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Cleaning Scots pine seedling stands with mechanical uprooters – a work quality comparison of two related devices

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Highlights

- The productivity of the narrower modified device was significantly better than the wider original device.
- Work quality did not differ significantly between devices when stand characteristics, regeneration success and pre-existing damage were taken into account.
- Results indicate that mechanical uprooting devices may be further developed to a cost-effective alternative to motor-manual techniques for the early cleaning of direct seeded commercial Scots pine stands.

Abstract

Commercial forests require early cleaning to ensure the unhindered and uniform growth of crop trees. In order to be cost effective, non-crop vegetation should be uprooted to prevent their recovery. Performing this work manually is a labour-intensive task but it can be done mechanically. We evaluated the efficiency of two uprooting devices in direct seeded Scots pine (*Pinus sylvestris* L.) stands ca. 1 m tall. Productivity and quality of the uprooting work was investigated across eight stands and ca. 160 sample plots in northern Karelia, eastern Finland. Time consumption of the uprooters was analyzed through a linear regression model and the work quality through a multilevel multivariate model in terms of the number of individual Scots pine seedlings, processing units (i.e., a bunch of seedlings to be harvested in the future) and broadleaves. The productivity of the narrower modified device was significantly better in terms of time consumption than the wider original device. Work quality did not differ significantly between devices when stand characteristics, regeneration success and pre-existing damage were taken into account. Results indicate that mechanical uprooting devices may be further developed to a cost-effective alternative to motor-manual techniques for the early cleaning of direct seeded commercial Scots pine stands.

Keywords mechanized silviculture; *Pinus sylvestris*; early cleaning; productivity
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1 Introduction

In general, young commercial forest stands must be tended to help standardize the spatial distribution of trees and to decrease competition between commercially valuable conifers and faster growing broadleaved trees by removing competing seedlings, especially broadleaves (Hyvän metsänhoidon… 2014). Young stand management techniques and the timing of their application in Scots pine (*Pinus sylvestris* L.) stands have been studied since the 1970s (Jakkila and Pohtila 1978; Ikäheimo and Norokorpi 1986). These studies were based on the assumption that a one-time cleaning and/or thinning treatment is sufficient to ensure good growth and development until the first commercial thinning. More recently, Saksa and Miina (2010) have investigated a two-stage treatment incorporating early cleaning and pre-commercial thinning.

Both naturally regenerated and direct seeded Scots pine seedling stands require cleaning. Broadleaf saplings encourage moose browsing and thereby promote the incidence of mechanical damage to tree tops, and all broadleaves taller than crop seedlings must be removed (Miina and Saksa 2006, 2013). According to Heikkilä and Härkönen (1993), moose damage on Scots pine is more common when broadleaved trees, mainly birches (*Betula* spp.), occur at high densities and as overgrowth in mixed stands. Under such conditions, cleaning may reduce the risk of moose damage to Scots pine (Härkönen et al. 1998, 2008). Removing the preferred tree species of moose in particular, i.e., aspen (*Populus tremula* L.) and rowan (*Sorbus aucuparia* L.) (Bergström and Hjeljord 1987; Månsson et al. 2007), can help reduce herbivore damage (Löyttyniemi and Lääperi 1988). Furthermore, removal of aspen reduces the incidence of pine twisting rust (*Melampsora pinitorqua* Rostr.) due to its role as a secondary host for the pathogen (Kurkela 1973).

Forest managers must decide when and how to clean broadleaves from direct seeded or naturally regenerated Scots pine seedling stands and the extent to which pine seedlings should be thinned in order to maximize seedling growth rate and eventual quality of harvested timber. In total cleaning, all broadleaves and excessively advanced Scots pines are removed prior to any subsequent pre-commercial thinning. In point cleaning, all broadleaves and Scots pines are removed within a ca. 1 m radius of crop seedlings (Miina and Saksa 2013).

Different combinations of treatment and its time of application affect eventual timber quality (Salminen and Varmola 1990). Fahlvik et al. (2005) studied the effects of treatment timing on 1–7 m tall stands and treatment intensity on external quality indicators of Scots pines in over 8 m tall stands in naturally regenerated and direct seeded Scots pine seedling stands in southern Sweden. Results suggested that earlier thinning increased the thickness of the thickest braches in stands with 3000 or less seedlings ha^{-1}. Fahlvik et al. (2005) did not find any significant effects of seedling density and the timing of cleaning in combination, although it can be assumed that the effects of early thinning are directly proportional to treatment intensity (Ulvcrona et al. 2007). According to Ulvcrona et al. (2007), density of the remaining trees after cleaning had a greater influence on growth and the number of branches than the timing of thinning in naturally regenerated and direct seeded Scots pine seedling stands in northern Sweden.

