Original scientific paper

Effect of Tree Form on the Productivity of a Cut-to-Length Harvester in a Hardwood Dominated Stand

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Abstract

It is commonly accepted that tree form has an impact on the productivity of single-grip harvesters. However, it remains unclear, which elements of tree form are significant and to what degree they impact harvesting productivity. This is of particular importance in hardwood dominated stands, where hardwood trees often exhibit complex and variable stem and crown architecture that can complicate and prolong the processing phase. With the development of specialized harvesting heads, hardwoods, which were mostly subject to motor-manual operations, are now increasingly being cut and processed with fully mechanized harvesting systems. The goal of this pilot project was to determine the effect of tree form on the productivity of mechanized cut-to-length harvesting. A time and motion study of a single-grip harvester, operating in a hardwood dominated stand, suggests that the presence of a fork or a large branch on the main stem can reduce machine harvesting productivity by 15 to 20%.

Keywords: tree characteristics, hardwoods, time and motion study, mechanized harvesting, single-grip harvester, processing, Canada

1. Introduction

There is growing interest in using single-grip harvesters in hardwood dominated stands of northeastern North America. However, for certain northern hardwoods, such as sugar maple (*Acer saccharum* Marsh.), stem form is very complex and wood density is relatively higher compared to most commercial hardwoods (examples of oven dry wood densities: sugar maple, 705 kg/m^3; white birch (*Betula papyrifera* Marsch.), 588 kg/m^3; trembling aspen (*Populus tremuloides* Michx.), 424 kg/m^3 (Jessome 1977)). These physical characteristics make the processing phase more challenging and reduce the average harvesting productivity for those species compared to softwoods. Such differences in average harvesting productivity between species have been reported (Huyler and LeDoux 1999, Nurminen et al. 2006, Hiesl 2013) but no studies could be found that determined which tree characteristics actually caused the differences.

In the spring of 2013, the Northern Hardwoods Research Institute (NHRI) introduced a tree classification system that includes a rating of tree form (Pelletier et al. 2013). According to Pelletier et al. (2013), this classification system is seen as an opportunity to improve predictions of harvester productivity and the selection of harvesting systems, amongst other benefits. As such, a pilot study was designed to meet two objectives: i) determine if there is a link between the harvesting productivity of a single-grip harvester and stem form as defined in the new tree classification system; ii) determine if there are other potentially significant stem form characteristics that influence single-grip harvesting productivity.

2. Methodology

The pilot study was limited in extent to a single machine and operator, during day shifts over a one week period. It was designed following an explanatory mixed methods approach (concurrent nested strategy) (Terrell 2012, Creswell 2014). Data were mainly collected via a time and motion study of individual trees harvested. This was complemented by the

