CORRELATING PRODUCTION OF ACCUMULATING FELLER-BUNCHERS

P. A. Peters
MEMBER
ASAE

ABSTRACT

The field performance of accumulating feller-bunchers reported in the United States and Canadian literature is reviewed. The major variables affecting feller-buncher performance in trees per productive machine hour (TPPMH) are average stand tree diameter at breast height (DBH), initial stand trees/ha (TPHA), and trees per accumulation (TPACC). The correlation between these variables is used to determine TPPMH as a linear function of DBH only. Slopes ranged from -6 to -25 TPPMH/DBH (trees/cm/h) for the feller-bunchers considered. Accumulating feller-bunchers should be considered for use in stands with DBH = 15 to 30 cm and shear or saw diameter should be two to three times DBH.

KEYWORDS. Forestry, Feller-Bunchers, Timber production, Forest engineering, Forest operations, Logging.

INTRODUCTION

Feller-bunchers have become increasingly popular since their introduction in the late sixties. The ability to accumulate trees in the cutting head before dropping them in a bunch has made feller-bunchers practical and economical for harvesting stands with average tree diameter at breast height (DBH) between 15 and 30 cm. Feller-buncher cutting heads have become increasingly sophisticated. Currently, in the southern United States there is much interest in cutting heads using saws to reduce damage to sawlogs. As equipment becomes more sophisticated and expensive, the need to operate more efficiently increases.

Deciding which feller-buncher to purchase or determining the most efficient use of a feller-buncher is not a simple decision. Feller-buncher production is affected by an interaction of stand diameter, stand density, unmerchantable trees, trees per accumulation, tree volume, slope, rough terrain, and operator skill. Tree size as measured by DBH is commonly reported as a major variable influencing production. Almost without exception, as DBH increases, trees harvested per hour decreases, but volume produced per hour increases. However, quantitative methods for estimating feller-buncher production as a function of DBH are generally not available.

The primary purpose of this article is to correlate feller-buncher production with DBH using U.S. and Canadian literature on the field performance of accumulating feller-bunchers. A secondary purpose is to recommend machine selection guidelines related to DBH.

LITERATURE REVIEW

Several types of field studies of feller-buncher production are reported in the U.S. and Canadian literature. The first type are those that present equations for trees per productive machine hour (TPPMH) and for trees per accumulation (TPACC) as functions of DBH (Gingras, 1988; Ashmore et al., 1983). The first type was the most useful for the purposes of this article. The second type presents equations for TPPMH as a function of DBH but not for TPACC (Lanford and Sirois, 1983; Schroering et al., 1985). The third type does not present any equations, but reports TPPMH, TPACC, DBH, and trees per hectare (TPHA), (Greene and McNeel, 1988; Huyler, 1982). The fourth type reports TPPMH, may report DBH and TPHA, but does not report TPACC (Sturos and Thompson, 1986; Folkema, 1984). This type was reviewed, but not used because the relationship between TPACC and DBH is the core of this present investigation.

In a recent study by Forest Engineering Research Institute of Canada (FERIC), a Timbco 2518 and a John Deere 693 feller-buncher were monitored in intensive, short-term time studies to determine the major variables affecting production (Gingras, 1988). The major variable was DBH; other significant variables were TPHA, the ratio of unmerchantable to merchantable trees, TPACC, slope, and terrain roughness. For both machines, regression equations are presented for TPPMH and TPACC. TPACC was a linear function of DBH for both machines. This interesting study was a departure for FERIC in that they normally report shift level, long-term data. Ashmore et al. (1984) made a similar study of a Hydro-Ax 411. They reported equations for TPPMH and TPACC as a function of DBH.

A summary of the feller-buncher, field performance data from cited literature that served as the data base for this study is presented in Table 1. Lanford and Sirois (1983) presented equations for TPPMH for Franklin 170, JD 544, and Hydro-Ax 511 machines. Greene and McNeel (1988) reported the performance of JD 643, CAT 518, Barko 775, and Hydro-Ax 611 machines, all operating with sawheads.

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The author is **Penn A. Peters**, Project Leader, Northeastern Forest Experiment Station, Morgantown, WV.

The Greene and McNeel study is the only one in the data base (Table 1) that reported on sawhead productivity.

Variables Affecting Production

Trees per productive machine hour (TPPMH) is the selected measure of feller-buncher production for this study. Equations for estimating feller-buncher production in TPPMH are presented in Table 2. The most significant variables affecting production are TPACC, TPHA, and DBH. Other variables that are sometimes significant are unmerchantable trees/ha, operator technique, brushiness, slope, and terrain roughness. Gingras (1989) indicated that some variables, e.g. slope, do not significantly affect production until certain threshold values are reached.

TPHA and DBH are inversely related; as DBH increases, TPHA decreases. The relationship between TPHA and DBH is shown in figure 1, data points and regression equation are from the literature data base, Table 1. The equation,

$$TPHA = 2280.9 - 3.471\ (DBH)^2,$$

$$r^2 = 0.845,\ se = 175, \qquad (1)$$

will be used to eliminate TPHA as a variable in estimates for TPPMH and TPACC. If equation 1 is not representative of the stand to be harvested, it would be better to use TPHA and DBH independently to estimate TPPMH or TPACC.

