A ROBUST PRODUCTIVITY BENCHMARK FOR GRAPPLE YARDING IN FAST-GROWING TREE PLANTATIONS

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Introduction

The goal of this study was to produce a general benchmark for the productivity of innovative grapple yarding techniques in plantation forestry, based on a large number of observations, conducted over extended periods on multiple teams. Only that way, can one produce reliable benchmarks for this technique, which may integrate the inherent variability introduced by terrain, machine type, individual team proficiency and seasonal fluctuations. In particular, the study aims at 1) determining reference values for net productivity and utilization, 2) categorizing downtime, 3) discriminating between equipment options and 4) modeling net productivity as a function of relevant independent variable. Such knowledge will allow accurate operation planning, which is crucial to precision management.

The study was conducted within the large plantation established and managed by the Grand Perfect Sdn Bhd consortium 45 km east of Bintulu, in Sarawak, Malaysia, where 12 complete yarding operations were running, each consisting of four machines: an excavator-base grapple yarder for extracting whole-tree loads to the landing edge, a second excavator placed near the yarder and tasked with moving loads from in front of the yarder to the stack, a third excavator stationed on the slope for feeding pre-bunched loads to the grapple carriage, and finally a fourth excavator used as a mobile tailhold, turned on only during line change - this last one being an old machine valuable for its weight more than for its power. The excavator-base yarder was equipped with a double drum hydraulic winch set, a tower extension bolted onto the boom stick, and an innovative remote-controlled grapple carriage. The yarder was set up in a semi-live shotgun skyline configuration (Figure 1).
Field work for this research was conducted between 4 October 2016 and 25 May 2017. In order to integrate all possible variability, the study covered all 4 plantation districts. For the same reason, the study included all 12 machine teams, which represented two slightly different set ups.

The compartments were all monocultural black wattle, planted between 1997 and 2003 at a 3 x 3 m final spacing. Treatment was a clearcut at the end of rotation, without any previous thinning. At the time of cut, most compartments were aged between 10 and 15 years. The pre-harvest inventory determined the following stand characteristics: mean diameter at breast height = 18.7 ± 5.2 cm; total height = 19.5 ± 2.8 m; stocking = 225 ± 140 m$^3$ ha$^{-1}$. In fact, rotation age was longer than originally planned, but growth stagnated after the first 7-8 years and therefore conditions can be considered representative of normal black wattle plantations, and more in general of hardwood plantations in tropical and sub-tropical countries.

A data collection sheet was designed for collecting the following data on a daily basis: machine and operator ID, begin and end of shift (h:min), duration of any delays longer than 5 min (min:ss), description of the delay, duration of each extraction cycle (min:ss), number of pieces in each load (n°), line length (m). On the same form, a separate page was designed for introducing the total length and the diameter at the top and the butt ends of all pieces in a sample load, which was to be measured four times a day at regular intervals (08:30 h, 10:30 h, 13:30 h and 17:00 h). For the purpose of the measurements, each team supervisor was equipped with forms, digital stopwatch, laser range-finder, inclinometer, caliper and measuring tape. Five research days were spent to train yarder teams to record information accurately, and data sheets were regularly collected and checked by the operation manager.

Eventually, the complete dataset included 555 shifts, for a total of 1346 lines, 54000 valid cycles and 3517 h of worksite time (excluding 239 h of study delays, which were removed from the dataset). The study covered the extraction of over 125000 m$^3$ or over 240000 stems, with total length between 10 and 30 m.
Results and Discussion

Daily production averaged 226 m$^3$ for a mean shift duration equal to 6.3 h (Table 2). Mean piece and load size were 0.5 m$^3$ and 2.4 m$^3$, respectively. Mean productivity was 63 m$^3_{ub}$ PMH$^{-1}$, or 39 m$^3_{ub}$ SMH$^{-1}$, depending on whether delays were excluded or included, respectively. Teams commonly worked 2.4 lines per shift, with a mean length of 103 m and a maximum length of 250 m. That resulted in a mean extraction density of 0.9 m$^3$ per m of line.

Utilization averaged 63%, with small differences between teams. A $\chi^2$ analysis of the frequency of delay events showed that team 7 had a significantly lower occurrences of mechanical delay and line change events, pointing at higher mechanical reliability and better organization of the harvest area as the possible reasons for the better performance of team 7. In fact, mechanical availability was high for all machines and never went below 89%.

The analysis of covariance showed that net work productivity in m$^3$ per productive machine hour (PMH) was affected by piece size, yarder type (heavy or medium) and by the interaction of piece size with yarder type. All these effects were significant at $<0.0001$ level, for $\eta^2$ values of 10%, 1% and 1% respectively.

![Figure 2 - Productivity of the excavator-based yarder as a function of piece volume (line length distance = 100 m, stacking distance = 20 m)](image)

The net productivity of teams 1, 4, 6 and 8 was between 20% and 30% higher than the grand average, and the difference was significant. While this differences could partly depend on better working conditions, they hinted at the effect of operator skills on operation performance. Therefore, these teams were marked as "top teams" and the group was tested as an independent variable in multiple regression analysis, in order to check if the effect of team choice was significant in addition to the effects of work conditions. The model was highly significant and could explain half of the variability in the data pool. The relationships described by the model were all logical:
productivity increased with piece volume and the number of pieces in a load, and decreased with both line length and stacking distance. Productivity was lower for the medium yarders, and the difference between the two yarder types increased with piece size, with heavy yarders performing increasingly better with larger trees, also because they were fitted with smaller grapples and may have encountered more difficulty when trying to accumulate many pieces in a single load. Top teams were more productive than the average, but their margin eroded with piece size, indicating that with a large piece size most operators can achieve a high productivity, and that skills are really tested with small pieces rather than with big ones. The model was successfully validated. Reserved data were predicted with an error of 0.3%, and the difference between actual and predicted productivity figures was not significant (p = 0.6943).

Conclusions

The productivity benchmarks estimated in this study are especially robust, because they were obtained from a long-term study that covered multiple teams and accumulated an exceptionally large number of observations, as prescribed by the classic canons of benchmark development. The figures and the model offered in this paper fill an urgent knowledge need, as the new grapple yarding technique is becoming increasingly popular and attracts growing attention. While gained specifically on one yarder make and plantation type, the information in this study can be extended to other similar machines and plantations, because the sheer volume of data allows cautious generalization.

Note - A full version of the paper has been published Open access as: