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A Techno-Economic Evaluation of Bracke and M-Planter Tree Planting Devices

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Techno-economically reasonable mechanization of tree planting has proved to be a difficult task in the Nordic working conditions. Although planting machines and combinations of base machine and planting device have been developed since the 1970s, mechanized planting has not been cost-competitive to manual planting. The aim of this study was to find out work time distributions, productivities, costs and effects of different work difficulty factors on productivities and costs of the state-of-the-art Nordic planting devices, Swedish Bracke and Finnish M-Planter, and to compare the devices with each other. The theory of comparative time studies was the base for the experimental design of this study. In the average working conditions, productivity (E_{15}) of M-Planter (236 seedlings/hour) was 36.0% higher than that of Bracke (174 seedlings/hour). Here, M-Planter performed planting work 23.4% cheaper than Bracke. However, the difference depended greatly on the working conditions; the more stones or stumps the smaller the difference, and the more slash the bigger the difference.

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1 Introduction

Techno-economically reasonable mechanization of tree planting has proved to be a difficult task in the stony and erratic Nordic terrains, where in addition slash and stumps have usually been left on the site after clear cutting. Already in the 1970s, some highly automated and continuously working planting machines such as Swedish Silva Nova and Finnish Serlachius were developed, but planting with these machines turned out to be too expensive compared to manual planting, although the quality of work was satisfactory (Kaila 1984, Hallonborg et al. 1995). The mechanization rate of tree planting in Nordic forests is still clearly under 5%.

A need to improve productivity of planting work by mechanization is nowadays much greater than during the past decades. Firstly, it seems that labor shortage in forestry will degenerate strongly after the year 2010 (Työvoiman saatavuus… 2005). The lack of labor will be emphasized in tree planting, because forest owners are less and less able and eager to do it themselves (Karppinen et al. 2002). Secondly, there is a need to decrease silvicultural costs to keep up the profitability of forestry under the conditions of decreasing real stump prices (Uotila 2005), and thus to preserve forest owners' motivation on forestry (Harstela 2004a).

The fundamentals of techno-economically reasonable mechanization are high enough productivity compared to manual work, reasonable prize in relation to the productivity, good technical availability and adequate utilization of the annual capacity. The main principles for cost-efficient mechanization of tree planting can be described by drawing an analogy with the five development steps of wood harvesting. These are: 1) processing appears to be faster than in manual work; 2) two or more work elements can be done simultaneously; 3) two or more different tasks are done by the same machine; 4) multi-processing is possible; and 5) intermittent working method is replaced with continuous working (Harstela 2004a). Further, the quality of the mechanized work must be as good as in manual work.

Today the state-of-the-art planting devices are much less automated than the continuous machines introduced in the past decades. After dropping of the highly automated machines, the development of the planting devices has followed to the abovementioned mechanization principles. Ilves planting device, introduced in the early 1990s, based on principles 1 and 2, but turned out uneconomical compared to manual planting (Rummukainen et al. 2002). In Bracke, introduced in the early 1990s too, also the principle 3 came true, because soil preparation and planting works were combined into the same device. Bracke's mounding blade inverts a piece of soil including humus and mineral soil upside down on undisturbed soil (spot mounding) after which the seedling is planted to the middle of the mound (Saarinen 2006). The quality of work by Bracke proved to be as good as in manual planting on similar spot mounds. However, the costs were still a bit higher than those of the combination of manual planting and separate mechanized mounding (Saarinen 2004).

Ecoplanter was the first planting device under whom also the principle 4 came true, because it had two mounding and planting units working simultaneously. However, in the case of Ecoplanter, the advantage of multi-processing was partly lost, because mounding was based on a rotation principle that proved to be slower than the inverting method employed by Bracke (Sønsteby and Kohmann 2003, Saarinen 2006). In addition, the quality of mounds made by the rotation method turned out to be inadequate; the surface layer of the mounds made by Ecoplanter is a mixture of humus and mineral soil that does not prevent pine weevil damages as well as inverted mounds with pure mineral soil layer over the top (Petersson et al. 2005).

