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SHORT COMMUNICATION

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High-pruning of European beech (*Fagus sylvatica* L.) and pedunculate oak (*Quercus robur* L.): work efficiency for target pruning as a function of tree species, pruning height, branch characteristics, pole saw type and operator

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ABSTRACT

The objective of this study was to establish an operational model of productive work time per tree (work efficiency) for high-pruning of young European beech and pedunculate oak depending on tree species, pruning height, branch characteristics, pole saw type and operator. The final model included all of these independent variables with branch characteristics specified in terms of number of live branches and cross-sectional area of the thickest branch at the cut. Work time increased with increasing values of each of the three numeric variables. For a given pruning height the size of the largest branch was for all practical purposes more influential than the number of live branches. Beech took 28% longer to prune than oak. The German Ergo-Schnitt saw was 21% slower than the Japanese Silky Hayauchi saw. The variation in worker performance within our study was larger than that attributed to tree species and pruning equipment.

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High-pruning; bottom-up pruning; target pruning; pole saw; beech; oak; work efficiency

Introduction

Beech and oak species in Europe comprise more than 20% of the forest area stocked with broadleaved trees across EU and some associated countries (Hemery 2008). They consequently represent a substantial potential for timber production. The area of European beech (*Fagus sylvatica* L.) has been estimated at 120,000 km^2 and timber producing oak species, including pedunculate oak (*Quercus robur* L., 49,000 km^2), sessile oak (*Q. petraea* (Matt.) Liebl., 38,000 km^2), downy oak (*Q. pubescens* Willd., 39,000 km^2) and some warm temperate oaks (> 36,000 km^2), account for around 150,000 km^2.

For beech and oak, large quantities of timber are available at relatively low prices as compared to less common hardwood species. Nevertheless, silvicultural interventions to improve wood quality may be profitable if they result in an increased proportion of high- or premium-quality timber (Wilhelm and Rieger 2013).

High-pruning in young stands could help to improve timber quality substantially, especially in heavily thinned stands with thick branches, but it requires a high input of labour. The most common method for pruning of young hardwood stands is by pole saw, i.e. using a hand saw mounted on an extension pole. In this paper we investigate and quantify the work time needed for manual high-pruning of European beech and pedunculate oak.

The objective of the study was to establish an operational model of work efficiency (net or productive work time per tree) for target pruning of young beech and oak depending on pruning height, branch characteristics, pole saw type and operator. Our study was concerned only with bottom-up pruning and was carried out only for European beech and pedunculate oak. Due to similar wood properties within each genus, we believe that the resulting model is valid also for other species of beech and oak.

Material, methods and terminology

The work study for high-pruning of beech and oak was conducted during 2009, 2011 and 2012 in four thinning experiments in Denmark. The experiments include two sites for European beech (experiments no. 1416 in Boller Upper Forest and no. 1417 in Rold Forest, both located near the city of Horsens) and two sites for pedunculate oak (experiments no. 1516 in Haslev Orned near Haslev and no. 1517 in Brendstrup Forest near Aarhus).

The pruning was carried out to install long-term experiments investigating the influence of thinning and pruning on the growth and stem quality of beech and oak. The work study was conducted within the framework set by the design of the thinning experiments and therefore included severe reductions in crown length, the pruning of overly thick branches and the creation of overly large pruning wounds that may not be recommended for use in operational forestry.

Based on guidelines by the International Union of Forest Research Organizations (IUFRO) (Björheden 1995) the work study may be specified in terms of work task (defining pruning and the pruning method), conditions of work (stand characteristics and weather conditions), work object

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(pruning height and branch characteristics), study objects (pruning equipment and operators) and statistical design. In the sections below we outline each of these. We also present the method of work measurement and the statistical methods used to analyse the observations. Pruning was conducted during full work days, so the length of the tested pruning periods were up to 8 h and included normal breaks for meals and maintenance of equipment.