Density of Scots pine seedling stand affects diameter growth, natural pruning and branch mortality. According to studies concerning the quality and development of direct seeded Scots pine seedling stands, seedling density should be 3000–4000 seedlings ha^{-1} to ensure a crop of high quality timber (Persson 1977; Varmola 1996). Hynynen et al. (2005) evaluated the performance of a Scots pine seedling stand at a density of 3000–4000 seedlings ha^{-1} from early cleaning to the harvesting of energy wood when trees were ca. 10 m tall. Stand management regimes that aim to improve timber quality recommend a seedling density after regeneration of 4000–5000 direct-seeded pine seedlings ha^{-1}, and after early cleaning the same density for both pines and broadleaves together (Äijälä et al. 2014).

Treatment effects on the quality of Scots pine stands have been well studied in Finland (e.g., Salminen and Varmola 1990; Pukkala et al. 1998; Varmola and Salminen 2004; Saksa and Miina 2010). Parallel research has been conducted in Sweden (e.g., Fahlvik et al. 2005; Ahnlund Ulvcrona 2011), and general recommendations with respect to the timing, intensity and number of treatments have been proposed. For example, Finnish forest management practice recommendations state that early cleaning in Scots pine seedling stands should be applied when pine seedlings are less than 1 m tall to density of 4000–5000 seedlings ha^{-1} comprising both broadleaves and pine seedlings together with pre-commercial thinning on 5–7 m tall stands to density of 2000–2200 trees ha^{-1} (Äijälä et al. 2014).

When broadleaves are removed by cutting with a clearing saw or blade in young Scots pine seedling stand, the remaining stumps quickly sprouts new leaders and will soon require further cleaning (Maltamo et al. 1989). Devices that uproot broadleaves provide a more permanent treatment, often being the only treatment required before the first commercial thinning. In Norway spruce (*Picea abies* [L.] H. Karst.) seedling stands, Heikkinen (2009) and Kukkonen (2011) suggest that 60–70% of stands require cleaning with an uprooter only once, and pre-commercial thinning of the remaining 30–40% of stands is made easier and faster because of it.

When consider mechanized uprooting, direct seeded Scots pine seedling stands need to be well established and ca. 1 m tall and operation should be done in adequately accurate manner by experienced operators, like in spruce seedling stands studied by Rantala and Kautto (2011) and Hallongren and Rantala (2013).

Uprooting devices are attached to harvester booms and use hydraulic jaws to grip and lift several sprouts from the ground at a time while simultaneously breaking their roots (Hallongren and Rantala 2013). The Naarva uprooter (Pentin Paja Ltd.) can reportedly clear an average of 0.14–0.16 ha of spruce seedling stand per productive work hour (PWh_{15}, all delays max. 15 minutes included), i.e., 6.3–7.4 h ha^{-1} (Rantala and Kautto 2011; Hallongren and Rantala 2013), which is similar to the speed of manual cleaning. Therefore, the competitiveness of uprooting is greatly dependent on how well the treatment prevents the need for later pre-commercial thinning. In a wider context, uprooting devices attached to harvesters and possibly also to forwarders in the future lead to higher capacity utilization rate during summer and help to improve machine contractors' competitiveness.

The costs for the P25 (P25_v1 in this study) in spruce seedling stands have been studied by Hallongren and Rantala (2013). The total hourly cost of uprooting is approximately USD 81 ha^{-1} and the average uprooting cost ca. USD 400–600 ha^{-1}, depending on, for example, the hourly machine utilization costs. With measured minimum time consumption, uprooting costs were ca. USD 230–340 ha^{-1} and with measured maximum time consumption USD 640–960 ha^{-1}. The average productivity under average conditions for the P25 was 6.28 pwh ha^{-1}.