A new prototype device M-Planter, introduced in the year 2006, based on the same mechanization principles 1–4 as Ecoplanter, but employed the spot mounding as soil preparation method. A general technical implementation of M-Planter is relatively simple keeping the price and technical availability of the device at reasonable levels. From the standpoint of overall quality of work, M-Planter seems to be on the same level with Bracke (Härkönen 2008). Today there are 26 Brackes and 5 M-Planters operating in Finland and few Brackes in other Nordic Countries. The rest of the device types mentioned have mainly been withdrawn from the actual use. As yet there are not any continuously working planting machines or devices that fulfil the mechanization principle 5.

Bracke (P11.a Planter) and M-Planter were chosen to this study as they represent the state-of-the-art planting devices in techno-economic terms. Earlier studies have shown that the more stones and slash there is the lower is the productivity of Bracke (Saarinen 2004). However, there was a lack of models describing the dependence of productivity of Bracke on these work difficulty factors. In addition, it has raised increasing interest what kind of an effect the number of stumps has on productivity of planting devices, because a share of regeneration areas from which stumps are lifted for energy use is increasing rapidly (Harstela 2004b). There were not any prior techno-economic research results available concerning M-Planter to this study.

Altogether, the aim of the study was to find out work time distributions, productivities, costs and effects of the work difficulty factors stoniness, share of slash cover, and the number of stumps on the productivity and costs of Bracke and M-Planter and to compare the two devices to one another from a techno-economic perspective.

2 Materials and Methods

The experimental design of the study based on the theory of comparative time studies, where the aim is to find out relative differences in performance levels of the machines under consideration (Harstela1991). The work study data was collected and work difficulty factors measured during autumn 2007. All the work study data was videotaped. The work study data consisted in observations on working with Bracke and M-Planter planting devices in three research areas (A, B and C) located in Kainuu Region, Finland. The research areas represented typical Finnish forest lands; thickness of humus layer varied between 11 and 16 cm, soil texture varied from fine to coarse, and both moraine and sorted soil types were represented.

The research areas were clear-cut and divided into two (A, B) or three (C) blocks. Then, each block was handled with one out of the three treatments to achieve varying working conditions for planting devices in terms of share of slash cover and number of stumps. The treatments were as follows: slash and stumps left (B, C); slash removed but stumps left (A, C); and both slash and stumps removed (A, B, C). Adequate variation in the third work difficulty factor concerned, stoniness, was taken into account when choosing the research areas. The two drivers (D0 and D1) drove two tracked excavators from which one (Kobelco 200 SRLC) was equipped with Bracke and another (Kobelco 135 SRLC) with M-Planter planting devices in each block. D0 had previous experience on working with Bracke and D1 with M-Planter. Drivers practiced with the unfamiliar device for one working day before the data collection started.

The capacity of Bracke's seedling cassette was 72 and M-Planter's 162 seedlings. In the case of Bracke, an observation unit i.e. replicate of the work study was a planting work of two seedling cassettes (2×72 seedlings) starting from the first movement of a device with a full seedling cassette and ending at the moment when the last seedling of the second cassette was planted. In the case of M-Planter, an observation unit was a corresponding planting work of a seedling cassette. Also the time spent on the filling of the seedling cassettes was measured. D0 planted 52 (2×26) cassettes with Bracke and 25 cassettes with M-Planter, whereas D1 planted 56 (2×28) cassettes with Bracke and 27 cassettes with M-Planter. The data included 3–4 replicates per driver per device from each block. Altogether, the data consisted in 106 replicates meaning planting work of 160 seedling cassettes with the total capacity of 16 200 seedlings. Seedlings were 1½ years-old Norway spruce (*Picea abies*) grown in Plantek 81F seedling trays.

The work measurement method used in analyzing the video data was a work sampling method, which is a method of finding the percentage occurrences of certain work elements by statistical (random or interval) sampling (Kärkkäinen 1975, ILO 1979). The sampling interval used was 10 seconds and the total number of observations in the time study 24,869. The work time distributions for the combinations of base machine and planting devices were created on the basis of effective working time (E_0) including the time of filling the seedling cassettes that was taken into account as a device-specific mean value ($n_{Bracke} = 52$ (2×26); $n_{M\text{-}Planter} = 17$). The rest of the observations ($n = 91$) on filling the seedling cassettes were excluded from the data, because they included extra operations related to the data collection.