Pruning and pruning method

In line with agreed forestry terminology (Ford-Robertson 1971; Helms 1998) the work task high-pruning may be defined as the removal of branches from a standing tree above a man's reach. High-pruning may also involve singling of forks, i.e. the removal of superfluous multiple stems. In the context of this investigation the objective of pruning was to improve the stem quality of pre-selected potential future crop trees up to a certain height.

Our study was concerned only with bottom-up pruning (removing all branches from below to a certain height above ground level) and comprised manual high-pruning using a hand saw mounted on an extension pole (the equipment is further specified below). Pole saw pruning may be performed as target pruning or close-cut (flush) pruning (Figure 1). Target pruning is the most commonly used method for forest trees as well as for street, park and landscape trees (Kerr and Evans 1993; Dujesiefken and Stobbe 2002; O'Hara 2007; Wilhelm and Rieger 2013). Our study focused on this method.

With target pruning the branch is cut immediately outside the branch collar (Figure 1). The cut was initiated on the upper side of the branch close to the stem and followed the edge of the intersection of the branch and the branch collar, using the usually visible transition line as a sighting target for the cut (hence the name of the method). The instruction was to leave the bark of the branch collar undamaged.

Large or heavy branches were cut in two operations to avoid unintended branch stubs and bark stripping on the stem. The initial cut was located well outside the branch collar to leave a stub that was subsequently pruned according to the prescriptions.

Stand characteristics

The pruning of beech was performed on pre-selected potential future crop trees in six heavily thinned plots of experiments 1416 and 1417. Both stands originate from natural regeneration that germinated mainly in 1984.

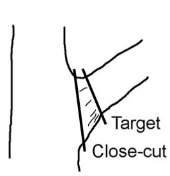

Figure 1. Natural target and close-cut (flush) pruning. With target pruning the branch is cut immediately outside the branch collar using the transition line as a sighting target for the cut. With close-cut or flush pruning, the branch is cut parallel to the stem close to the stem periphery (but not quite flush).

In 1998 (age = 14 years, stand top height ≈ 2.5 m) all six plots were thinned by mulching in two perpendicular directions, leaving remaining trees in evenly dispersed squares of approximately 1 m^2 in a type of chequerboard pattern. The tractor mulching treatment removed an entire 1–2 m swath of young beech trees both transversally and longitudinally through the stand. Transversal mulching left alternating denuded and stocked strips of beech, while subsequent longitudinal mulching created a type of chequerboard pattern of disconnected, fully stocked 1-m^2 squares of beech. The 1-m^2 squares were still fully stocked at age 14 years and remained so until age 18–19 years. In summary, stand density was reduced from 125,000 to 12,500 trees ha^{-1}, but remained unchanged in the approximately 800 1-m^2-squares ha^{-1}. In 2002 (1416, age = 18 years) or 2003 (1417, age = 19 years) one potential crop tree was selected in each 1-m^2-square and all other trees were removed by thinning (using a brush cutter).

In 2003 approximately one third of the remaining trees (average total height = 6.12 m) were pruned to an average height of 3.17 m (range: 1.46–4.30 m). In 2009 (age = 25 years) three plots were thinned to a residual stem number of approximately 200 ha^{-1} and in all six plots a similar number of trees were pruned or re-pruned.

The pruning of oak was performed on pre-selected potential future crop trees in four heavily thinned plots of experiments 1516 and 1517. The stand including 1516 originates from a sowing of acorns in 1991 on a meadow formerly used as grassland. The two stands including 1517 originate from a planting of 3-year transplants in 1993 on former agricultural land.

All four plots were thinned selectively to a residual stem number of 1000 ha^{-1} in spring 2002 (1516, age = 11 years) or autumn 2003 (1517, age = 14 years). In 2011 potential future crop trees were identified in each plot (approx. 175 ha^{-1} in three plots and 115 ha^{-1} in one plot) and subsequently pruned. Some of these were considered reserve trees and pruned less than the main crop trees. In 2012 twenty additional trees were pruned in experiment 1516 to provide a more balanced data set for one of the pruning operators.

The potential future crop trees for pruning were selected based on criteria of a regular spatial distribution, the absence of forking below 6 m, a straight and vertical stem, a healthy and symmetric crown, absence of epicormic branches, no signs of spiral grain and the absence of other visible stem defects.

