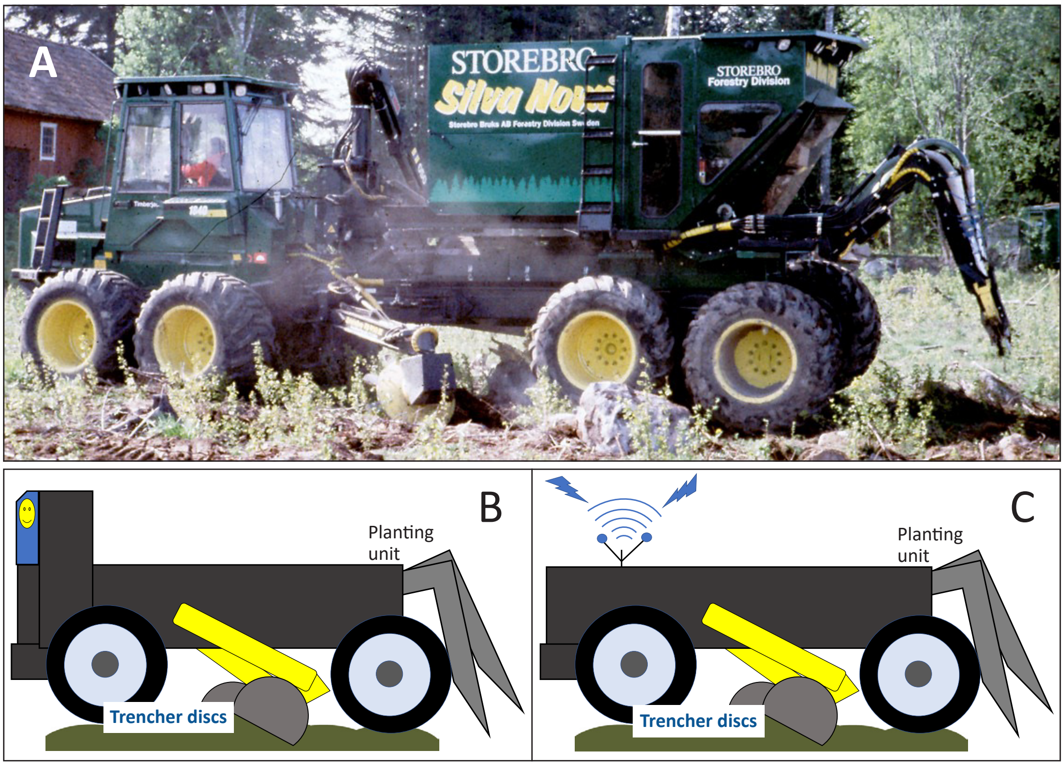

Figure 3. Panel A: The original Silva Nova was operated by 2 persons (photo: Skogforsk). Panel B: Silva Nova 2.0, a conceptual machine configuration operated by a single operator. Panel C: Silva Super Nova, a conceptual autonomous (or alternatively radio-controlled) machine configuration. The conceptual configurations might be equipped with standard trencher discs (as the original Silva Nova, panel A) or alternatively with Kovesen-discs (see Sundblad & Hajek 2014).

Materials and Methods

SIMULATING SILVA NOVA 2.0, SILVA SUPER NOVA, AND SCARIFICATION WITH 3-ROW DISC TRENCHER

Impulse – time, distance and spacing

We used a discrete-event simulation to analyze the Silva Nova systems and scarification with a 3-row disc trencher. The basic unit of analysis in discrete-event simulation is time; in this study more precisely impulse duration (Table 2, 0.6 or 0.16 s). Moreover, irrespective of the system, the impulse length (distance travelled during one impulse) was 0.15 m.

The time consumed during a given period is the sum of the impulse durations ($n \times 0.6$ or $n \times 0.16$ s, Table 2), in which n is the number of impulses. And similarly, the distance travelled during a given period is the sum of the impulse lengths ($n \times 0.15$ m).