Stoniness, slash and stumps were measured for each replicate from three experimental plots ($r = 3.99$ m) located systematically on the tracks of the base machines after planting. Each three plots included nine systematically located observation points. Thus, there were 27 observation points per replicate. In the data collection, stoniness was taken into account as a number of points where a stone was less than 20 cm in depth, slash as a number of points where was slash cover, and stumps as a total number of stumps ($\varnothing > 10$ cm) within the plot. However, to make the paper easier to read, stoniness and amount of slash are presented as percentage shares of area,

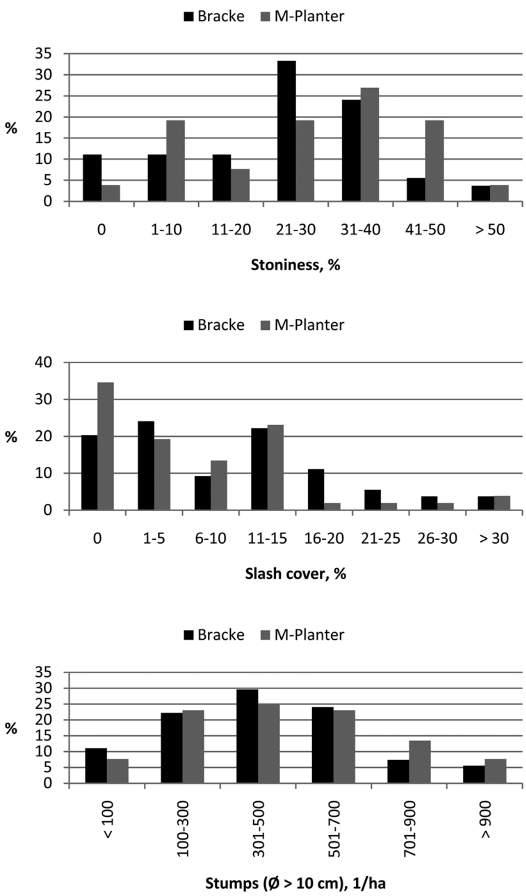

Fig. 1. The distributions of work difficulty factors stoniness, share of slash cover and number of stumps (∅ > 10 cm) in the planting areas concerned.

and number of stumps as hectare-specific (ha^{-1}) number. The replicate-specific stoniness varied from 0% to 59.3%, the share of slash cover from 0% to 37.0%, and the number of stumps from 0 to 1266 per hectare (Fig. 1).

Multiple linear regression analysis was applied to study the effects of device, driver, and work difficulty factors (stoniness, share of slash cover and number of stumps (∅ > 10 cm)) on productivity of planting work. The regression model was built based on E_0 excluding the time of filling the seedling cassettes. The variable selection method used was an enter-method. In this method, all variables that are used as predictors (type of device, driver, stoniness, slash, stumps and their interactions) are entered into the model in a single step. The type of device [Bracke, M-Planter] and driver [D0, D1] were included in the model as dummy variables coded as 0 and 1, respectively.

The productivity values (based on E_{15}) used in cost accountings were derived from the regression model by taking time of filling the seedling cassettes, relocation times and assumed ratio (0.90) of E_{15} to E_0 into account. The capital costs were handled by the reducing balance method of depreciation with the annual depreciation share of 25%. The interest rate applied was 5%. The base machine was assumed to be employed year-round. The planting work was expected to be done five months annually in 1½-shift work system. Table 1 presents the main factors used in calculating fixed costs for the base machine and planting devices.

Table 1. Main cost factors used in accounting of fixed costs of the base machine and planting devices.

	Bracke	M-Planter	Base machine
Purchase price, €	44000	55000	135000
Calculatory residual value, €	5259	6017	41053
Life time, h (E_{15})	7500	7500	12000
Total working time (T_0), h/year	1320	1320	2900
Insurance and administration, €/year	-	-	6000

When calculating relocation costs, it was assumed that 4000 seedlings are planted per planting area, relocation distance between consecutive planting areas is 14.5 km (Rantala and Saarinen 2006) and relocation unit costs are 2.2 €/km (Väätäinen et al. 2006 (updated)). Salary costs were set as 18.70 €/hour (E_{15}) including social expenses, vacation pay and wage administration. Drivers' travelling expenses were estimated to be 1.83 €/hour (E_{15}). Fuel costs of planting work assumed to be 10.80 €/hour (E_{15}), maintenance costs 5.00 €/hour (E_{15}) and other variable costs 2.00 €/hour (E_{15}) for both devices.

