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SHORT COMMUNICATION

Productivity of a single-grip harvester in a beech dominated stand: a case-study under Bavarian conditions

Eric R. Labelle, Johannes Windisch and Philipp Gloning

Forest Operations, Department of Ecology and Ecosystem Management, Technische Universität München, Freising, Germany

ABSTRACT

Forest conversion from spruce dominated forests to close-to-nature stands with considerable proportion of deciduous tree species is of high importance in Germany. During mechanized harvesting operations, the complex tree architecture and high wood density of deciduous tree species, in particular of beech, pose a challenge during the processing phase. Usually more powerful machinery is required than for softwood stands of comparable age and tree dimensions. This pilot-study assessed the productivity of a TimberPro 620-E single-grip harvester with a LogMax 7000C harvesting head in a mature mixed-wood stand located in southern Germany. A total of 82 trees previously inventoried were harvested using one of two silvicultural treatments (clear-cut or selective-cut). A conventional time and motion study was performed using a hand-held computer on the selected trees that were harvested. Results demonstrated considerable differences in percent distribution of the harvesting related work cycle elements between the two tested silvicultural treatments, particularly with machine movement. Based on single-tree recovered volume estimations, average harvesting productivity during the clear-cut was 31% higher for spruce compared to beech trees. During the selective-cut, average harvesting productivity was 33.9 m^3/PMH_0 for spruce compared to 23.4 m^3/PMH_0 for beech, thus indicating a 45% higher productivity in spruce recorded during the pilot study.

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Mechanized operations; spruce; hardwoods; selective-cut; clear-cut

Introduction

The use and associated productivity of machines during ground-based forest operations has been well documented, particularly in softwood stands. In Germany, single-grip harvesters capable of felling, delimbing, and bucking stems into different assortments have been the preferred machine in softwood mechanized forest operations. However, with the advent of a higher proportion of forest stands being managed in a close-to-nature regime, the distribution and frequency of deciduous trees are increasing. Due to their higher wood density and generally more complicated stem and crown architecture, deciduous trees can present more pronounced challenges compared to softwood trees, in particular when dealing with fully-mechanized harvesting systems. When using a single-grip harvester, trees of larger diameter often require a back-cut before the head is repositioned at the base of the tree in order to complete the felling. Aside from this technique, most of the challenges in mechanized deciduous operations are linked to the processing phase where trees are delimbed and bucked to size. During this work element, large branches and complex tree crowns can considerably reduce harvesting productivity, especially if product recovery is of high importance (Spinelli et al. 2011; Kleinschmit 2015; Labelle et al. 2016). Despite the growing shares of deciduous trees in German forests, published literature on how these tree species can affect harvesting productivity remains scarce, particularly when considering large single-stem tree volume as commonly found in beech (*Fagus sylvatica* L.) dominated stands. A recent study by Labelle et al. (2018) reported that single-grip harvesters are indeed capable of handling and processing large-diameter beech trees and that pre-notching particularly large diameter trees with chain saws can help to achieve higher overall productivity. However, this multi-site study was only performed in stands subjected to selective-cuts. With a high frequency of wind throws occurring, and thus often creating considerable patches of downed trees, further information of high removal rate silviculture on harvesting productivity was needed.

A pilot study was therefore conducted to address the following research objective.

i) Quantify the effects of tree species (beech and spruce) and silvicultural treatments (clear-cut and selective-cut) on harvesting productivity of a single-grip harvester.

Results and experiences learned throughout the study will be used to formulate a larger scale project aimed at evaluating the influence of deciduous tree characteristics on fully-mechanized forest operations performed in a central European context.

Materials and methods

Stand description

The harvest block was near the town of Titting (48° 9.851′N and 11° 2.682′E) in the federal state of Bavaria, Germany. It was a 4.5 ha mixed-wood stand consisting of common beech, Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* L.), with a species composition of 65%, 30%, and 5%, respectively. The stand was of mixed age varying between 75 and 110 years with an average age of 90 years and with an estimated standing volume of 280 m^3/ha. The terrain topography was generally gentle with less than 5% slope.