The spacing between the rows is 2 m irrespective of the system. Thus, the Silva Nova systems' theoretical working width is 4 m (i.e. *1*+2+*1*), while it is 6 m for the 3-row disc trencher (i.e. *1*+2+2+*1*). Hence, the systems in the present study have slightly narrower working width than the systems presented in Table 1. A wider working width increases productivity, but then the seedlings must be planted more densely within each row if the same stocking rate is to be planted.

Travelling speed in perfect conditions

Since the Silva Nova 2.0 and Silva Super Nova are completely conceptual machine configurations, we were required to theoretically (and for many parts in simplified manner) determine the functionality of these systems. Firstly, the theoretical maximum travelling speed under completely perfect, obstacle-free, conditions was set to 15 m/min (Table 2). Data on the travelling speed of the original Silva Nova was used as a reference when determining applicable speeds for these new conceptual variants of the former Silva Nova. Because Silva Nova 2.0 and Silva Super Nova do not have an extra operator observing planting work quality, and since our ambition is to increase planting work quality from the level of the original Silva Nova, the maximum travelling speed of the Silva Nova 2.0 and Silva Super Nova was set below the level of the original Silva Nova.

Since no applicable Nordic reference for the travelling speed of a 3-row disc trencher was found, we used a Canadian study by Ersson et al. (2016) as reference when determining applicable speed for the disc trenching. Based on Ersson et al. (2016), we set the maximum travelling speed to 55 m/min for 3-row disc trencher under perfect conditions without any obstacles.

Obstacles affecting speed, productivity and silvicultural results

To make the simulation more realistic, we added some obstacles in our model based on the sampling by Larsson (1976). Adding obstacles to our simulation model was a relatively straightforward process as the obstacle sampling by Larsson (1976) was tailored directly for the purpose in question; i.e. simulating obstacle occurrence for a single trenching disc during continuous scarification. Based on Larsson (1976), the applied boulder quota corresponded to 30 %.

Each obstacle was technically of the same size in our simulation model. Each obstacle was 0.15 m long which equaled the impulse length, and each obstacle covered sideways the whole trail width (Figure 4).

Obstacles affected work in different ways. Each obstacle rendered a time penalty. For the 3-row disc trencher, the penalty was 0.1 s per obstacle. Meanwhile, the Silva Nova systems were assumed to be more sensitive to obstacles and the penalty was set to 0.2 s per obstacle. Obstacles did not affect distance travelled but (because of increased time consumption) decreased travelling speed (hereafter called simulated speed). In addition, obstacles affected silvicultural results, or more precisely the length of the microsite and the distance between the planted seedlings.

Silvicultural criterion 1: minimum lengths of microsites and planting spots

The length of a microsite is dependent on the number of obstacle-free impulses (Figure 4). For the Silva Nova systems, the minimum length of a microsite was 0.75 m (5 × 0.15 m; Figure 4). Meanwhile, for the 3-row disc trencher, the corresponding minimum length was 0.45 m (3 × 0.15 m; no figure shown). Irrespective of the soil preparation system, each outset of a microsite includes a constant gap of 0.3 m (2 × 0.15 m) because of the necessary distance before the discs start to form a proper planting spot (Figure 4).

We assumed a manual planter to be more capable than automated planting unit to efficiently use the whole length of a single planting spot. Therefore, the minimum length of planting spots differed between the systems. For the Silva Nova systems, the minimum planting spot length was 0.45 m (3 × 0.15 m). Thus, the minimum length of the aforementioned microsite (0.75 m) is sum of the gap (0.3 m) and planting spot (0.45 m; Figure 4). Meanwhile, for the 3-row disc trencher, the minimum planting spot length was 0.15 m; and thus, the aforementioned minimum length of microsite (0.45 m) is sum of the gap (0.3 m) and planting spot (0.15 m; no figure shown).