The relocation time (Rt) including preparatory works in planting areas was estimated to be 10% from total working time (T_0) for a planting device having lower productivity (E_{15}) and determined according to Eq. 1 for another device, because Rt was expected to increase as a function of productivity (E_{15}). Annual amount of E_{15} of the base machine was determined according to the planting device concerned. In Eq. 1, *P* refers to productivity (E_{15}), index *H* to a device with higher productivity and *L* to another device.

$$Rt_H = \frac{P^H}{P^L} RtL \tag{1}$$

The mean values of the work difficulty factors used to equalize the working conditions were as follows: stoniness 26.3%; share of slash cover 8.8%; and number of stumps 460 ha^{-1}. Finally, sensitivity analyses were carried out to study the effects of working conditions on the differences in productivity (E_{15}) and unit costs (€/seedling) between the devices. In these analyses, the input value of the work difficulty factor under special interest was varied, where as the others were set as mean values.

3 Results

A share of successfully planted seedlings from the total number of seedlings filled in seedling cassettes was 96% (15 561 seedlings). Effective working time (E_0) distributions for both planting devices were similar (Fig. 2). "Mounding + planting" was the most time consuming working stage (47%) followed up by "other boom movements" that took approximately one fourth of E_0. The average time needed to fill the seedling cassette of Bracke was 223 seconds (72 seedlings) corresponding 15% of E_0. In the case of M-Planter, filling the seedling cassette took 366 seconds (162 seedlings) on the average corresponding 14% of E_0. Altogether, the abovementioned three work stages took 88% of Bracke's and 85% of M-Planter's E_0.

Measured mean productivity (E_0) of M-Planter (240 seedlings/hour) was 34.6% higher than that of Bracke (178 seedlings/hour). Productivity figures varied more in the case of M-Planter (N = 52; std. 61.18) than in the case of Bracke (N = 54; std. 37.89) (Table 2). However, a comparison of the devices in equalized working conditions based on E_{15} is presented later on this section.

In general, stoniness and number of stumps decreased productivity of planting work, whereas share of slash cover had no statistically significant effect on it (Table 3). However, productivity of Bracke decreased more in relation to that of M-Planter when share of slash cover increased. On the other hand, productivity of M-Planter weakened more than that of Bracke when stoniness or number of stumps increased. Stumps slowed working pace of D1 more than that of D0. Triangular interactions of device, driver and the work difficulty factors were also modeled, but left away from the model presented in Table 3, because they were not significant predictors of productivity.

The regression model was used to compare the devices in equalized working conditions. When the work difficulty factors were determined as their mean values, and the time needed for filling the seedling cassettes, and assumed ratio of E_{15} to E_0 were also taken into account, productivity (E_{15}) of M-Planter (236 seedlings/hour) was 36.0% higher than that of Bracke (174 seedlings/

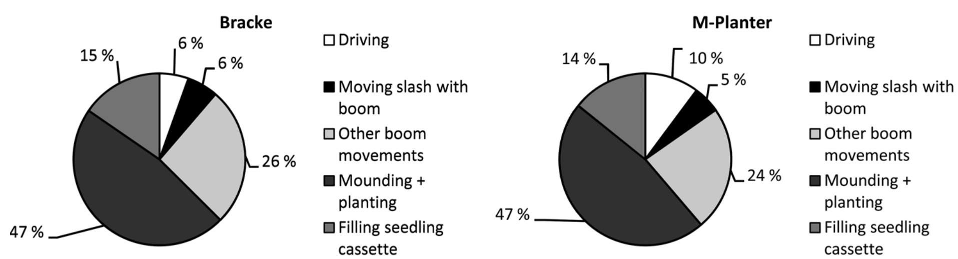

Fig. 2. Effective working time (E_0) distributions.

Table 2. Measured mean productivities (seedlings/hour) of the planting devices and drivers based on effective working time (E_0) including filling of seedling cassettes.