CONTACT Eric R. Labelle eric.labelle@tum.de Forest Operations, Department of Ecology and Ecosystem Management, Technische Universität München, Hans-Carl-von-Carlowitz-Platz 2, Freising D-85354, Germany

Machine specifications

Operations were performed with a 2005 TimberPro 620-E six-wheel single-grip harvester equipped with a LogMax 7000C harvesting head mounted on a 9.6 m long telescopic boom. The harvesting head had a feed force of 42.1 kN at a speed of 5.2 m/s (LogMax 2016). The bar length was 900 mm with a maximum cut capacity of 750 mm. Harvesting was performed during regularly scheduled forest operations using a single and experienced operator working only during day shifts.

Layout and field data collection

The harvest block was divided into two plots adjacent to one another to assess the influence of two silvicultural treatments on the productivity of the harvester. The first plot (A) had an area of 0.5 ha and was subjected to a clear-cut where all merchantable trees were to be harvested. The second plot (B) had a size of 4 ha and was treated with a selective-cut, where trees to be harvested were selected by the district forester following the group selection method. Table 1 shows the allowed assortments. Spacing between the pre-existing machine operating trails (centerline to centerline) was 30 m.

Before operation commenced, inventory of the 52 pre-selected trees in plot B was performed where species and measurements of tree diameter at breast height (dbh) with cm accuracy and heights with 0.5 m accuracy were recorded and entered into a hand-held computer. Each of the trees inventoried were also marked with an individual number painted on the bark on two sides of the tree for future identification. Due to time and logistics restrictions, only tree dbh was measured for the 30 trees to be harvested in plot A, while tree heights were later calculated based on species dependent functions derived from the measurements from plot B (Equations (1) and (2)):

$$h_{beech} = 5.5221x^{0.4169} \tag{1}$$

$$h_{spruce} = 7.5881x^{0.3501} \tag{2}$$

where h is the species specific tree height in meters and x is the dbh in cm

Throughout harvesting operations, continuous time and motion measurements were collected for every study tree (only those that were completely handled by the harvester) using a hand-held computer equipped with the software UMT Plus.

Data analysis

Standing merchantable volume per harvested tree was then calculated using species dependent stem volume equations (Equation (3) for beech and Equation (4) for spruce) developed by Zianis et al. (2005), with dbh, and height of individual trees as input. A similar calculation was performed for trees in the clear-cut (Plot A), while using the calculated heights obtained from the species specific regression functions between tree dbh and height of trees in plot B.

$$V_{beech} = \left[\left(16.641 \times 10^{-3} + 0.72179 \times 10^{-3} \times D \times H^2 + 0.00252 \times 10^{-3} \times D^3\right)/1000\right] \tag{3}$$

$$V_{spruce} = \left[\left(\left(D^2/100 \times \pi\right)/4\right) \times (H \times 0.45)\right)/1000\right] \tag{4}$$

where: V = single tree volume (m^3ob)
D = diameter at breast height (cm)
H = height of tree (dm)

Using standing merchantable volumes as basis for harvesting productivity could over-estimate results since not the entirety of standing merchantable volume is recoverable during forest operations. To present more realistic numbers, we applied species dependent tree volume reduction factors of 15% for spruce and 35% for beech to convert from estimated standing merchantable volume to recovered volume. These reduction factors were obtained from the Bavarian State Forest who manage all Bavarian public forests and represent average operational conditions. All harvesting productivity results herewith were calculated with the estimated recovered volumes.