A total of 52 beech trees and 136 oak trees were included in the work study (Table 1). All were target pruned. In addition to these, and as part of another pruning experiment, one operator flush pruned 32 oak trees. These were not included in the work time study we present here.

During the analyses, one observation of oak was excluded as an outlier (more information below). In the final data set, 13.5% of the beech trees had a *dbh* of less than any of the oaks (10.2 cm), and 17.8% of the oak trees had a *dbh* of more than any of the beeches (17.1 cm).

Weather conditions

Beech was pruned during June and August 2009. During work days the weather was generally sunny with temperatures

Table 1. Stand, tree, branch and pruning characteristics (mean, minimum and maximum values of key variables). Legend: *dbh* = stem diameter at breast height, h = total tree height, n_b = number of live branches n_d = number of dead branches, n_e = number of epicormic branches, n_n = , number of nuisance cuts = $n_d + n_e$, d_h = horizontal over-bark branch diameter (at the cut), d_v = vertical over-bark branch diameter (at the cut), $a_t = \pi \cdot d_h \cdot d_v/4$, l_p = pruned height interval or pruning length (distance from lowest live or dead branch before pruning to lowest remaining branch after pruning), h_p = pruning height (height above ground level of the lowest remaining, live branch).

	Beech (n = 52)				Oak (n = 135)			
Variable	Mean	Median	Min	Max	Mean	Median	Min	Max
dbh (cm)	11.86	11.75	3.5	17.1	15.39	15.30	10.2	21.5
h (m)	9.70	9.70	7.60	11.70	10.91	10.90	8.15	13.80
n_b	14.4	14.0	8.0	22.0	6.3	6.0	1.0	24.0
n_d	0.0	0.0	0.0	0.0	10.4	10.0	1.0	29.0
n_e	22.1	22.0	4.0	42.0	3.2	0.0	0.0	32.0
n_n	22.1	22.0	4.0	42.0	13.6	11.0	1.0	53.0
d_h (cm)	6.9	6.7	3.1	12.9	7.2	6.8	1.8	17.4
d_v (cm)	9.4	9.5	3.7	23.0	10.3	10.1	3.0	28.0
a_t (cm^2)	53.1	48.8	9.0	138.3	61.4	56.8	5.0	178.4
l_p (m)	3.63	3.49	1.50	6.15	3.65	3.70	0.82	7.15
h_p (m)	6.18	6.41	3.05	6.95	5.75	5.93	2.97	8.52
$(n_b + n_d + n_e)/(h_p–l_p)$ (m^{-1})	10.36	9.78	5.4	18.1	5.55	5.13	1.3	16.4
$n_b/(h_p–l_p)$ (m^{-1})	4.25	3.90	2.1	9.3	1.73	1.68	0.2	4.3

around 15°C–20°C. Oak was pruned during March and April 2011 and supplementary trees during August 2012. During work days the weather was generally overcast or sunny with temperatures around 10°C–20°C.

Pruning height

To comply with the design of the thinning experiments most beech trees were pruned to a final pruning height of 6 m or more, but some test or reserve trees were pruned less (Table 2). To enlarge the range of observations for pruning height, while still complying with the design of the thinning experiments, a roughly equal number of oak trees was pruned to between 4 and 6 m or between 6 and 8 m, while some few were pruned either less or more (Table 2).

Following pruning, the height above ground level of the lowest remaining, live branch was measured for each individual tree. In the analysis, this variable was used as an indicator of pruning height (h_p; Table 1) although the true pruning height (i.e. the location of the highest cut) was always located below the lowest remaining, live branch.

Branch characteristics

When designing the study we believed that a combination of pruning height and some branch characteristics would rank among the most important and easily measured variables that correlate with productive work time. These include the number of branches, the cross-sectional area of the thickest branch at the cut and the location of the lowest branch (dead or alive).