		N	Mean	Min.	Max.	Std. Dev.
Bracke	D0	26	208	170	266	24
	D1	28	150	110	213	24
	Total	54	178	110	266	38
M-Planter	D0	25	205	149	298	41
	D1	27	272	144	351	60
	Total	52	240	144	351	61
Total	D0	51	207	149	298	33
	D1	55	210	110	351	76

Table 3. A multiple linear regression model for predicting productivity (based on E_0 excluding the filling of seedling cassettes) of planting work.

Predictors	β	Std. Dev.	t	p
Constant	461.1	22.1	20.8	<0.001
[Device=Bracke]	–231.3	26.4	–8.8	<0.001
[Driver=D0]	–119.9	27.8	–4.3	<0.001
[Bracke] * [D0]	189.0	17.8	10.6	<0.001
Stoniness	–2.655	0.453	–5.862	<0.001
Slash	0.560	0.897	0.624	0.534
Stumps	–0.120	0.030	–4.043	<0.001
[Bracke] * Stoniness	1.766	0.582	3.034	0.003
[Bracke] * Slash	–1.030	1.039	–0.992	0.324
[Bracke] * Stumps	0.059	0.036	1.657	0.101
[D0] * Stoniness	–0.144	0.586	–0.245	0.807
[D0] * Slash	–1.668	1.035	–1.612	0.110
[D0] * Stumps	0.075	0.036	2.097	0.039
$r^2=0.73$				

hour). Accounting of planting unit costs for the devices, presented in Table 4, was based on these productivity figures.

Annual relocation times (Rt) for Bracke and M-Planter were 132 and 180 hours, respectively (see Eq. 1). Thus, the annual amount of E_{15} of Bracke was 1188 hours and that of M-Planter 1140 hours. Hourly fixed costs of M-Planter were 10.2% higher than those of Bracke. At the annual level, M-Planter needed more relocations than Bracke that caused 0.51 €/h (E_{15}) higher relocation costs which come out as slightly higher (1.3%) variable costs of planting work. The total hourly cost of M-Planter was 4.1% higher than that of Bracke. However, unit costs per planted

Table 4. Fixed costs, variable costs, total costs and unit costs of Bracke and M-Planter planting devices (based on E_{15}).

	Bracke	M-Planter	M-Planter compared to Bracke
Base machine, €/h	12.43	12.66	1.9%
Planting device, €/h	6.15	7.82	27.1%
Fixed costs, €/h	**18.58**	**20.48**	**10.2%**
Variable costs, €/h	**39.70**	**40.21**	**1.3%**
Total costs, €/h	**58.28**	**60.69**	**4.1%**
Unit costs, €/seedling	0.34	0.26	–23.4%

Table 5. The percentage differences in productivities (based on E_{15}) and unit costs of the devices in varying working conditions.

		Work difficulty factor								
		Stoniness, %			Slash cover, %			Number of stumps, ha^{-1}		
		0	25	50	0	15	30	0	400	800
M-Planter compared to Bracke, %	Productivity	52.1	36.9	18.0	30.2	40.4	52.7	46.6	37.4	27.5
	Unit costs	–31.5	–24.0	–11.8	–20.0	–25.9	–31.8	–29.0	–24.2	–18.3

seedling of M-Planter were 23.4% lower than those of Bracke (Table 4).

The difference in productivity and in planting unit costs between the devices depended much on the working conditions; the more stones or stumps the smaller the difference, and on the other hand, the more slash the bigger the difference (Table 5). Increase in stoniness from 25% to 50%, for instance, decreased the productivity difference between the devices in half. On the other hand, the difference between the devices in productivity was 30% when there wasn't any slash on the site, but more than 50% when slash covered 30% of the site (Table 5).

4 Discussion

In studies concerning mechanized forest work, it is often difficult to eliminate the inter-individual effects caused by the differences in drivers' motivation and skills on results (Harstela 1991, Siren 1998, Ovaskainen et al. 2004). Although the approach of comparative time studies was applied, one has to be careful when generalizing the results of this study to concern mechanized planting in a broader sense. In this study, standard deviation of productivity of one driver (D1) was more than double compared to that of another (D0). This might indicate that the time spent for practicing with the unfamiliar device was not long enough or the drivers were not motivated to do their best with both devices. However, the observed productivity values of Bracke were well in line with the previous research carried out in Finnish forest conditions (Arnkil 1997, Rummukainen et al. 2002, Saarinen 2006).