Hence, the accuracy of Silva Nova systems' planting arm was expressed numerically as follows: 0±0.225 m (i.e. 3 × 0.15 m / 2), where 0 = the centre of planting spot (Figure 4). Meanwhile, for the 3-row disc trencher system, the placing of a seedling depends on how a manual planter chooses a planting spot. This planting was expressed numerically as follows: 0±0.075 m (i.e. 0.15 m / 2), where 0 = the centre of planting spot (no figure shown).

Silvicultural criterion 2: distance between the planted seedlings

To avoid successive seedlings being planted too close each other, some additional requirements were applied. For the Silva Nova systems, the minimum distance between the centre points of successive planting spots was set to 1.2 m (8 × 0.15 m) but considering the inaccuracy of automatic planting arms, the actual distance could be as short as 0.75 m (1.2 - 2 × 0.225 m, Table 2, Figure 4). Meanwhile, for the 3-row disc trencher, the corresponding minimum distance setting was set to 1.05 m (7 × 0.15 m), but considering how manual planters choose planting spots, the actual distance could be as short as 0.9 m (1.05 - 2 × 0.075 m, Table 2, no figure shown).

Conducting the simulations

Simulations were conducted using the program packages of ExtendSim AT 9.2 (Imagine That Inc.) and Enterprise guide 7.1 (SAS Institute Inc.).

Table 2. Some parameters used in productivity simulations. Irrespective of the system, the length of the impulse (distance) equals 0.15 m.

System	Impulse duration	Theoretical maximum speed	Minimum distance between the seedlings	Minimum length of microsite
Silva Nova systems	0.6 s	15 m/min	1.2 m[a)] [±2 × 0.225 m][b)]	0.75 m
3-row disc trencher	0.16 s	55 m/min	1.05 m[a)] [±2 × 0.075 m][c)]	0.45 m

[a)] Minimum distance between the centre points of successive planting spots.

[b)] The precision of a planting arm is ±0.225 m.

[c)] Depending on how manual planters decide to place the seedling, “freedom” is ±0.075 m.