Table 2. Distribution of pruned trees by pruning height (h_p, 1-m classes).

h_p (m)	Beech (%)	Oak (%)
2–3	0.0	0.7
3–4	5.8	5.2
4–5	1.9	12.6
5–6	5.8	34.8
6–7	86.5	40.8
7–8	0.0	3.7
8–9	0.0	2.2

All of these variables are relatively easy to assess in operational forestry, based on visual judgement or simple measurements of sample trees. More detailed measurements were considered, including the cross-sectional area of each branch and the location of branches along the stem (height above ground level), but these were overly expensive to measure.

In line with this, the measurement of branch characteristics for each tree (Table 1) included the number of pruned live branches (n_b), dead branches (n_d), epicormic branches (n_e), the horizontal and vertical over-bark diameters of the thickest pruned branch (d_h and d_v, respectively, measured at the cut) and the height above ground level of the lowest pruned branch (h_l).

The cross-sectional area of the thickest branch (a_t) was calculated as $a_t = \pi \cdot d_h \cdot d_v/4$ (assuming an approximately elliptical shape), and the pruned height interval or pruning length (l_p) was derived as $l_p = h_p – h_l$. Generally, dead branches and epicormic branches require little effort to prune, but may slow down the work process as they hinder saw positioning. For the analysis we lumped these together under the term nuisance cuts (n_n) and set $n_n = n_d + n_e$. The number of pruned live branches per metre of stem was calculated as $n_b/(h_p–h_l)$, and the total number of pruned branches (live, dead and epicormic) per metre of stem as $(n_b + n_d + n_e)/(h_p–h_l)$.

The size of the thickest branches ranged within the same order of magnitude for both species, but beech had more branches than oak (Table 1). The occurrence of some very thick branches is obviously due to early heavy thinning. Moreover, forks were singled on 16 beech trees and 16 oak trees. These were included among branch measurements.

Due to previous pruning six years earlier, no beech trees had any dead branches to prune. Nevertheless, the number of nuisance cuts for beech (i.e. epicormic branches) was generally substantially larger than for oak.

Pruning equipment

The pruning was performed using extension poles mounted with German Ergo-Schnitt or Japanese Silky Hayauchi saws. Both saws were manufactured from Japanese high-carbon steel. The saw blades were changed at regular intervals during the test, i.e. when the operator felt that this was needed to ensure optimal performance throughout.

The Ergo unit included an ERS390–8 saw (390 mm, labelled Shogun on the back) mounted on a round ERS490 glass-fibre pole with three sections (minimum length 2.33 m, maximum length 5.16 m, total operating weight 2.480 kg). The Silky unit included a 177–02 Hayauchi saw (390 mm) mounted on an oval 179–39 3-extension aluminium alloy pole with four sections (minimum length 2.44 m, maximum length 6.30 m, total operating weight 3.140 kg).

The Ergo saw was made from SK-5 steel (0.75%–0.85% C), had 8 teeth per 30 mm and a special position for every 5th tooth (kerf 2.0 mm, blade thickness 1.4 mm). All teeth were induction hardened. The Silky saw was made from hard-chrome plated SK-4 steel (0.9%–1.0% C) and had a 4-retsume teething (four rows of teeth) with 6.5 teeth per 30 mm (kerf 2.3 mm, blade thickness 1.5 mm). The teeth were not induction hardened (impulse hardened). Both saws had a lower sickle to undercut branches.

Operators

The pruning was performed by four workers or operators, all of which were males aged 25–35 years. All of the operators had a background in forestry and experience of manual forestry work, including pruning. All operators pruned some trees before the work study began to practice the work study procedure.

Statistical design

The statistical design of the work study was limited by requirements imposed by the thinning experiments in terms of number of trees available for work time study and was further limited by staff availability. Within these frames a roughly even distribution of pruning tools was attempted for each operator (Table 3). For each species, the trees were distributed randomly among operators.

Work measurements

Following the generally accepted IUFRO nomenclature for forest work study (Björheden 1995) we distinguish between productive (direct) and supportive (indirect) work time. From each of these, measures of work efficiency may be derived, in our case expressed as work time per tree.