In mechanized uprooting, worksite suitability and treatment timing are key factors affecting work quality and productivity (Hallongren and Rantala 2013). Furthermore, several uprooting devices have been developed and the service provider must select an appropriate machine for the task. Uprooting can be classified as routine work in which a set of possible patterns from which ones enact particular service performances that are functionally similar but not necessarily the same (Pentland and Rueter 1994). As in other fields, operator´s skills depends on three things: (1) accurate assessment of e.g. customer's wishes and stand required; (2) development of an action plan i.e., worksite selection and timing with the correct device and within budget; and (3) how well they perform the uprooting work, e.g. motivation and skills (Lillrank 2003). This may be controlled with using the same operator in work studies. Routine processes such as uprooting require the assessment of input information and rely on tacit knowledge (Nonaka and Takeuchi 1995), and learning within a routine process can be seen as the development of more fine-grain assessment categories (Feldman 2000). A simple four-class analysis illustrates the possible outcomes of routine processes: (1) right things done right, (2) right things done wrong, (3) wrong things done right, and (4) wrong things done wrong (Lillrank 2003). The quality of uprooting can be analyzed through the idea of routine processes, i.e., how well the operator manage to select the right device (e.g. type of Naarva or other), conduct the work at the right time, select the right seedlings for removal and leave the best crop-tree seedlings and fulfil the objectives of the client.

The aim of this study was to investigate the suitability of two uprooting devices used to carry out the early cleaning of direct seeded Scots pine seedling stands. Efficacy was evaluated in terms of the outcome, i.e., work quality. When cleaning direct seeded commercial Scots pine seedling stand, the operator must be able to select between high and low quality seedlings and clean the stand accordingly, leaving an optimal density and distribution of high-quality crop seedlings. In addition, approximate productivity of uprooting operation was investigated.

2 Material and methods

2.1 Study design

The study was based on comparative work study of the Naarva P25 uprooter (P25_v1) as shown in Supplementary file 1, available at http://dx.doi.org/10.14214/sf.1514, and a new device version based on the same unit but ca. 20 cm narrower (P25_v2). P25_v1 uprooted a total of 26.1 ha from four stands in 2012, and the P25_v2 uprooted 25.0 ha from four stands in 2013. All stands were cleaned during midsummer when the leaves were at their maximum size and they all located within 100 km radius in northern Karelia, eastern Finland (62–63°N, 30°E). With respect to soil preparation, two of the sites were patched while six had received disc trenching. Seedlings were ca. 6–7 years old when the uprooting treatment was applied. Inventories were made in eight direct seeded Scots pine seedling stands (A–H in Table 1) before and after cleaning operations, during the same season when uprooting was applied; stands A–D in 2012 and E–H in 2013.

A systematic grid of 20 m^2 ($r = 2.52$ m) circular sample plots was established on each stand and the center of each plot was determined with GPS (Garmin Legend HCx) and marked discretely. Twenty sample plots were established in stands larger than 2.0 ha. Prior to uprooting, the number of Scots pine seedlings and the number and species of broadleaves (e.g., *Betula* spp. [birch], *Populus tremula* [aspen] and *Sorbus aucuparia* [rowan]) were determined in each sample plot. Up to five Scots pine seedlings (>30 cm) and up to five of each broadleaf species (>30 cm) closest to the center of each plot were selected and measured for height. Also, the inclination of each sample plot and the number of surface obstacles such as stones and stumps (>20 cm height) was estimated. The effect of inclination was divided according to visual estimation into three categories, (1) no effect, (2) inhibited movement of the base machine, and (3) inhibited use of the uprooter. In addition, the number of poor quality Scots pine seedlings, herbivore damage (e.g., moose, *Alces alces*) and disease symptoms (e.g., pine twisting rust, caused by *M. pinitorqua* or Scleroderris canker caused by *Gremmeniella abietina* Morelet and resin top disease caused by *Cronartium flaccidum* Wint. or *Peridermium pini* Lev.) were evaluated and recorded prior to uprooting. The success of regeneration activity was measured in each sample plot in terms of target seedling densities; if target density was reached regeneration result was successful, otherwise not. The operator was unaware of sample plot locations.

A skilled operator with several years of uprooting experience used two different base machines, a medium-sized harvester Valmet 901.2 in 2012 and a Valmet 911.3 in 2013. Valmet 901.2 weight 14 820 kg, its engine has 6.6 l stroke volume, power of 125 kW at 2200 rpm and

Table 1. Main characteristics of the eight research stands before and after uprooting.