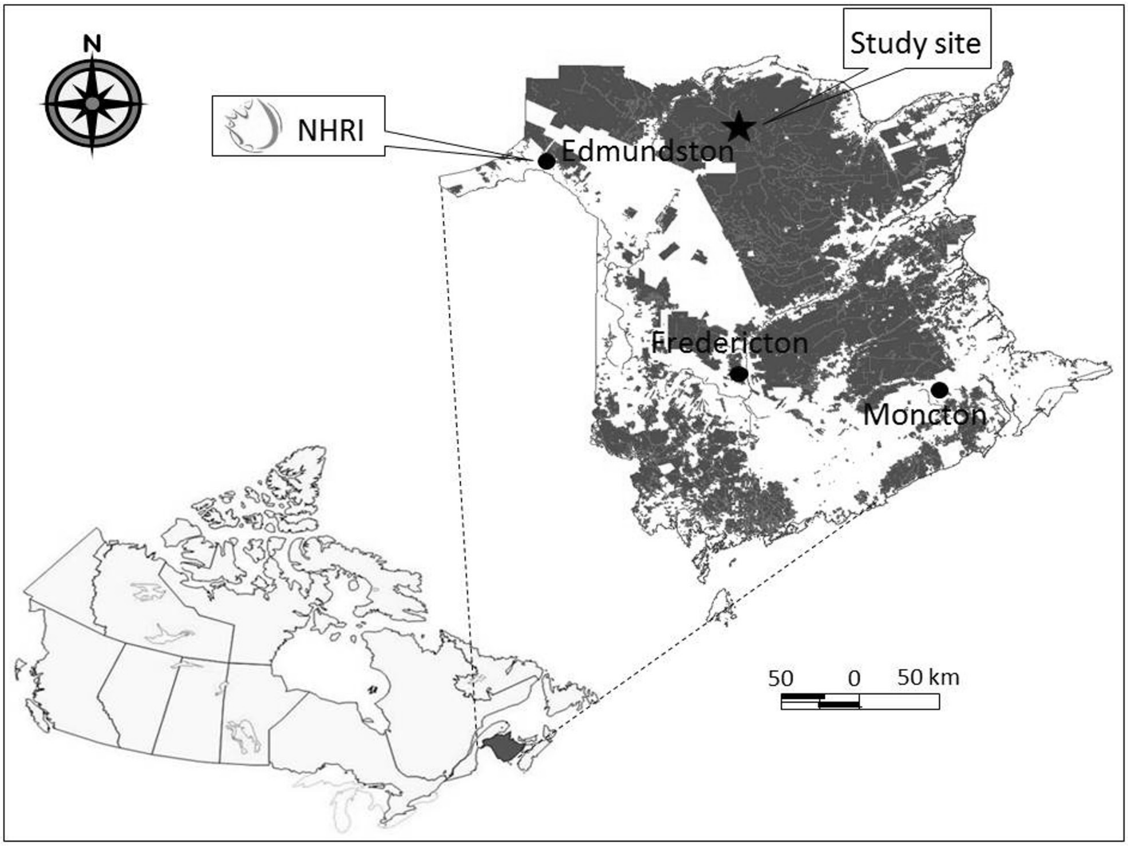

Fig. 1 Location of time and motion study site depicted by star symbol

filming of the entire harvesting process to allow *a posteriori* analysis of the variability in the results and to obtain a broader perspective on the influence of stem form (the qualitative portion of the explanatory mixed methods approach).

2.1 Site, stand, and harvesting system description

The study was conducted during regular forest operations on public lands in northwestern New Brunswick (47° 28′ N; 66° 37′ W: Fig. 1). The test area is part of the Atlantic Maritime ecozone and within the climatic zone 4D characterized by having between 1200–1400 annual degree days > 5° C, and 500–550 mm of precipitation from May to September (Rees et al. 2005).

The harvest prescription was an overstory removal where all merchantable trees, except sugar maple and yellow birch (*Betula alleghaniensis* Britton.) with a *DBH* less than 26 cm are normally harvested. However, for the purpose of this study, sugar maples from 10 to 26 cm *DBH* were also harvested to allow gaining insight on harvesting productivity in the lower tree *DBH* categories, thus making the results of the harvest prescription more in line with a clear felling operation. Trees were processed within the harvest area. The target lengths for sawlogs were 265 cm and 287 cm (8′6′′ and 9′4′′), but the mill also accepted short logs of random lengths between 200 cm and 265 cm (6′6′′ to 8′6′′). For pulplogs, the target length was 265 cm (8′6′′) for 90% of the volume with the possibility to produce shorter logs in random lengths down to 112 cm (44′′) to maximize volume recuperation.

A test area of approximately 2 hectares with a high proportion (60%) of sugar maple and a slope of less than 10% (southern aspect) was delineated for the study. The stand had an average pre-harvest merchantable basal area of 30 m^2/ha, average tree density of 618 stems/ha, average tree quadratic mean diameter of 33 cm, and average tree height of 19 m. Similar stand and site conditions are commonly encountered in mechanized forest operations in New Brunswick.