In this study, the research areas represented typical Nordic planting sites in terms of the variation in work difficulty factors concerned. Stoniness, for instance, fell to class 2/5 (area A) or 3/5 (areas B and C) in the classification introduced by Berg (1986). All measured work difficulty factors correlated negatively with the productivity of planting work. However, there were differences between the devices in this sense; an increase in stoniness or in number of stumps decreased M-Planter's productivity more than Bracke's, whereas an increase in share of slash cover decreased productivity of Bracke more than that of M-Planter. When the experimental design of the work study was decided, it was assumed that the soil type has no significant effect on productivity of the planting work. However, the planting tubes were a few times blocked up by fine soil in the research blocks, where soil was both wet and fine fractioned. This might explain some part of the residual variance of productivity in the regression model presented.

Bracke was used in the work study with bigger base machine than M-Planter. However, it seems that the size of the base machine has not significant effect on productivity of excavator based planting devices (see Arnkil 1997, Rummukainen 2002, Saarinen 2004). In general, there is no difference in requirements set for the base machine between Bracke and M-Planter. Therefore, the cost accounting was based on the assumption of using the same type of base machine with both devices. The cost accounting based on an assumption that the base machine is employed year-round. In addition, it was assumed that the base machine operates without any longer interruptions during the planting period. In spite of these, the fixed costs of the base machine were more than 20% of the total costs of planting work. This means that it is very difficult to make mechanized planting competitive with manual planting without finding year-round work for the base machine. In practice, the use of second-hand base machines can reduce fixed costs. However, this leads often to higher variable costs and lower capacity utilization rate so that the end result is somewhat similar to that of using new machines (Bright 2004).

On the average, M-Planter performed planting work clearly cheaper than Bracke. Still, it must be kept on mind that in practice also technical availability and utilization rate of the annual capacity of the devices can have great influence on planting costs. In Finland, compared to the current market price of broadly used chain of mechanized mounding and manual tree planting, it seems that in the average working conditions the planting unit costs of M-Planter are to some extent lower and the costs of Bracke a little bit above of them. However, one must not only take the variation between the drivers but also the effects of different work difficulty factors carefully into account in the planning of annual work programs for the planting devices. In general, it seems reasonable to select areas with few stones or stumps for the device types, such as M-Planter, equipped with two planting heads. On the other hand, it is argued to direct areas from which slash has removed for planting device types, such as Bracke, operating with only one planting head.

According to Rantala and Saarinen (2006), it seems that with the current rate level there is only very small difference between the maximum annual planting capacity of Bracke and the amount of planting work required for profitable investment on the device. Thus, misplacing the devices to unsuitable regeneration areas leads easily to unprofitable investments. According to the results of this study, there seems to be some more margins in this respect when M-Planter is concerned.

There is still plenty of room for technical development of the devices and for entirely new machine concepts, too. As far as current devices are concerned, a development target is the capacity of the seedling cassettes and operational principles related to filling of seedling cassettes; doubling the capacity or cutting time of filling seedling cassettes into half in some other way would decrease the unit costs of both devices more than 5 percents. However, developing new technical solutions means making trade-offs between improvements in productivity and costs of the device. From the technical standpoint, at least visibility of planting places from the cabin and weight of the planting head are limiting factors in development work. When developing technical features related to the seedling cassettes, seedling logistics including production and packing systems should be taken into account.

When it comes to the development of new machine or device concepts, the mechanization principle concerning continuous working method could be a next step. Amount of regeneration areas where working conditions are suitable for a continuously working planting machine or combination of base machine such as forwarder and planting device will presumably increase in the future, because growing amount of slash and stumps are collected for energy purposes. Despite the operating principles applied, automation is still for the most part an unutilized possibility to improve the productivity of mechanized planting. Further, information and communication technology offers all the time new solutions exploitable also in planning and implementation of mechanized planting. In addition, sensor technology, that is one of today's most quickly developing area of technology, could offer suitable solutions for mechanized planting for example in terms of recognizing appropriate planting places within the planting sites.

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