Productive work time for pruning is the work time spent directly on the pruning of a tree (pruning *per se*), including sawing branches, positioning the pole saw, re-positioning the operator's headgear during pruning to reduce irritation from sawdust, sunlight or rain, assessing and re-assessing the situation, etc. We also refer to this as net work time.

Supportive work time is that portion of work time spent on activities performed to support pruning, but not directly adding to completion of the work task. This includes moving between trees (relocation), identifying the next tree to prune (planning), preparing and maintaining equipment (preparatory and service time).

This study is concerned only with net or productive work time. Other activities during the pruning operation were not quantified. Productive work time per tree (w) was measured with a stop watch using a full second as the base unit. Time keeping began when the operator was ready to prune the first branch (with the pole saw resting on the branch) and ended when the last branch had been sawn and the pole saw had been retracted.

The work study included a total of 187 trees.

Table 3. Distribution of pruned trees by tree species, pruning saw and operator in the final data set. Operators are identified by coded initials.

	Beech			Oak			
Operator	Ergo	Silky	Total	Ergo	Silky	Total	*Grand total*
AND	12	14	26	0	20	20	*46*
JON	0	17	17	24	39	63	*80*
MIK	0	0	0	17	15	32	*32*
NIE	7	2	9	12	8	20	*29*
Total	*19*	*33*	*52*	*53*	*82*	*135*	*187*

Statistical models

The objective was to quantify and express in an operational, statistical model the influences of tree species, saw type, operator, pruning height and branch characteristics on the productive work time for high-pruning of beech and oak. In addition to pruning height we tested pruning length as a predictor variable. The potential predictor variables based on branch characteristics included the number of pruned live branches, the number of nuisance cuts and the cross-sectional area of the thickest pruned branch. Saw type and operator were considered as class variables.

All statistical analyses were done using SAS version 9.2 (SAS Institute, Cary, NC, USA). Data were analysed and hypotheses were tested based on analyses of covariance. Based on inspection of residual plots, R^2 and transformation tests, logarithmic transformations of the candidate regression variables were found to perform better than no or alternative transformations.

To ensure that our model was easily calibrated even with few observations per combination of tree species, pole saw type and operator, and that predictions are readily understood, a fixed effect model was chosen. In mathematical terms, the full model may be specified as

$$\ln w_i = \mu + \alpha_k + \sum (\beta_j \ln X_{ij}) + \varepsilon_i$$

where w denotes productive work time per tree (work efficiency) for pruning, μ is the overall mean, α is the specific adjustment of the mean for each class variable (tree species, saw type and operator), β are coefficients, X is one of the five independent continuous variables (h_p, l_p, n_b, n_n and a_t), $\varepsilon \sim N(0,\sigma^2)$ are model residuals, subscript i identifies the tree (tree number), subscript j identifies the independent variable, and subscript k identifies the class variable.

Hypotheses testing for significant model terms was based on the usual F-test with $F_r = ((\mathrm{RSS}_r - \mathrm{RSS}_f)((\mathrm{df}_r - \mathrm{df}_f))/(\mathrm{RSS}_f/\mathrm{df}_f)$, where RSS denotes the residual sum of squares, df denotes degrees of freedom, and subscripts f and r refer to the full and the reduced model, respectively. If the hypothesis provides as good a model as the alternative, the F will be small. If the model is not adequate compared with the full model, then F will be large compared with the critical value of the $F_r(\mathrm{df}_r–\mathrm{df}_f,\mathrm{df}_f)$ distribution.

The model was iteratively reduced using a backward elimination process until all remaining variables were significant. The level of accepted significance was set at $P = 0.001$. Interaction terms were reduced before main factors. For simplicity, no three-factor or more complex interactions were considered during model development. The tests were based on the assumption of homogeneous variance and normal distribution of errors. These assumptions were justified by the log-transformed data, but not completely by the untransformed data.

Model performance was evaluated primarily on the basis of extensive analyses of residual plots. To reveal possible trends in model predictions and to evaluate the assumption of variance homogeneity, studentized residuals were plotted against predicted values and versus predictor variables, both in transformed and untransformed scales. Possible influential observations were identified using Cook's D statistic (one was identified and removed in the final analysis).