The cut-to-length machine observed was a Landrich single-grip tracked harvester equipped with a Ponsse H8 processing head with topsaw mounted on a 10 m long boom (Table 1 and Fig. 2, Landrich 2012). The

Table 1 Manufacturer's specifications for Landrich single-grip harvester (Landrich 2012)

Traction type	Steel rigid tracks – D6 undercarriage
Weight, kg	28,440 with H8 head and fluid levels full
Engine/power, kW	Mercedes Benz – OM906LA Tier 3/205 kW
Width/length/height, m	3.240/8.035/3.675
Boom maximum reach, m	9.965
Head	Ponsse H8 with top-saw
Maximum felling diameter mm	820
Maximum delimbing diameter, mm	740
Delimbing feed rate, m/sec /force, kN	5 / 30

operator had fifteen years' experience in mechanized operations. Most importantly, he had been operating the Landrich, equipped with the above-mentioned processing head, for a three year period and was very comfortable and efficient at using its top saw. The harvester was equipped with an onboard computer providing optimized bucking solutions. However, because of the high variability in the geometry of sugar maple stems for a given tree diameter, the operator made little use of the bucking solutions proposed. No adjustments of the parameters in the onboard computer were made nor were any guidelines given concerning the use of the proposed optimized solutions. Therefore, the bucking of stems into roundwood products was entirely left to the discretion of the operator.

2.2 Tree form classification

Several key characteristics (forks, inclination, etc.) can be assessed to characterize tree form (Larson 1963, Millet 2012). The tree form classification system developed by the NHRI is an assessment of the first 5 meters of each tree on the vertical axis (Pelletier et al. 2013). The classification is derived from the presence and location of large branches and forks, curves, and lean (Table 2). A large branch was defined as having a diameter greater than one third of the main stem (measured below the branch). A fork was also defined as having a diameter greater than one third of the main stem below the fork but where it is impossible to identify the main stem (leader) above the fork (Pelletier et al. 2013).

Fig. 2 Landrich single-grip harvester (courtesy of ALPA Equipment Ltd)

Table 2 Description of the eight tree form classes (adapted from Pelletier et al. 2013)

F1 – Ideal tree form	*F2* – Acceptable tree form
– A single stem in the first 5 meters – Without curve or with a curve on one axis – Inclination of less than 15° from the vertical axis	– A single stem in the first 5 meters – Light curve on 2 axes or 1 significant curve on the stem – Inclination of less than 15° from the vertical axis
F3 – Poor tree form	*F4* – Unacceptable tree form
– A main stem and the presence of large branches in the first 5 meters – The multiples branches represent potential for roundwood products	– Multiple stems or branches in the first 5 meters – The multiple branches have no potential for roundwood products
F5 – Poor tree form	*F6* – Poor tree form
– Multiple stems are present between 0.3 and 1.3 meters from the base of the tree – Single crown	– A single stem in the first 5 meters – Light curve – Significant inclination of more than 15° from the vertical axis
F7 – Acceptable tree form	*F8* – Poor tree form
– A principle stem which is divided into a fork between 2.5 and 5 meters from the base of the tree – Inclination of less than 15° from the vertical axis	– Multiple stems are present under 0.3 meters from the base of the tree – Can represent a clump of trees from the same species or various tree species

At the onset of the study, a parallel tree form classification scheme was used to provide additional information. Firstly, form classes *F5* and *F8* were eliminated since they essentially represent two or more trees from the standpoint of the usual forest inventory. Instead, each stem of the *F5* and *F8* trees was classified into one of the remaining classes. Secondly, a class »*F9*« was created for trees that forked at heights between 5 and 10 meters, as work by Plamondon (2010) has shown a significant reduction in harvesting productivity of a single-grip harvester when processing trees with a fork below 10 meters.

2.3 Field procedure and instrumentation

Before forest operations commenced, 278 sugar maple trees were pre-assessed as potential study trees. The selection was based on two criteria: i) attempt to cover the full spectrum of form classes and *DBH*, ii) maintain sufficient spacing between consecutive study trees to allow the research assistant to differentiate logs originating from study trees during the subsequent log measurements for volume estimations. As a result, about one out of every six standing trees was selected as a sample. Study trees were numbered sequentially with paint at breast height. Form and *DBH* (2 cm classes) of each tree were recorded by a research assistant experienced with the tree form classification system.

Continuous time and motion measurements were collected for all trees using the software TS-1000 (Gingras 2006). Work cycle was divided in the following elements: felling; processing; moving; brushing; rearranging logs and delays (any complete stop of the machine over a few seconds was recorded as a delay and associated cause was noted). Time per individual study tree was extracted from this data set. The complete time and motion data set was also used to determine a standard duration for work elements that are not common to every tree such as machine movement, brushing of understory vegetation, and for rearranging logs in piles. A short description of each timing element is presented in Table 3. Merchantable volume per tree was obtained by Smalian's formula using two perpendicular diameter measurements (inside bark) at each end of the logs (mm accuracy) and length measurements to the nearest centimeter.