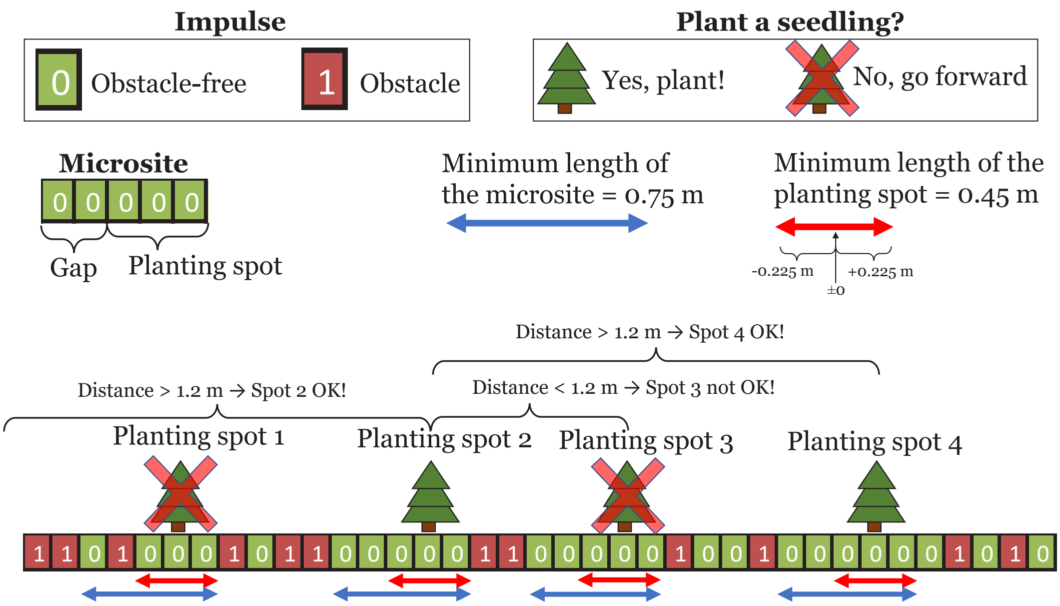

Figure 4. A simplified sketch on the simulation principles and criteria for Silva Nova systems. Impulse length, with or without obstacles, is 0.15 m. The shortest acceptable length of each microsite is 0.75 m (5 × 0.15 m). Meanwhile, the minimum spacing between the seedlings is 1.2 m (8 × 0.15 m); or more precisely when considering an accuracy of ±0.225 m, the shortest distance can be 0.75 m (1.2 - 2 × 0.225), see Table 2. There is no planting in spot 1 because the microsite is too short; planting spot 2 is OK; planting spot 3 is too close to spot 2; and finally planting spot 4 is OK. Although the figure illustrates the Silva Nova systems, the basic principles are similar for the 3-row disc trencher even if some of the criteria is different (See Materials and Methods). Moreover, the figure illustrates a single row, but the simulation can comprise an unlimited number of rows.

BRACKE P11

The productivity of Bracke P11 represented intermittently advancing systems, i.e. mounding with planting, and was based on the model of Laine and Saarinen (2014), see Table 3. We found the model of Laine and Saarinen (2014) to be applicable in our study because "stoniness" (corresponding to obstacles in our study) is the only work difficulty factor they included in their model. Hence, we used 30 % as stoniness.

Two operators participated in Laine and Saarinen's (2014) study operating two different machines, Bracke P11 and Risutec. To correspond to an average operator, we multiplied the operator-performance estimate with 0.5 (Table 3). Moreover, Risutec-related estimates were excluded. Entering these values into the model gave a productivity level of 245.2 seedlings per PMh. This, in turn, converts into a time consumption of 9.0 PMh per ha given that 2200 seedlings per ha are planted (c.f. Table 1).

Table 3. Bracke P11's productivity in terms of seedlings per productive machine hour (PMh) as determined by Laine and Saarinen (2014).

Variable	Estimate (seedlings/PMh)	The estimate multiplied by	Product (seedlings/PMh)
Intercept	331.4	1	331
Operator 1	-106.5	0.5	-53.2
Stoniness (%)	-1.1	30	-33.0
Sum			245.2

Results

Silva Nova systems: Silva Nova 2.0 and Silva Super Nova

The simulated travelling speed was 12.6 m/min. The time consumption for planting and soil preparation was 3.3 PMh/ha, corresponding to productivities of slightly over 500 seedlings/PMh. Hence, simulated time consumption for Silva Nova systems was about 40 % less than the reference level (cf. Table 1).

In general, the Silva Nova systems' seedling distribution was positively skewed. Moreover, about 55 % of the seedlings were planted 1.2-3.0 m from their closest row-wise neighbour, while nearly 20 % of seedlings were 4.2-10.2 m from their closest row-wise neighbour. The mean row-wise distance between the seedlings was about 3 m. The Silva Nova Systems planted slightly less than 1700 seedlings per ha during the simulation. But, there were also areas up to 30-35 m2 without any planted seedlings at all. Nevertheless, most of blocks nearly reached the target level of >2000 seedlings per ha.

Scarification with 3-row disc trencher

The simulated travelling speed was 36.6 m/min. Hence, the time consumption for soil preparation was 0.76 PMh/ha giving a productivity of slightly over 4800 planting spots/PMh. The simulated time consumption in our study was ca 55 % less than the reference level (cf. Table 1).

Moreover, the scarification with the 3-row disc trencher created nearly 3700 planting spots/ha with average row-wise distance of 1.4 m (from centre to centre) between successive planting spots. More detailed results are not available for the scarification with 3-row disc trencher.

Bracke P11

The Bracke P11 was not simulated but its time consumption was calculated as 9.0 PMh per ha based on Laine and Saarinen (2014). Hence, the calculated time consumption was nearly 30 % less than the reference level (cf. Table 1).