For prediction, the final model was transformed backwards and corrected for logarithmic bias (see, for example, Baskerville 1972; Newman 1993). This was done by adding $\mathrm{MS_e}/2$ to the intercept prior to backwards transformation ($\mathrm{MS_e}$ denotes the mean square error).

Results

The productive work time per tree (w) ranged from 170 to 1920 s for beech (mean = 775.8 s, $n = 52$) and from 40 to 2089 s for oak (mean = 626.2 s, $n = 135$). The productive work time depended on pruning height (h_p), the number of live branches to cut (n_b), the cross-sectional area of the thickest branch (a_t), tree species (beech or oak), saw type (Ergo or Silky) and operator. Pruning length (l_p) and the number of nuisance cuts (n_n) did not influence work time per tree. All two-factor interactions except $\ln n_b \times \ln h_p$ were statistically insignificant. Parameter estimates for the final model quantify the influence of each of these factors as well as the variation among operators involved in the study (Table 4).

Table 4. Parameter estimates in the final model of work efficiency (w) for pruning of beech and oak with ln w as dependent variable; $n = 187$, $R^2 = 0.790$, $\mathrm{MS_e} = 0.59348$. Measurement units: w in s·tree^{-1}, n_b is unitless, h_p in m, a_t in cm^2. The model can be considered valid for pruning heights of 3.0–8.5 m.

Variable	Estimate
Intercept	−0.9021
$\ln h_p$	2.9375
$\ln n_b$	1.4338
$\ln a_t$	0.5019
Adjustment by species	
Beech	0.2478
Oak	0.0000
Adjustment by saw	
Ergo	0.1868
Silky	0.0000
Adjustment by operator	
AND	−0.9330
JON	−0.3879
MIK	−0.4115
NIE	0.0000
Interactions	
$\ln n_b \times \ln h_p$	−0.6915

Work time increased with the numeric value of all tree mensurational variables. Work time for beech was $e^{0.2478}/e^0 = 1.281$ times or 28.1% larger than for oak, the Ergo saw was 20.5% slower than the Silky saw, and the fastest operator in this investigation used 39.4% of the work time used by the slowest worker. The only significant interaction term was negative, indicating a marginally faster pruning than predicted by the main factors when both pruning height and the number of branches increase.

Throughout the range of calibration data, the model performed well with balanced studentized residuals. This holds for tree species (mean value of studentized residual, beech: 0.00255, oak: −0.00067) as well as operators (range of mean values of studentized residuals for operators: −0.00020 to 0.00028).

Discussion

Our model of productive work time per tree (work efficiency) for high-pruning of beech and oak included a range of variables reflecting the skills and strength needed for the work. In addition to tree species and saw type, the final model included pruning height, the number of branches and their (maximum) size. Pruning length and the number of nuisance cuts (dead branches and epicormic branches) had no influence on work time. When using the model for prediction of work time per tree, it should be corrected for logarithmic bias by adding $\mathrm{MS_e}/2$ to the intercept prior to backwards transformation.

Comparing work efficiency across species

Oak was faster to prune than beech and for a given pruning height, for example 6.5 m, the size of the thickest branch was for all practical purposes more influential than the number of branches to cut, within the range of variation in branch characteristics present in our study (Figure 2). We can identify two possible reasons for this: a difference in basic density of beech and oak branches or a higher moisture content in beech than in oak branches because beech was pruned during summer and oak was pruned mainly during spring.

The basic density of beech and oak wood is quite similar (Moltesen 1988) and the overall basic density of whole beech branches is similar to that of the stem (Skovsgaard and Nord-Larsen 2012). We therefore hypothesise that the slower pruning of beech could be due to a larger proportion of reaction (tension) wood on the upper side of beech branches near the stem. We did not measure this characteristic as part of the study.