Harvesting productivity per tree was calculated in terms of cubic meter of logs per productive machine hour. To further assess differences in harvesting productivity, tree forms were separated into »acceptable« (F1, F2, F7) and »unacceptable« (F3, F5, F6, F8) categories, as suggested by Pelletier et al. (2013).

In order to analyze and explain *a posteriori* the variations in individual tree harvesting productivity, a digital video camera was mounted in the cab of the harvester and pointed directly towards the harvesting head. The videos were also used to provide a broader perspective on the influence of stem form on specific cycle elements, including non-productive time.

Table 3 Description of key machine cycle time elements

Generic timing elements	Tasks included
Move	Travel between trees or to separate products
Brush	Cutting non-commercial/merchantable trees and cleaning area to pile logs
Head positioning	Head is moving towards the tree
Fell & drop	Cutting tree
Process	Processing tree (this element indicates the end of a cycle)
Operational delay	Machine stoppage

2.4 Statistical analyses

Statistical analyses were performed with the Minitab 17 statistical package. To assess the effect of tree form on machine productivity, one-way analysis of variance (ANOVA) was performed and means were compared using the Tukey pairwise test. Machine productivity and recovered volume were the response variables studied, whereas tree form classes and tree *DBH* were terms used for comparisons. A significance level of 5% was used throughout all statistical analyses.

3. Results and Discussion

Time and motion observations were made during 15.4 hours, which allowed observing the harvest of 645 trees in 14.1 productive machine hours (*PMH*). The average cycle time required to complete all elements of these 645 trees was 1.31 productive minutes, which is similar to the average delay-free cycle time of 1.29 minute per tree recorded by Huyler and LeDoux (1999) during mechanized *CTL* operations of a mixed wood stand. On average, 12% of the time was used for positioning the felling head and felling the trees, 71% for processing, and the remaining 17% for movement of the machine, brushing the understory, and rearranging log piles.

Out of the 278 trees that were pre-assessed, only 109 were actually recorded during the time and motion studies in the field together with 536 other trees (not pre-assessed trees) for a total of 645 trees. Not all of the 278 initially identified study trees could be monitored due to logistical challenges and from this point forward, all results will pertain to those 109 study trees. Individual tree harvesting productivity ranged from 2.8 to 51.6 m^3/PMH with an average of 18.5 m^3/PMH, which is similar to the range of 4 to 47 m^3/PMH reported by Puttock et al. (2005) for a cut-to-length operation in a mixed-wood stand in Eastern Canada. Again, when not discriminating between *DBH* classes,