Stand	Size (ha)	Number of plots	Mean (SD) height of pine (cm)		Mean (SD) density of pine (seedlings ha^{-1})		Mean (SD) height of broadleaf saplings (cm)		Mean (SD) density of broadleaf saplings (seedlings ha^{-1})		Mean (SD) density of damaged seedlings (ha)	Regeneration result (% successful)
			before	after	before	after	before	after	before	after		
A	2.2	19	65 (12)	89 (18)	8740 (4370)	5600 (2770)	120 (40)	69 (8)	10 950 (7420)	605 (615)	870 (740)	89
B	6.6	20	70 (15)	94 (20)	4680 (1770)	3250 (1560)	105 (33)	80 (17)	4280 (2450)	550 (560)	500 (585)	80
C	7.2	20	92 (23)	104 (23)	5080 (1440)	3900 (1150)	121 (72)	56 (12)	3880 (2060)	550 (670)	900 (530)	90
D	10.1	20	103 (26)	134 (28)	4180 (4850)	3380 (3130)	161 (115)	79 (25)	4780 (4850)	250 (470)	500 (900)	55
E	11.5	20	78 (19)	86 (28)	4100 (2240)	2780 (1800)	121 (49)	61 (12)	5730 (6130)	700 (830)	1180 (960)	70
F	4.1	20	95 (18)	101 (24)	3730 (2070)	2850 (1710)	140 (60)	78 (22)	10 880 (7310)	850 (1330)	1400 (930)	70
G	5.1	20	104 (26)	107 (30)	4800 (2370)	3330 (1480)	176 (118)	63 (17)	3580 (2760)	500 (560)	1130 (840)	85
H	4.3	20	95 (28)	97 (21)	7530 (4200)	4680 (1980)	116 (41)	56 (20)	3450 (7230)	75 (240)	1500 (1340)	95

Fig. 1. Uprooting device P25_v1 (Photo: Ville Kankaanhuhta).

torque of 650 Nm at 1400 rpm. Valmet 911.3, in turn, weight 16 300 kg, has 7.4 l stroke volume, power of 150 kW (2200 rpm) and torque of 1000 Nm (1500 rpm). Valmet 901.2 has a hydraulic system's flow of 221 l min^{-1} at 1700 rpm and 230 bar system pressure and Valmet 911.3 313 l min^{-1} at 1650 rpm and 255 bar, respectively. The boom was similar (outreach 10 m) in both years but Valmet 901.2 has a lifting torque of 142 kNm and slewing torque of 33.7 kNm, whereas Valmet 911.3 has 186 kNm and 40.8 kNm. The original P25_v1 is rectangular shaped (125 cm × 205 cm) and cleans ca. 2.5 m^2 per cycle as shown in Fig. 1, and the size of narrower P25_v2 is 105 cm × 205 cm. Productive work time (PWh, with all delays excluded) spent uprooting was recorded by the operator's stop watch for each stand during a cleaning event and excluded all stoppages. The operator completed a form for monitoring work time at each stand, which provided details concerning the time spent uprooting or for other activities and scheduled breaks, etc. The operator had the opportunity to give his own estimate of the inclination effect on movement of the base machine and use of the uprooter on each stand.

In all eight stands the target density was 3000–4000 seedlings ha^{-1}, of which 1500 should be individually grown high-quality Scots pine seedlings. The remaining 1500–2500 seedlings may consist of broadleaves or Scots pine seedlings growing in pairs or groups of three or more seedlings. These pairs or groups of seedlings are named "processing units" since they form separate units that will be handled as one in next silvicultural operation, mainly energy wood harvesting (first commercial harvesting). The operator received clear instructions with respect to target densities of individually growing Scots pine seedlings and was told to record seedlings growing in pairs or small groups as either one or two seedlings based on the area they occupied with respect to the target density. In the analysis, the number of Scots pine seedlings in pairs and groups were assigned a value of 1.5 when calculating the total number of pine seedlings growing in a processing units after uprooting.

After uprooting, the center of each sample plot was located either by finding the marker or via GPS if the marker had been destroyed during cleaning. The number and species of remaining broadleaves and Scots pine seedlings were determined after uprooting as well as any uprooting damage in terms of likely cause and extent. Damage was scored as either (1) minor, if the pine seedling would likely survive the injury, or (2) serious, if the pine seedling could no longer be considered viable. Damage was caused by the base machine or the uprooting device itself. The height (>30 cm) of three pines closest to the center mark and any remaining broadleaves were also measured. In addition to mechanical damages, damage caused by herbivores or fungal pathogens was also evaluated from individually grown Scots pine seedlings after uprooting.