During the time and motion study, individual work cycles were divided into the following elements: *boom-out; felling; processing; manipulation; moving; operational and non-operational delays*, which are further described in Labelle et al. (2018). The complete time and motion dataset was used to compute a standardized duration for work elements that were not common to all trees, such as machine movement (*moving*) and *manipulation* and the mean values were set per tree. All data presented in this manuscript focuses on productive machine hours with the use of PMH_0 indicating that all non-productive time (operational and non-operational delays) were removed from analysis. Once the data was organized for analysis, one-way ANOVA's were performed in Minitab 17 to determine if the dependent variables (harvesting productivity, duration of work cycle elements) were influenced by silvicultural treatment, tree species, tree dbh, or tree volume. Considering the inherent influence of a priori tree volume on harvesting productivity, a multiple regression model was also performed in SPSS Statistics 24 with harvesting productivity selected as the dependent variable and silvicultural treatment, tree species, and standing tree volume set as predictors. The significance level of 0.05 was used in all statistical tests.

Table 1. Product assortments with required lengths and top diameters.

Tree species	Assortment and length (m)	Small-end diameter (cm without bark)
Spruce	Saw log (5)	≥12
	Saw log (4)	≥12
	Pulpwood (2)	≥7
Beech	Industrial wood (4)	≥8
	Industrial long wood (> 4)	≥25

Results and discussion

Description of harvested trees

Despite not showing any statistical difference, the average dbh of spruce trees (34.3 cm) in the clear-cut treatment was 15% higher than for beech trees (29.7 cm; Table 2). However, a statistical difference in dbh (p = 0.036) was detected between species in the selective-cut, where spruce trees had on average a 13% larger dbh. Even though the average diameter of spruce trees was noticeably higher than

Table 2. General information from harvested trees along with one-way ANOVA results (different superscript letters indicate a statistical difference at alpha = 0.05 between species within the same treatment).

Treatment	Species (sample size)	DBH of harvested trees [cm]		Estimated standing merchantable volume [m^3/tree]†		Estimated recovered volume [m^3/tree]‡	
		Average	Standard error	Average	Standard error	Average	Standard error
Clear-cut (Plot A)	Spruce (15)	34.3^a	2.27	1.18^a	0.178	1.01^a	0.151
	Beech (15)	29.7^a	2.15	1.13^a	0.157	0.74^a	0.102
Selective-cut (Plot B)	Spruce (22)	43.6^a	1.96	2.03^a	0.197	1.73^a	0.167
	Beech (30)	38.6^b	1.42	2.11^a	0.153	1.37^a	0.100
Total	All (82)	37.5	1.16	1.74	0.100	1.28	0.076

† Estimated standing merchantable volume derived from species dependent stem volume equations.
‡ Estimated recovered volume after applying species dependent reduction factors from the standing merchantable volume (35% reduction for beech and 15% reduction for spruce).

that for the beech trees, estimated standing merchantable volumes, as expressed in m^3/tree, were very similar between species but varied greatly between silvicultural treatments.

When applying the species dependent volume reduction factors to obtain estimated recovered volumes, differences between species within a respective silvicultural treatment were much higher. Clearly, beech trees observed the highest volume reductions due to the applied reduction factor and now showed 36% and 26% reduction in volume compared to spruce for clear-cut and selective-cut treatments, respectively.

Distribution and duration of work cycle elements

The highest time percentage was linked to the *processing* element for both treatments and species tested (Figure 1). For beech trees, approx. 64% of the average cycle time was attributed to *processing*. This result was in line with results from Labelle et al. (2016), where the element *processing* accounted for an average of 71% of the entire cycle time during a high removal silvicultural treatment in a sugar maple (*Acer saccharum*) dominated stand harvested with a Landrich single-grip harvester in eastern Canada. When considering only spruce trees, about 45% of the average work cycle was associated with *processing*. This result is comparable with findings from Dvořák (2010) who reported that on average 51% of the cycle time of a Ponsse Ergo single-grip harvester, for spruce trees with an average volume of 1.17 m^3/tree, was related to *processing*. In the current study, differences in the percent distribution and ranking of time consumption per element begin to occur for the remaining work elements depending on silvicultural treatment or species harvested. A higher percentage was linked to the *moving* element for both species during the selective-cut (above 25% of total productive time) as compared to the clear-cut (below 13% of total productive time).