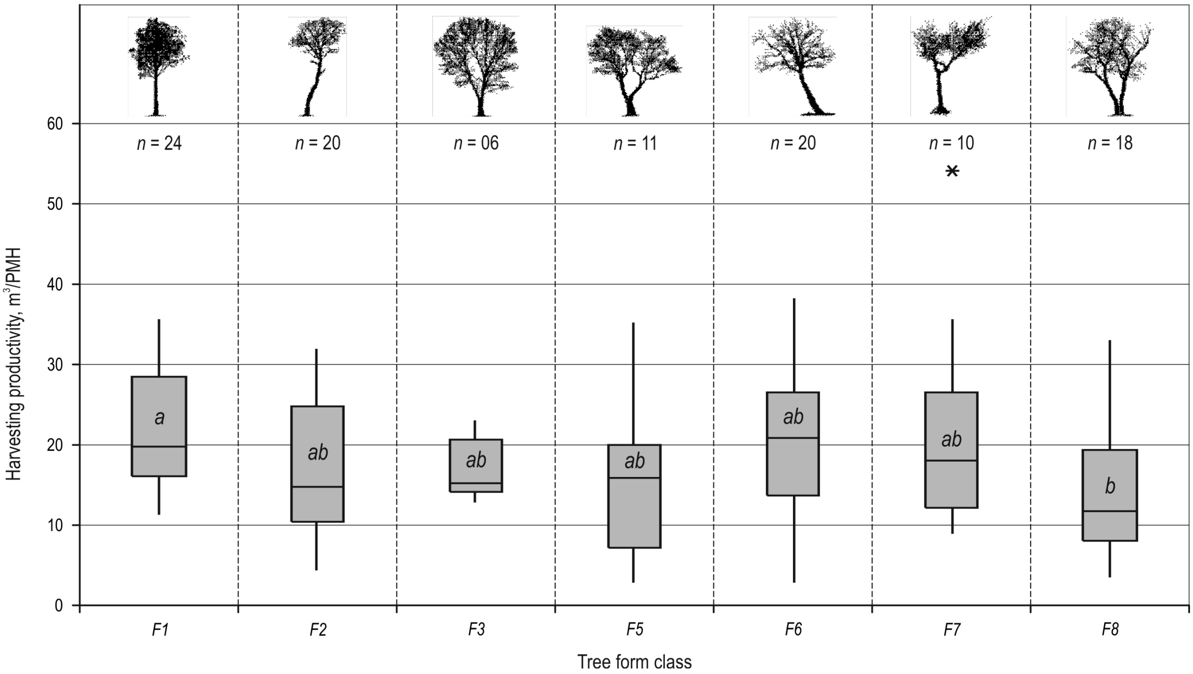

Fig. 3 Harvesting productivity per tree form class along with sample size. Different lower case letters indicate a statistical difference between means at alpha 0.05. Tree schematics are only displayed for a visual representation of different form classes

mean harvesting productivity ranged from 13.6 m^3/PMH for *F8* trees to 22.4 m^3/PMH for *F1* trees with statistical differences between the two means (Fig. 3). Aside from a considerable difference in average *DBH* (24.6 cm and 35.6 cm) between trees of form *F8* and *F1*, respectively, no further explanation for this statistical difference can be provided. *F8* trees are defined by having a fork below 0.3 meters. The limited observations suggest that it is not simply this fork that caused the reduction in productivity but rather the simultaneous combination of other defects and forks on those trees.

When separating tree forms into acceptable or unacceptable groups as suggested by the NHRI classification, 54 were acceptable form and 55 unacceptable. In comparison to acceptable trees, the average *DBH* of the »unacceptable« trees was 5% smaller, the observed average harvesting productivity (m^3/PMH) was 18% lower (significantly different $p = 0.032$ based on a one-way ANOVA) and volume recovered was reduced by 16% (Table 4). This trend is also consistent with results provided by Ramantswana et al. (2013) that indicate a reduced harvesting productivity for *Eucalyptus grandis* stems of poor form (branches >5 cm maximum diameter at trunk) compared to those of good form when using an excavator-based harvester equipped with a Waratah HTH616 harvester head. The harvesting productivity of unacceptable trees being significantly lower than that of the acceptable trees (Table 4), a separate regression analysis was performed for each form category. When applying a regression with a power function, it is possible to observe that unacceptable trees have a harvesting productivity lower than acceptable trees across all *DBH* (Fig. 4). However, the models only explain between 25 and 32% of the variability, meaning that other factors play a dominant role in explaining individual tree productivity. In an expanded study offering better representation, data could be analyzed via a single regression using both stem size and form as variables to provide clearer evidence into the influence of stem form on harvesting productivity. This could result into an improved model of single-grip harvester productivity in hardwood stands. High variability was apparent in both unacceptable and acceptable tree forms and revealed discrepancies in the expected influence of stem forms on machine harvesting productivity. In some instances, trees classified as being of unacceptable form showed the highest harvesting productivity compared to trees of similar size that were classified as acceptable (False negative prediction). In other cases, trees classified as acceptable showed the lowest harvesting productivity compared to trees of similar size classified as unacceptable (False positive prediction). Two approaches were taken to analyze these discrepancies: i) reclassifying which form classes were deemed acceptable on the basis of the presence of forks; ii) a qualitative analysis of the recorded video footage.

The reclassification of all trees that had forks in the first 10 meters as being unacceptable resulted in 42% of the trees changing category. However, this reclassification did not reduce the discrepancies in the expected influence of stem form as there were just as many trees of acceptable form with the lowest productivities and trees of unacceptable form showing some of the highest productivity.