Discussion

COST-EFFICIENCY AND SENSITIVE ANALYSIS

The simulation results did not only confirm current knowledge but basically strengthened it; scarification with disc trencher can efficiently create many planting spots per hectare making scarification followed by manual planting the most effective non-autonomous alternative. Meanwhile, mounding with planting (Bracke P11) was the most time-consuming alternative. However, the productivity of Bracke P11 was not simulated like the other systems, but rather modelled based on current scientific literature. This is a methodological incoherence but considering the large productivity differences between Bracke P11 and the rest of the systems, this methodological incoherence is not of pivotal importance.

If we assume the costing values in Table 1 to be realistic, Silva Nova 2.0 is more (22 %) expensive than disc trenching and manual planting. However, the present study points towards a slightly larger difference in favor of disc trenching and manual planting. On the other hand, according to Table 1, Silva Super Nova was cheaper (12 %) than disc trenching and manual planting. However, because of the speculative nature of Table 1's costing values, it is difficult to say which one of these two systems is most cost-efficient. Therefore, conducting comprehensive sensitivity analyses would be far-fetched and highly speculative since we do not have any concrete blueprints of these conceptual next generation Silva Nova systems.

However, some circumstances affecting Silva Nova systems' competitiveness could be shortly discussed. The Silva Nova systems could regain their relative position (contra the 3-row disc trencher) in Table 1 if the Silva Nova systems' average travelling speed increases by 35 %. Moreover, increasing the working width (i.e. the spacing between rows, 2 m in this study), also increases productivity. But then the seedlings must be planted more densely within each row given the same stocking rate. That being said, seedling density or more precisely spatial distribution is one thing to consider. According to current literature, seedlings can be in groups (at least to some extent) without any significant effect on growth (Salminen & Varmola 1993; Davidsson 2002; Lundqvist & Elfving 2010), which means that closer seedling spacing within rows should not be a problem. Rectangularity can also aid mechanized pre-commercial thinning (Lindman et al. 1985; Bergkvist & Nordén 2004).

The simulation showed that the silvicultural results in terms of occurrence of empty areas lacking seedlings are a relative weakness of Silva Nova systems. However, in practice these empty spaces need not be a problem. Recent research from the Swedish Forest Agency shows that the net present value of a block is optimized when planting only 1000-1500 seedlings per ha depending on site fertility (Krekula et al. 2018). Such empty spaces will invariably be, in general, filled with naturally regenerated trees anyway. This tendency results in the establishment of mixed forests, which are preferable over monocultures for many reasons (Jonsson et al. 2019).

MININOVA

The unpublished system analysis (by Isabelle Bergkvist, Skogforsk) includes one more system which was excluded from the present study (and also from Table 1). The system is called MiniNova. The reason for the exclusion was the lack of knowledge on MiniNova's functionality and working principals.

Anyway, the basic idea of the MiniNova is that it only has a single scarification and planting unit, which makes the machine more agile than the Silva Nova systems. Agility is essential to avoiding obstacles and steering the machine around obstacles. Preferably, the MiniNova will be equipped with sensors to avoid obstacles even underground, meaning that the MiniNova should be able sustain good performance even on obstacle-dense blocks. Small blocks are MiniNova's competitive advantages thanks to its small size and consequently relatively low relocation cost.

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Appendix 1: Probability for a distance being obstacle-free

Table 4. Applied probability distribution for given distance being obstacle-free.

Distance (m)	Probability	Notification
0	1.00	
0.15	0.70	
0.30	0.49	
0.45	0.34	Single microsite of 3-row disc trencher obstacle-free
0.60	0.24	
0.75	0.17	Single microsite of Silva Nova system obstacle-free
0.90	0.12	
1.05	0.08	
1.20	0.06	
1.35	0.04	
1.50	0.03	
1.65	0.02	
1.80	0.01	
1.95	0.01	
Etc.	<0.01	

Based on Larsson (1976)