The evaluated work quality indicators were (1) whether the set target density of 3000–4000 seedlings in terms of processing units ha^{-1} was reached; (2) 1500 well-spaced and high quality pine seedlings ha^{-1} remaining after uprooting; and (3) the number of broadleaves remaining in the stand after uprooting. Pine seedlings were considered to be growing individually i.e. well-spaced and unimpaired if the nearest seedling was >0.5 m away. Work quality was also evaluated in terms of the relative proportions of pine seedlings, broadleaves, poor quality (herbivore or fungus) and damaged seedlings before and after uprooting.

2.2 Analysis

The productivity of each uprooting device was analyzed through a linear regression model that applied the restricted maximum likelihood (REML) estimation method in PASW Statistics 17.0. The linear regression model was used to examine how uprooter, stand attributes and worksite difficulty factors (i.e., surface obstacles, inclination) affect time consumption (PWh ha^{-1}) of uprooting. Stand attributes and worksite difficulty factors were evaluated through a stepwise elimination and the final model included only those variables with statistically significant ($p = < 0.05$) effects.

The quality of uprooting work outcome was evaluated through a multivariate multilevel model due to the hierarchical data structure i.e., sample plots within stands. Quality was modeled in terms of three sub-models: (1) the number of individually grown Scots pine seedlings; (2) processing units, and; (3) broadleaves. All were estimated simultaneously as dependent variables of each sub-model.

The numbers of individually grown Scots pine seedlings, processing units and broadleaves per sample plot were modelled by fitting of normally distributed multilevel sub-models:

$$n_{ji} = x'_{ji}\beta + u_j + \varepsilon_{ji}, \quad (1)$$

where n is either number of individually grown Scots pine seedlings, processing units or broadleaves, x' is a vector of fixed predictors, and β is a vector of fixed parameters. The subscript j refers to a stand and subscript i refers to a plot. The u_j is a random effect associated with the stand, and ε_{ji} is the normally distributed residual error term at the plot level (Eq. 1). In the case of multivariate multilevel models, the simultaneous estimation of the response variables enables the recognition of their correlations which in turn improves the estimates (Goldstein 1996). The predictors of the sub-models were site conditions. All but one of the fixed predictors included in the sub-models had to be logical and statistically significant ($p < 0.05$). Device was always included since it was of interest to evaluate its effect on work quality.

The multilevel multivariate model was estimated by applying the Restricted Iterative Generalized Least Squares (RIGLS) algorithm in MLwiN 2.26 software (Rasbash et al. 2012). Candidate models were mainly evaluated in terms of likelihood ratio and Wald tests using the χ^2 distribution. The model assumptions were checked via the estimated residuals required to follow a normal distribution. These checks were applied at both levels of hierarchy; the sample plot and stand level. According to these checks, the number of broadleaves (n_{br}) per sample plot was required logarithmic transformation, i.e., $\ln(n_{br} + 1)$.

Table 2. Uprooter productivity (PWh ha^{-1}) in terms of time consumption.

		Time consumption (PWh ha^{-1})			
Uprooter	N	Min.	Mean	Max.	SD
P25_v1	4	6.0	7.0	7.8	0.8
P25_v2	4	4.5	4.9	5.4	0.4
Combined	8	4.5	5.9	7.8	1.3

3 Results

3.1 Time consumption

The measured mean time consumption for both uprooters combined was 5.9 PWh ha^{-1} (standard deviation [SD] 1.3 PWh ha^{-1}). Separately, the mean rate was 7.0 PWh ha^{-1} (SD 0.8) for P25_v1, and 4.9 PWh ha^{-1} (SD 0.4) for P25_v2 (Table 2). In general, productivity was significantly different between uprooters and was not significantly affected by any of the stand characteristics (Table 3). In all eight stands, the potential effects of inclination and obstacles were so slight that they could be ignored.

3.2 Quality of uprooting operation

The quality of sown Scots pine stands was evaluated in terms of the number of individually grown Scots pine seedlings, processing units, and the number of broadleaves. The measured mean number of individually grown Scots pine seedlings ha^{-1} after uprooting was 1585 seedlings ha^{-1} (SD 965), the number of processing units 2786 ha^{-1} (SD 1340) and the number of broadleaves 509 ha^{-1} (SD 745). Using a multiplier of 1.5, the calculated number of Scots pine seedlings in pairs or groups corresponds to a total density of 3132 seedlings ha^{-1}, (i.e., within tolerance of the target) and an average of 1585 individually grown Scots pine seedlings ha^{-1}, which departs only 5.7% from the target density. The extent to which target density was met was highly dependent on the level of stand regeneration. In 18.2% of sample plots, target density could not be met due to poor regeneration. The target density of 3000–4000 seedlings ha^{-1} was met in 83.3% of successfully regenerated sample plots and the remaining 16.7% had received too much (i.e., low density) or too little (i.e., high density) uprooting. Minor seedling damages caused by uprooting were on average 85 and serious damage 125 pine seedlings ha^{-1}. After uprooting, seedling damages attributable to herbivores or pathogens were observed in 890 pine seedlings ha^{-1}, of which 58.8% were growing in pairs or small groups and will be removed for energy wood.