As the percent distribution of average work cycle time varied between treatments and species, it was also of interest to compare the distribution of work cycle elements in terms of average duration (seconds; Figure 2(a)) and also average duration in relation to the estimated recovered volume per tree (s/m^3; Figure 2(b)). As expected, the most time consuming work cycle element regardless of species and treatment was *processing*. For each respective species, the average *processing* time was longer in the selective-cut compared to the clear-cut. The main reason for this was the higher average diameter of trees harvested in the selective-cut (41 cm) compared to clear-cut (32 cm). Based on a Kruskal-Wallis test, a statistical difference (p = 0.018) in average *processing* time per tree was also observed between beech (110 s) and spruce (78 s) in the selective-cut treatment. With an increasing mean tree dbh, beech trees often exhibit complex crown architecture and average branch diameter increases, both combining to increase time required for *processing* when dealing with fully-mechanized systems.

Mean machine *moving* time between adjacent trees was longer for spruce trees (11.7 s) compared to beech trees (2.9 s) in the clear-cut. Due to the lower removal rate in the selective-cut treatment, machine *moving* was considerably higher for both species compared to the clear-cut. When combining results from both species, average machine *moving* per tree was increased by a factor of 7 (avg. of 7 s/tree in clear-cut and 55 s/tree in selective-cut) between clear-cut and selective-cut treatments.

The average delay-free cycle time in the clear-cut treatment was 96 s for spruce and 106 s for beech, for a combined average (both species) of 101 s/cycle (Figure 2(a)). Under the selective-cut treatment, average delay-free cycle time equalled 179 s for spruce and 216 s for beech.

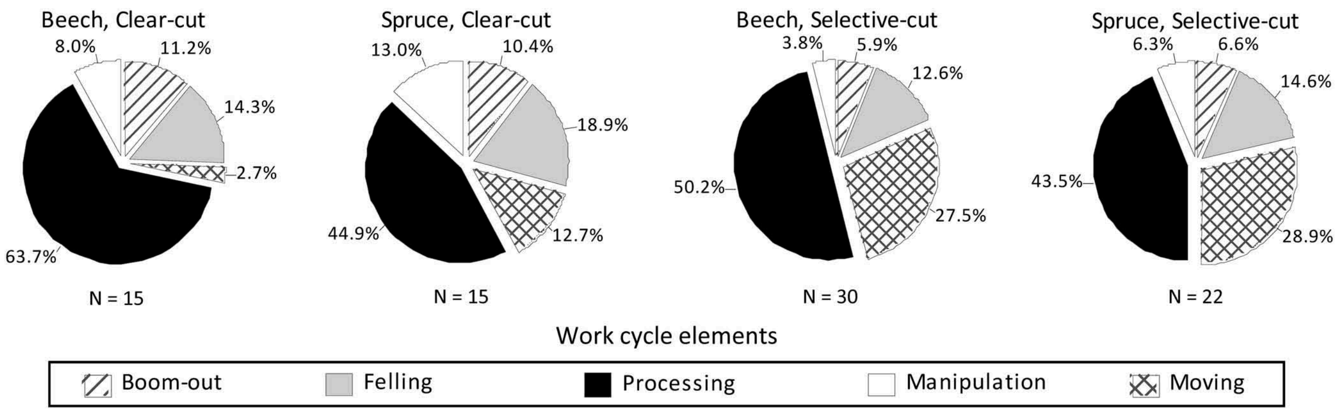

Figure 1. Average percent distribution of productive work cycle elements. Non-productive times were removed from analysis.