We then used the harvesting videos to examine ten acceptable and ten unacceptable trees. Of these, half had very high harvesting productivities across tree sizes and the other half had relatively low harvesting productivity. For the trees that showed the lowest harvesting productivity, four main observations were made (no particular order):

Presence of rot caused reductions in volume recovered and increased processing time as the operator tried to predict and buck bolts where the rot stopped in the stem. However, this tree characteristic is not considered a »form« characteristic.

Table 4 Average harvesting productivity observed as a function of tree form along with one-way ANOVA results (different lower case letters indicate a statistical difference at alpha=0.05)

Tree form		*DBH*, cm		Harvesting productivity, m^3/PMH		Volume recovered, m^3/tree	
	Number of trees	Avg.†	Stand. error‡	Avg.	Stand. error	Avg.	Stand. error
Acceptable	54	33.8^a	1.31	20.4^a	1.22	0.64^a	0.06
Unacceptable	55	32.0^a	1.84	16.7^b	1.13	0.53^a	0.05
Total	109	32.9	1.13	18.5	0.85	0.58	0.04

† average
‡ standard error

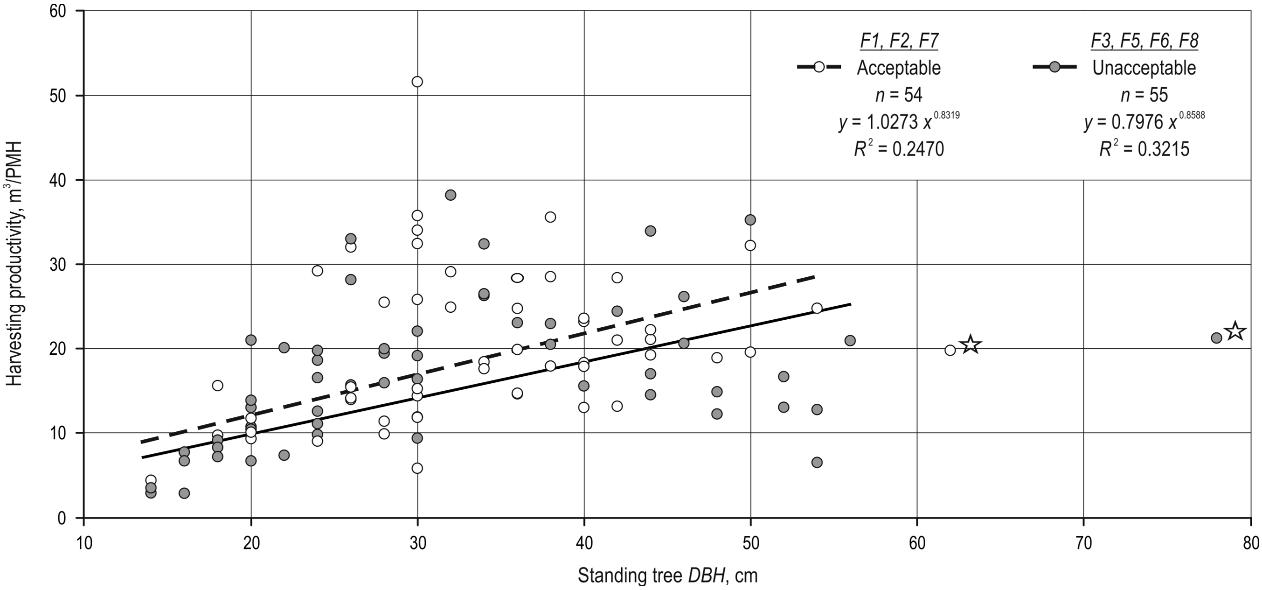

Fig. 4 Individual tree harvest productivity function of *DBH* for acceptable and unacceptable form categories. Due to a low frequency in the >60 cm *DBH*, the two data points identified by a star were omitted from the regression analysis

Presence of a crook along the stem often required releasing the tree to relocate the processing head beyond the crook causing delays for the repositioning of the head. It also often meant that the portion of the stem containing the crook needed to be cut off, hence reducing the volume recovered.