Table 3. Regression model for time consumption of Naarva uprooters (N = 8).

Variable	B	Standard error	*t*-value	*p*-value
Constant	9.115	0.725	12.57	<0.001
[Uprooter = P25_v2]	–2.125	0.459	–4.64	<0.005

R^2 = 0.78; R^2 (adj.) = 0.75

Table 4. Parameter estimates (SE in parentheses), χ^2 test values and variance components of the sub-models for the number of individually grown Scots pine seedlings (n_1), processing units (n_2), and broadleaves (n_3) on 20 m^2 sample plots.

	Sub-model for					
Predictor	n_1	χ^2 –value	n_2	χ^2 -value	$\ln(n_3+1)$	χ^2 -value
Intercept	3.2152 (0.3378)	90.58***	5.4616 (0.3229)	286.05***	0.4580 (0.1097)	17.43***
Poor regeneration result	–1.7441 (0.3405)	26.24***	–2.3635 (0.4195)	31.75***	0.1579 (0.1115)	2.00 ns
Poor quality pine seedlings	0.1541 (0.0769)	4.02*	0.4291 (0.1024)	17.56***	0.0265 (0.0262)	1.02 ns
Uprooter (P25_v2 vs. P25_v1)	0.0205 (0.4397)	0.002 ns	–0.3295 (0.3859)	0.73 ns	–0.0662 (0.1417)	0.22 ns
Random part: SD (u_j)	0.4905 (0.4306)		0.1323 (0.3685)		0.1490 (0.1386)	
Random part: SD (e_{ji})	1.6013 (0.5432)		2.2145 (0.7630)		0.5628 (0.1910)	

Note: for class variables (units not shown), value 0/1; 0 = Successful. The number of poor quality seedlings was counted at the sample plot level. * *significant at* 0.05, ***significant at 0.001 level. ns = *non-significant at* 0.05 level.

The effect of device selection on work quality was evaluated through a multilevel multivariate model in which stand was treated as a random effect and regeneration success and natural seedling damages (i.e., herbivore or pathogen) were treated as fixed effects (Table 4). In this model, the wider device (P25_v1) and good regeneration result were used as reference classes and the number of Scots pine seedlings damaged by herbivores or pathogens (poor quality pine seedlings) was treated as a continuous variable. Device selection had no significant effect on the work quality in terms of any quality indicators (the analytical sub-models, i.e.,) number of individually grown Scots pine seedlings, processing units or broadleaves.

In the case of no seedling damages in the reference class, the estimated mean density of individual pine seedlings after uprooting was 1608 seedlings ha^{-1} (500 × 3.2152, Table 4), which departed 7.2% from the general target of 1500 pine seedlings ha^{-1}. Correspondingly, the number of processing units ha^{-1} was 2731 and the number of broadleaves 290 ha^{-1}. As expected, poor regeneration reduced the number of pine seedlings ha^{-1} by 872 and the number of processing units by 1182 seedlings ha^{-1}, but did not significantly affect the number of broadleaves. Unexpectedly, seedling damages due to herbivores (moose) or fungal pathogens were positively related to the number of pine seedlings and processing units. However, the proportion of damaged pine seedlings in each sample plot cannot be considered an important variable influencing work quality and fewer seedlings may have made the plot easier to clean.

The multivariate multilevel model of the uprooting work provides an opportunity to study the correlatedness of the quality indicators at the stand and sample-plot levels. This approach yields a more comprehensive view of stand quality. The covariance structure of the random effects in the multivariate multilevel model is shown in Table 5. At the sample plot level, significant correlations were observed between the error terms of the sub-models for the number of processing units and individually grown pine seedlings (0.58) and the number of broadleaves and processing units (0.58). This means that, e.g., if there were more individual pine seedlings at the sample-plot than predicted by the model, the observed number of processing units was also higher than predicted. At the stand level, covariances were not statistically significant.