For any given diameter or cross-sectional area of the branch, beech branches may have been heavier than those of oak because beech was carrying full foliage while most of the oak trees had not yet flushed. We believe that heavier branches generally lead to faster pruning because the cut is more easily kept open during sawing, but the higher moisture

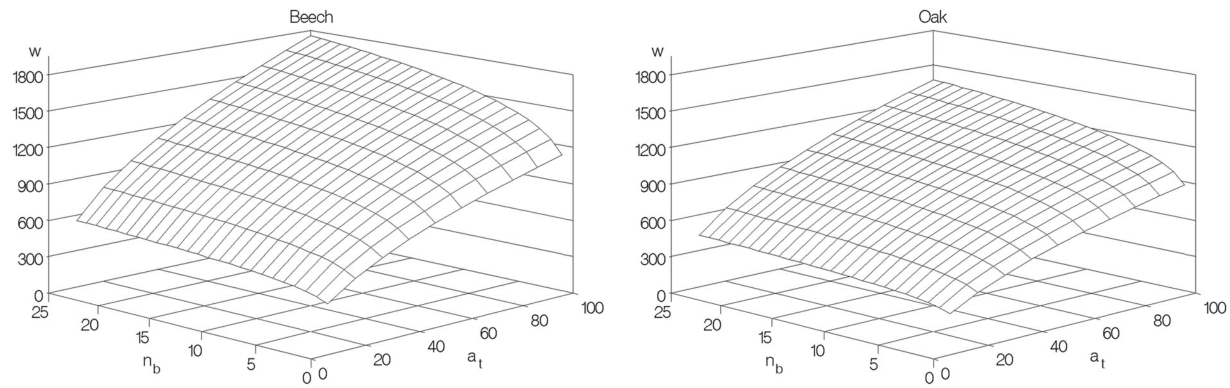

Figure 2. Predicted productive work time (w, s tree^{-1}) for target pruning of European beech and pedunculate oak depending on the number of branches per tree (n_b) and the cross-sectional area of the thickest branch (a_t, cm^2) to a pruning height (h_p) of 6.50 m. The graphs show the performance for our average worker (intercept adjustment = −0.43).

content during the growing season may have slowed down pruning. Alternatively, we therefore hypothesise that the slower pruning of beech could be due mainly to higher moisture content because of summer pruning. We did not measure the moisture content or the weight of branches, but we measured the length of the thickest branch (not used in the analyses) and found no significant differences between beech and oak.

When comparing our model of work efficiency for target pruning of beech and oak to a similar model for silver birch (*Betula pendula* Roth), but calibrated for a different group of workers (Skovsgaard et al. 2018), we found that birch is much faster to prune. Based on pruning to 6.50 m using a Silky saw and with specifications of (n_b, a_t) at the average for each species in our investigation, i.e. at (14.4, 53.1 cm^2) for beech and at (6.3, 61.4 cm^2) for oak, a birch tree of similar specifications is predicted by Skovsgaard et al. (2018) to take approximately 30% of the work time for beech and 27% of the work time for oak, when pruned by the top performer of each investigation, and 18% and 20%, respectively, when pruned as predicted for the average worker. This obviously relates to differences in wood properties, including the lower basic density of birch wood (Moltesen 1988), and possibly also to other species-specific characteristics.

Comparing the two saw types

The tendency of the Silky saw to be faster than the Ergo is consistent with the difference in carbon content, tooth design and kerf width. In plain terms, the saw teeth wear less and therefore remain sharp for longer with a higher carbon content. Chrome plating may further add to this effect. Moreover, the kerf, i.e. the width of material removed by the saw, is 15% larger for the Silky saw, and the larger lateral displacement of the teeth allows them to clear faster.

Another, unquantified factor is the influence of the extension pole. The round glass-fibre pole of the Ergo unit was more flexible and with increasing pruning height more easily bounced from the branches than the oval aluminium alloy pole of the Silky unit. Moreover, increased flexibility of the pole results in a reduced transfer of power to the sawblade.

Variation among workers

Based on our personal judgement of worker physique and performance consistency we consider the operator variation in the final model representative of (young) forest workers. Especially the three fastest operators had a high and consistent work performance equivalent of that which can be expected for a fit and skilled professional forest worker.