Presence of large branches (diameter greater than 10 cm; estimated from the video) on a merchantable portion of the stem often required multiple strokes from the processing head for proper delimbing. For some large branches, it was necessary for the operator to release the main stem and reposition the harvesting head to cut the branch.

Presence of forks along the stem's merchantable portion had mixed influences on harvesting productivity. The operator was seen to use five approaches to process forked trees:

⇒ When a tree forked below 1.3 meters (*F5* and *F8*), each fork was processed as separate trees with only a slight impact on harvesting productivity.

⇒ When a tree had large forks and clear access to them while the tree was still standing, the operator would cut and process the forks before felling the main stem. This appeared to be an efficient manner to process forked trees. Quantifying this apparent difference in productivity and identifying best practices in harvesting forked trees would warrant a follow-up study.

⇒ When a tree forked in two relatively small and straight stems, the forks were processed simultaneously (using the grapple to bend the forks inward), causing no apparent delays.

⇒ Whenever possible, forks were cut using the top saw while the main stem was processed. Severed forks were subsequently picked up and processed. This method appeared to be less efficient than when the forks were cut and processed from standing trees because picking up a fork on the ground sometimes posed a challenge.

⇒ When the use of the top saw to cut the forks was impractical due to tree position, the operator would release the main stem and align the head to cut the fork using the main saw. Grabbing the fork and proper positioning of the head to cut the fork appeared to be the cause of significant lost time. After having cut and processed the fork, the operator would pick up again the main stem, reposition the head at the beginning of the stem and continue its processing.

When looking at the videos of »unacceptable« trees with an above average harvesting productivity, it was observed that:

⇒ Trees exhibiting a significant lean (>15°) did not appear to have a lower harvesting productivity.

⇒ Trees that forked below 1.3 meters were processed as two independent trees and so did not appear to have a significant influence on harvesting productivity when those trees had no other significant defects.

As the goal of the tree classification system used was threefold; predict current and future product distribution, determine harvesting costs, and indicate priorities for tree removal, altering decision criteria aimed at improving the applicability of a single facet, in this case harvester productivity, might negatively impact the general performance of the system. Nevertheless, our observations suggest that for the objective of predicting harvester productivity in hardwood dominated stands, two complementary variables should be collected; presence of a fork or large branch within a height of 10 m instead of only the first 5 m as indicated by the current system, and excessive crooks. The importance of considering forks or large branches up to a height of 10 m because of the almost automatic necessity to release the main stem from the processing head to cut them cannot be understated.

The current study was limited in scope but still provided important and relevant findings concerning the influence of stem form on the productivity of a cut-to-length harvester. Through subsequent studies, additional information on the following elements could provide further insight.

Improvements to the groupings of form categories specifically targeted for harvester productivity would allow for better and more representative predictions. A more tailored approach could be useful when selecting trees to be removed during pre-commercial thinning and/or commercial thinning treatments in order to reduce harvesting costs of subsequent harvests.

Quantifying and observing the influence of rot (frequency, location within the stem, and severity) on volume recovered and machine productivity would provide complementary information, thus giving further insight on the effect of tree form and quality on the productivity of single-grip harvesters. This would allow understanding to what extent the productivity loss recorded with unacceptable trees is due to increased time consumption resulting from unacceptable form, and to what extent it is due to a lower value recovery.

4. Conclusion

Hardwood trees can present extra challenges for single-grip harvesters during the processing phase due to their crown architecture. While the extent of this study was limited, it nonetheless suggests that the use of a stem form classification system can improve our understanding of expected single-grip harvester productivity in hardwood stands. On average, trees of unacceptable form showed a 15 to 20% decrease in harvesting productivity compared to trees of acceptable form.

At the individual tree level, the stem form classification system used was not able to capture all of the variations. Many trees of unacceptable form showed very high harvest productivity, while trees of acceptable form showed low productivity. Analysis of the videos suggests that simple modifications to the classification system could be made to better account for large branches and forks in the section above the first five meters. This should result in an increased difference in harvesting productivity between trees of poor form versus those of good form.

Knowledge of the proportions of trees with different characteristics within a harvest area along with their impact on harvesting productivity could become a key indicator in a context of precision forestry. In addition to helping choose appropriate harvesting equipment, it could also suggest improvements in harvesting techniques and equipment.

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