Table 5. Covariances of the random effects at the sample plot level (lower triangle) and random stand level errors (upper triangle) for the number of individually grown Scots pine seedlings (n_1), processing units (n_2) and broadleaves (n_3). Standard errors and significances are shown in parentheses.

Response variable	n_1	n_2	$\ln(n_3+1)$
n_1	–	0.1819 (0.1507 ns)	–0.0314 (0.044 ns)
n_2	2.0482 (0.3378 ***)	–	–0.0317 (0.0361 ns)
$\ln(n_3+1)$	–0.0761 (0.0736 ns)	0.7188 (0.1187 ***)	–

*** significant at 0.001 level, ns = non-significant at 0.05 level.

3.3 Model fit

Fit of the multivariate multilevel model for work quality indicators was examined by comparing the variances of the random parts of sub-models with (full model) and without fixed effects (empty model) at the stand and sample plot level (Table 6). At the sample plot level, fixed effects accounted for 18% of the variance of the empty sub-model for the number of individually grown pine seedlings and 24% of the variance of the sub-model for the number of processing units. At the stand level, the influence of fixed effects was greater still. In the case of individually grown Scots pine seedlings, fixed effects explained 58% of the variance of the empty sub-model and 97% of the variance of the sub-model for processing units at this hierarchy level.

When the stand level was used as the random effect in the multilevel sub-models, the hypothetical correlatedness of the sample plots within stands due to e.g., site characteristics could be taken into account and quantified (ICC = Intra Class Correlation). The stand level contributed much less to variability than the sample plot level (Table 6). For example, the likeness of sample plots in the same stand was estimated to be 8.6%, 0.4% and 6.6% in terms of the number of individually grown pine seedlings, processing units and broadleaves, respectively.

Table 6. Influence of fixed and random effects on the total variation of the number of individual Scots pine seedlings (n_1), processing units (n_2) and broadleaves (n_3).

Response	Full model			Empty model			Influence of fixed effects (%)
	Variance estimate	Std. error	ICC (%)	Variance estimate	Std. error	ICC (%)	
Stand level							
n_1	0.2406	0.1854	8.6	0.5720	0.3651	15.5	58
n_2	0.0175	0.1358	0.4	0.5072	0.4218	7.3	97
$\ln(n_3+1)$	0.0222	0.0192	6.6	0.0223	0.0193	6.5	0.4
Sample plot level							
n_1	2.5641	0.2951	--	3.1265	0.3598	--	18
n_2	4.9040	0.5821	--	6.4720	0.7675	--	24
$\ln(n_3+1)$	0.3167	0.0365	--	0.3204	0.0369	--	1

Note: Full models are presented in Table 4. Empty models refer to sub-models estimated without fixed predictors. ICC refers to Intra Class Correlation.

4 Discussion and conclusions

Uprooting is a promising technique for pre-commercial thinning. In the context of direct seeded commercial Scots pine stands, the importance of an appropriate uprooting device was studied in terms of work productivity and quality. The time consumption of the narrower uprooting device (P25_v2) was significantly better than the broader original device (P25_v1). Work quality of the two devices did not differ significantly after the effects of stand characteristics, regeneration success and pre-existing damage from herbivores and pathogens were taken into account. Making the P25 uprooter 20 cm narrower has improved its time consumption from 7.0 to 4.9 PWh ha^{-1} in direct seeded Scots pine seedling stand. Explanations for the improved productivity may involve differences in handling and precision. The narrower device performed uprooting faster and more effectively since the size was more ideal in a dense seedling stand with target of certain density of individually growing Scots pine seedlings. According to operator, who has taken part in device development, the difference in engine power between the two base machines has no influence on time consumptions since the uprooting work does not demand for maximum power, being normally on average 1400 rpm while uprooting.

The combined productivity rate for both uprooters of 5.9 PWh ha^{-1} is quite similar to that measured in studies of uprooters operating in spruce seedling stand; on average 6.3–7.4 h ha^{-1} (Rantala and Kautto 2011; Hallongren and Rantala 2013) and also similar to the speed of manual cleaning. Although, the productivity rate varied from 4.9 (P25_v2) to 7.0 PWh ha^{-1} (P25_v1), P25_v2 being considerably better than previous measurements of other device versions. In previous study (Hallongren and Rantala 2013) the average cost for P25 (P25_v1 in this study) was USD 608 ha^{-1} in spruce seedling stand. When applying the same cost calculation factors and operating costs assuming that latest version (P25_v2) has same purchase price, the average cost for P25_v1 in pine seedling stand was USD 566 ha^{-1} and P25_v2 USD 396 ha^{-1}. As such, uprooting can be considered a viable technique for cleaning also in direct seeded Scots pine seedling stands. The costs of uprooting are substantially higher compared to motor-manual work but cost-efficiency can reach the level of motor-manual work if no later pre-commercial thinning is needed. If applied in both spruce and Scots pine seedling stands, machine contractors can operate more locally with less relocation costs which can improve their competitiveness.