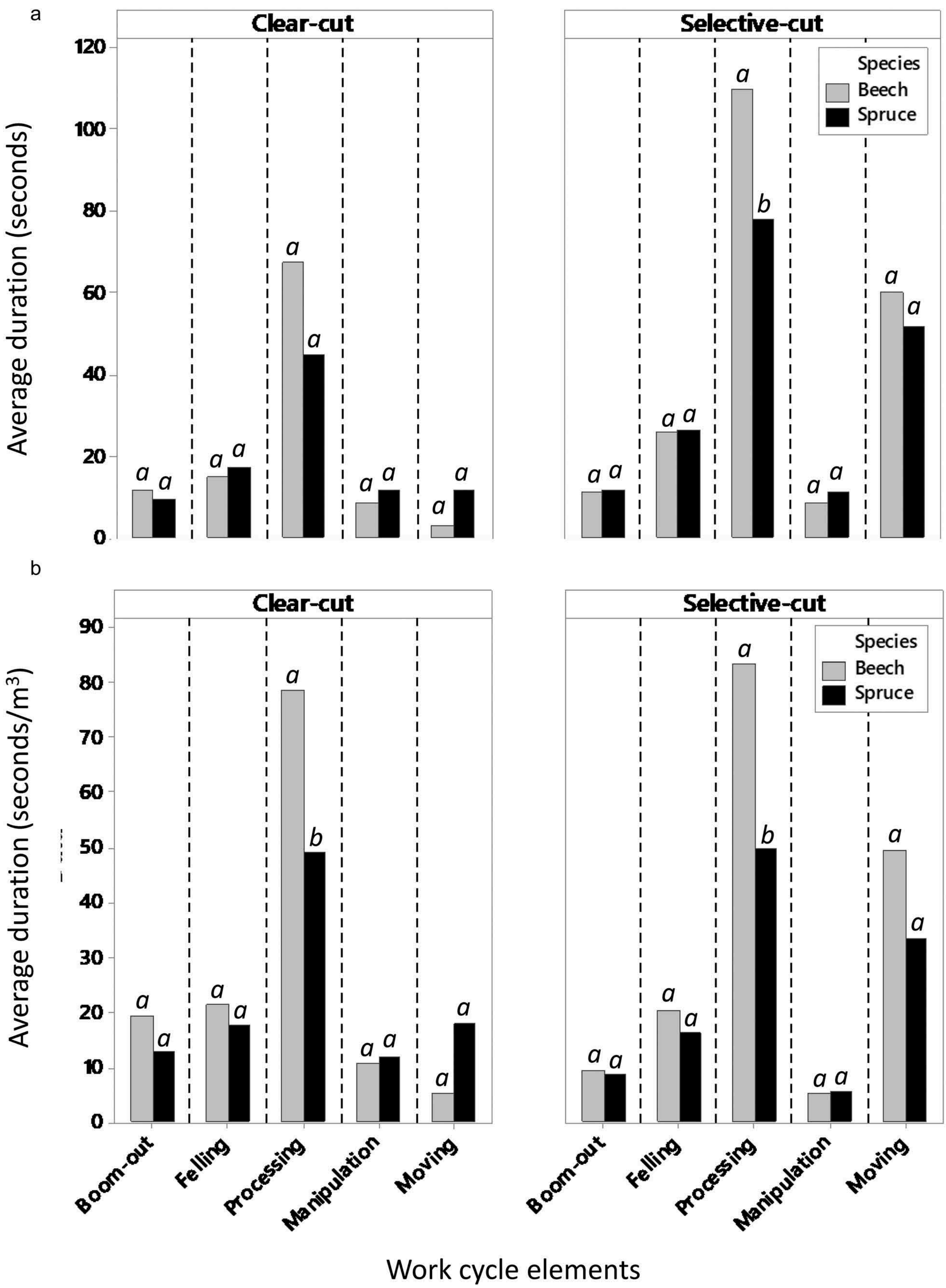

Figure 2. (a) Average duration of each work cycle element. (b) Average duration of each work cycle element in relation to the estimated recovered volume per tree (seconds/m^3) presented by silvicultural treatment and species. Different letters indicate a statistical difference at alpha = 0.05 between species within the same treatment and work cycle element based on one-way ANOVAs.