Interestingly, the variation in worker performance within our study was larger than that attributed to tree species and pruning equipment. This is in line with other recent research (Markmann 2012; Skovsgaard et al. 2018). Although worker performance may be influenced by weather conditions, the observed variation indicates that worker performance may override other influential factors and decisively influence the costs of pruning.

Model plausibility

Two previous studies of work efficiency for high-pruning of beech and oak allow for an assessment of model plausibility. Unfortunately they do not include complete specifications in terms of pruning height or branch characteristics.

The study in beech was performed with a Sandvik 285–6T saw (h_p = max. 5–6 m, $n_b = 5.3$, $d_h = 6$ cm) and resulted in an average productive work time per tree of 187 s (Heijnen 1986; Suadicani 1992). For these specifications, our model predicts 234–324 s for an average worker and 142–197 s for a top performer.

The study in oak was performed with an unspecified Sandviken pole saw (h_p = 3–6 m, branches ranging from "fine" to "coarse") and resulted in an average productive work time of 293–1273 s for pruning to 6 m (Žumer 1966). Our model ($n_b = 6.3$, a_t = 10–180 cm^2) predicts 311–1329 s for an average worker and 189–807 s for a top performer.

Model application

When applying the model for predictions in pruning operations one needs information on the average expected number of branches to prune on each tree and the average cross-sectional area of the thickest branch for the stand in

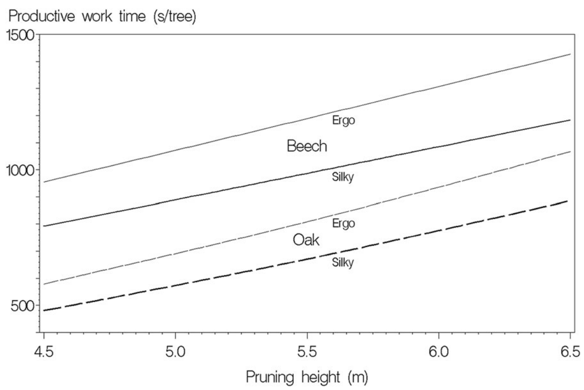

Figure 3. Predicted productive work time (w) depending on pruning height (h_p) for target pruning of European beech and pedunculate oak with Ergo and Silky saws. The lines were fitted for our average worker (intercept adjustment = −0.43) based on average branch characteristics in calibration data (beech: [n_b, a_t] = [14.4, 53.1 cm^2], oak: [6.3, 61.4 cm^2]).

question. Pruning height will usually be fixed at a given approximate value. The number of branches can be estimated based on counting, and branch size can be determined based on, for example, horizontal branch diameter.

In the beech stands we pruned, the vertical branch diameter of the thickest branch was on average 40% larger than the horizontal (range of d_v/d_h: 0.66–3.65). In the oak stands, it was 50% larger (range of d_v/d_h: 0.46–3.98). Based on this, branch cross-sectional area can be estimated as $\pi \cdot 1.40 \cdot (d_h)^2/4$ for beech and as $\pi \cdot 1.50 \cdot (d_h)^2/4$ for oak. The exact relationship obviously depends on branch as well as pruning angle (hence the large variation).

When pruning is conducted to the final pruning height in one operation (one crown lift) the dependence of productive work time on pruning height alone is of little interest, but simply determines a general level around which work time will vary depending on branch characteristics, pruning equipment and worker performance. If pruning is carried out in two operations at different stages of stand development (two crown lifts), the influence of pruning height may be of interest but, again, most trees will often be pruned to an essentially identical height.

According to the model a decrease in pruning height from 6.5 m (typical final pruning height) to 4.0 m (typical pruning height for a first lift) reduces work time by 41% for beech and by 55% for oak (Figure 3). These estimates assume branch characteristics similar to our mean values for each species and a work performance similar to our "average" worker. However, there tends to be smaller and fewer branches with earlier pruning, so savings on work time may consequently be larger.

In summary, we consider our model realistic for a range of conditions in operational forestry. It should be noted, however, that the model was calibrated based only on heavily thinned stands with quite thick branches. For practical applications, we recommend adjusting estimates based on the observed operator-specific performance level.

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