Early cleaning with uprooting was done quite intensively at a relatively early stage, selecting the most high-quality Scots pine seedlings at a young age. In order to achieve a target density of 3000–4000 seedlings ha^{-1}, a cost-effective solution is to allow some seedlings to grow in pairs or small groups from the perspective of individually growing, high quality Scots pine seedlings. Machine operator was instructed to score seedlings growing in pairs or small groups as one or two seedlings based on the area occupied by the pair or group, e.g., a tight cluster of three adjacent seedlings might be scored as one. Cleaning and thinning improve the growing conditions for individually growing Scots pine seedlings until the first commercial thinning when the density is reduced to 1100–1300 trees ha^{-1} (Äijälä et al. 2014). Therefore, the number of processing units and individually growing Scots pine seedlings are the most informative indices when evaluating the quality of uprooting in direct seeded Scots pine seedling stand.

The proportion of broadleaves compared to the aim of achieve the target density is an important factor affecting the quality of an uprooting operation. Almost all sample plots that failed to meet the target density had a significant proportion of (i.e., 40–100%) of broadleaves and fewer than 2000 Scots pine seedlings ha^{-1} prior to uprooting. Evaluating seedling quality and removing them in accordance with other objectives is a challenging task for the operator. Therefore, some incidental damage to Scots pine seedlings, especially individually grown seedlings must be accepted after uprooting. According to the model, the number of poor quality seedlings prior to cleaning is positively related to the number of processing units and individually grown Scots pine seedlings after uprooting. In dense Scots pine stands, susceptibility to fungal diseases such as Scleroderris canker increases (Niemelä et al. 1992; Nevalainen 1999). Furthermore, when aspen is abundant the risk of pine twisting rust increases (Kurkela 1973). We also observed a positive relationship between the number of poor quality Scots pine seedlings prior to cleaning and the number of broadleaves after uprooting. If the number of broadleaves was high initially it may have encouraged moose browsing (Heikkilä 1993; Heikkilä and Härkönen 1993), and this led to more Scots pine seedling damage due to herbivores. A dense Scots pine seedling stand containing many broadleaves is associated with lower Scots pine seedling quality overall. However, the higher proportion of damaged pine seedlings may have influenced the operator's decisions while uprooting: he may have intentionally or unintentionally left more pines and broadleaves when observed higher share of damaged pine seedlings. Research focusing on operators' decision making would offer interesting research topic in future.

Properly planned and controlled routine processes of uprooting offer the best possible outcome in terms of work quality. The objective is to standardize uprooting activity to ensure that work quality remains high across a diversity of forest landscapes. Performing the work at the right time, in a suitable location with the correct device in the hands of an experienced, skilled and motivated operator with clear instructions and quality control are the necessary elements of high quality work. Poor choices lead to low quality and expensive costs, even though the work itself would be implemented in a proper manner.

The generality of the productivity results are limited in that relatively few observations were made with both uprooting devices, and more extensive testing in a diversity of situations is necessary before guidelines for best practice concerning mechanized uprooting in direct seeded Scots pine seedling stand can be issued.

Based on the previous results, uprooting is suitable and competitive alternative for motor-manual early cleaning not only in planted spruce seedling stand (Rantala and Kautto 2011; Hallongren and Rantala 2013) but also in direct seeded Scots pine seedling stand. This may benefit the machine contractor by means of shorter operating range and relocation distance when both spruce and Scots pine seedling stands are suitable for the machine which can lead to higher profitability.

In the future, long-term development of these Scots pine seedling stands should be studied to be able to track the effects of uprooting, such as the need for later silvicultural operations and the reactions of Scots pine seedlings to early cleaning performed in a certain age to a certain density in diverse forest landscapes.

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Supplementary files

S1.pdf; Uprooting device (P25_v1) attached to harvester (Photo: Heidi Hallongren), available at http://dx.doi.org/10.14214/sf.1514.