The percent distribution and duration of work cycle elements presented thus far were influenced by tree species and silvicultural treatment performed. However, in addition to these two factors, the volume of individual trees should be taken into consideration. When considering the estimated recovered volume per tree, average work cycle elements exhibited very similar trends, expressed in seconds/m^3, to those discussed above (Figure 2(b)). The work cycle element *processing* again

Table 3. Average harvesting productivity as a function of silvicultural treatment and species along with one-way ANOVA results (different superscript letters indicate a statistical difference at alpha = 0.05 between species within the same treatment).

Treatment	Species	Number of trees	Harvesting productivity [m^3/PMH_0][†] Average	Standard error
Clear-cut (Plot A)	Spruce	15	36.0^a	2.89
	Beech	15	27.5^b	1.71
Selective-cut (Plot B)	Spruce	22	33.9^a	2.48
	Beech	30	23.4^b	1.45
Total	All	82	29.3	1.18

† Based on estimated recovered volume.

demonstrated the most noticeable differences between the two tested species. In the clear-cut treatment, *processing* consumed on average 60% more time for beech than for spruce, with a statistical difference (p = 0.008) between both species. For trees harvested in the selective-cut, the element *processing* was on average 67% higher for beech than spruce with again a statistical difference (p = 0.000) between the group means.

Harvesting productivity

Aside from removing any delays (operational and non-operational), results presented thus far contained all original time and motion data. However, since not all work cycle elements were common for every tree harvested, we determined standardized times for *moving* and *manipulation* and applied those on a per tree basis. From this point forward, all results will account for the above-mentioned time standardization. Irrespective of silvicultural treatment, harvesting productivity was statistically higher for spruce than beech (Table 3). Within the clear-cut treatment, average harvesting productivity was 31% higher (36.0 m^3/PMH_0) for spruce compared to beech (27.5 m^3/PMH_0), whereas this difference was increased to 45% in the selective-cut. To assess the influence of silvicultural treatment on harvesting productivity, one-way ANOVA's were performed between treatments for spruce and beech with no statistical differences detected (p = 0.573 for spruce and p = 0.092 for beech). An important caveat is the a priori difference in average tree size between species within a respective silvicultural treatment.

To consider the a priori difference in average standing tree volume between species, a multiple regression was performed using standing tree volume as covariate. Results of the regression model supported the well know piece-size/productivity relationship and attributed 48.3% of the harvesting productivity variation to the initial standing volume of trees, 14.5% to tree species (beech and spruce) and only 6.2% to the factor treatment (clear-cut and selective-cut). The remaining 30% of the variation in harvesting productivity could not be explained by the factors used in the model.

Through a regression analysis, Pausch (2002) found a harvesting productivity of 37 m^3/PMH_{15} (44.4 m^3/PMH_0) for a selective-cut of spruce at a tree volume of 1.6 m^3 using a Timberjack 1270A equipped with a Timberjack 746B harvesting head. Pausch (2002) also investigated the productivity of the same machine in a beech selective-cut while considering tree form. When focusing on trees with a straight stem, productivity was approx. 12 $m^3/PMH_{12.5}$ (14.4 m^3/PMH_0) lower for beech trees compared to spruce and this difference increased to 20 $m^3/PMH_{12.5}$ (24 m^3/PMH_0) when considering forked trees.

The average harvesting productivity for all beech trees was found to be 24.7 m^3/PMH_0. This result remains similar to findings from Labelle et al. (2018) who reported average harvesting productivity of 29.1 m^3/PMH_0 for a Rottne H20 single-grip harvester operated in a beech stand with an average dbh of 35.6 cm and individual tree volume of 1.7 m^3/tree (outside bark).

When presenting the harvesting productivity (m^3/PMH_0) of individual trees in function of tree dbh and adding a second order polynomial trendline, results from both species in the clear-cut treatment illustrate a common relationship where machine productivity increases with an increase in tree diameter until the optimum productivity is reached and then decreases with a further increase in diameter (Visser and Spinelli 2012; Figure 3(a)). In the clear-cut treatment, the sweet-spot of the tested TimberPro harvester varied depending on tree species with the highest peak productivities associated with a dbh of approx. 42 cm and 29 cm for spruce and beech, respectively. A higher harvesting productivity in spruce compared to beech was anticipated because of (i) larger average dbh, (ii) less complicated crown architecture and smaller average branch diameter (based on field observations), and (iii) average of 1.5 m taller trees for spruce compared to beech.

During the selective-cut, harvesting productivity results were more sporadic, particularly with respect to beech. In this silvicultural treatment, the data collected did not provide the same noticeable sweet-spot trend as was present in data originating from the clear-cut. In fact, when plotting a second order polynomial trendline, which yielded a respectable R^2 (0.75) for spruce, productivity increased with increasing tree dbh until the maximum diameter tested of 60 cm. One possible explanation for the different shapes of the two spruce curves (clear-cut and selective-cut) could be linked to the low number of samples above 45 cm dbh in the clear-cut plot. Concerning beech trees harvested in the selective-cut, the trendline applied had a very poor coefficient of determination of 0.18. The higher variability in harvesting productivity for beech compared to spruce is not uncommon because of the known influences of tree form and branch size on harvesting productivity (Labelle et al. 2016).

A strong and well-documented positive relationship exists between tree dbh and its corresponding piece size (m^3/tree) (Spinelli et al. 2010). Very similar trends as shown in Figure 3(a) were observed for both species, in particular within the clear-cut treatment (Figure 3(b)). The only noteworthy difference was for the beech trees harvested within the selective-cut treatment, where the slope of the trendline was more pronounced with an increase in estimated recovered volume per tree. However, because of the relatively low sample size, one should be careful not to extract too much from this tendency.

Study limitations

This pilot study served as a first step to understand the potential influence in harvesting productivity between beech and spruce trees. Authors acknowledge the small sample size but due to the nature of the live operations, the information presented was the maximum that could be collected. Ideally, targeting a stand where similar standing volume per tree between tree species would have been preferred and allowed for a clearer comparison

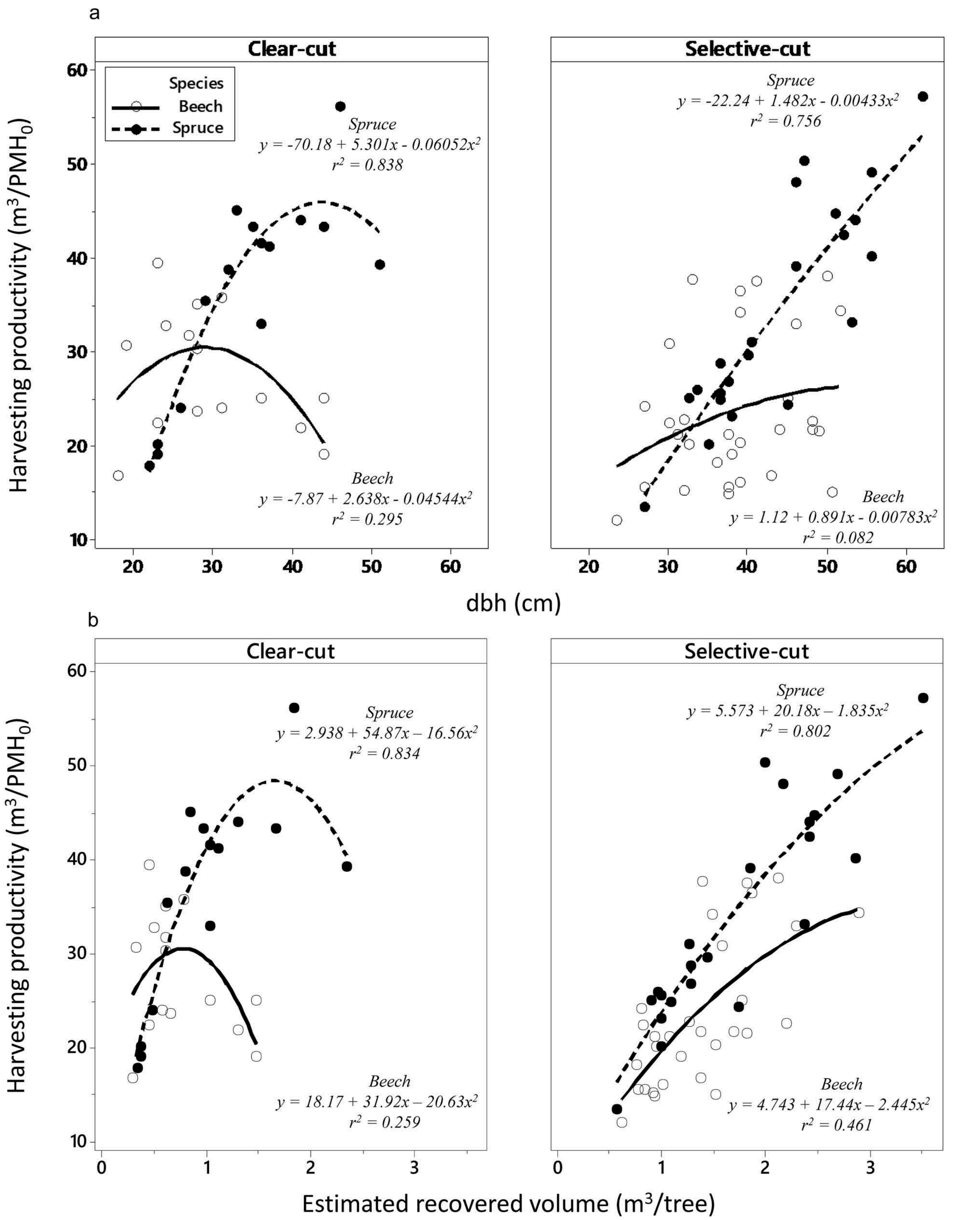

Figure 3. Harvesting productivity data for beech and spruce trees in function of (a) dbh for clear-cut and selective-cut and (b) estimated recovered volume (m^3/tree) along with second order polynomial functions and associated coefficients of determination.

in harvesting productivity between the tested species and silvicultural treatments. However, because of the high variability in tree attributes, in particular size, such stands offering similar sized spruce and beech trees could not be found within the window of operations given. Species dependent volume reduction factors presented in this article were not arbitrarily set but were derived from multi-year operational monitoring of harvesting operations performed on public forests in Bavaria. Nevertheless, caution should be used when considering volume recovery as these might change with stand and tree conditions, as well as with products expected from the operations.

Conclusions

This pilot study investigated the influence of different tree species (beech and spruce) and silvicultural treatments (clear-cut and selective-cut) on the harvesting productivity of a TimberPro 620-E single-grip harvester taken to represent the general pool of large capacity single-grip harvesters. Despite the limited sample size and differences in average tree size, interesting preliminary findings were discovered that can be used as the basis for an expanded project. Average harvesting productivities during the selective-cut (most frequently used silvicultural treatment in Germany) were 33.9 m^3/PMH_0 for spruce compared to 23.4 m^3/PMH_0 for beech, thus indicating a 45% higher productivity for spruce trees within the pilot study.

For safety and productivity reasons and because more forest cover has been and will most likely continue to be converted to mixed-wood stands, it is highly probable that the use of single-grip harvesters will increase to allow the mechanization of a higher proportion of deciduous species. Additional research and insight on determining which tree related characteristics influence mechanized harvesting productivity the most in mixed-wood or hardwood stands is warranted.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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