Trees Per Accumulation

TPACC is a significant variable affecting the productivity of accumulating feller-bunchers (Table 2). TPACC, in turn, is affected by DBH, shear (or saw) diameter (SHD), accumulator design, and operator technique.

Consider the relationship between TPACC and DBH (fig. 2). The individual data points are case study results reported in Table 1. Average stand diameters (DBH) range from 13-30 cm. Based on personal experience, the author hypothesizes that this range (13-30 cm) represents the practical operating limits for accumulating feller-bunchers. There appears to be little advantage of accumulating over non-accumulating feller-bunchers in stands with DBH greater than 30 cm, since TPACC ≅ 1 when DBH = 30. The qualitative correlation between TPACC and DBH is surprisingly good when you consider the data represent a mix of clearcut and thinning harvests, hardwood and softwood harvests, different machines, saws and shears, and different operators. More trees can be accumulated in small DBH stands. But even in the smallest stands, the trees/accumulation is relatively modest (<5). Also, TPACC is more variable in small DBH stands. Data are lacking in the case study results to explain this variation. Five regression curves are shown in figure 2: one by Ashmore, two by Gingras, a linear fit, and a quadratic fit. The equations by Ashmore and Gingras are discussed in Appendix A. The linear fit and the quadratic fit were determined by regression analysis of the data points. The linear equation is:

TABLE 1. Field performance of feller-buncher shears and saws

Author, Machine	Carrier	Head	Stand	Silviculture	DBH (cm)	Shear (saw) Diameter (cm)	TPACC	TPHA	TPPMH
Greene 1	JD 643	Rotosaw	Yellow Pine	Mixed	23.0	52.5	1.3	-	127
Greene 2	CAT 518	Rotosaw	Yellow Pine	Mixed	22.0	52.5	1.5	-	149
Greene 3	BARKO 775	KR saw	Yellow Pine	Mixed	29.5	52.5	1.1	-	173
Greene 4	BARKO 775	KR saw	Yellow Pine	Mixed	22.5	52.5	2.0	-	267
Greene 5	JD 643	KR saw	Yellow Pine	Mixed	19.0	52.5	2.2	-	322
Greene 6	HAX 611	HAR saw	Yellow Pine	Mixed	25.0	51.0	1.2	-	167
Lanford 1	FR 170	MBK shear	Loblolly	Clearcut	15.0	37.5	3.1	1396	109
Lanford 2	JD 544	MBK shear	Loblolly	Clearcut	17.0	37.5	2.0	1272	214
Lanford 3	JD 544	Rome shear	Loblolly	Clearcut	20.5	51.0	2.0	949	146
Lanford 4	HAX 511	MBK shear	Loblolly	Clearcut	20.0	51.0	1.7	830	207
Lanford 5	JD 743A	JD shear	Loblolly	Row thin	14.0	45.0	3.4	1680	182
Lanford 6	JD 743A	JD shear	Loblolly	Sel. thin	13.5	45.0	4.5	1680	200
Ashmore 1	HAX 411	HAX shear	Southern Pine	Row thin	20.0	40.0	1.9	724	110
Ashmore 2	HAX 411	HAX shear	Southern Pine	Row thin	15.5	40.0	3.4	1680	244
Ashmore 3	HAX 411	HAX shear	Southern Pine	Row thin	11.0	40.0	6.6	1670	316
Schroering 1	FR 105	TW shear	Loblolly	Row thin	15.5	30.0	4.0	1668	200
Schroering 2	FR 105	TW shear	Loblolly	Sel. thin	14.0	30.0	4.3	1668	154
Huyler	JD 644	MBK shear	No. Hardwoods	Sel. thin	23.5	51.0	1.25	655	62
Ward 1	HAX 511	MBK shear	Hickory-oak	Clearcut	20.5	51.0	1.57	543	117
Ward 2	HAX 511	MBK shear	Hickory-oak	Clearcut	20.5	51.0	1.88	543	-
Gingras 1	JD 693	HAR shear	Jack Pine	Clearcut	18.0	51.0	2.1	1240	170
Gingras 2	TMC 2518	TNC shear	Spruce	Clearcut	16.5	51.0	4.5	1310	210
Stokes	MBL	MBK shear	Loblolly	Sel. thin	13.0	38.0	2.9	1672	98

Note: JD = John Deere, CAT = Caterpillar, HAX = Hydro-AX, FR = Franklin, TMC = Timbco, MBL = Morbell, KR = Koehring, HAR = Harricana, MBK = Morbark, TW = Tidewater, TNC = Tenco, DBH = Average tree diameter at breast height removed, TPACC = Trees per accumulation, TPHA = Trees per hectare, TPPMH =Trees per productive machine hour.

TABLE 2. Equations for estimating feller-buncher production in trees per productive machine hour (TPPMH) or productive minutes per tree (PMPTR)*

Description* TPPMH PMPTR	(a)† Y=	(b) Y=	(c) Y=	(d) Y=	(e) Y=	(f) Y=	(g) Y=	(h) Y=	(i) Y=	(j) Y=	(k) Y=	(l) Y=
Constant	0.091	0.118	0.047	0.066	214.7	108.1	-0.199	-0.026	-0.222	0.142	0.34	0.34
DBH	0.000787	0.000787	0.00347	0.00400	-4.2	-	-	-	.005433	-	-0.00709	-0.00709
DBH2	0.00014	0.00014	0.00014	0.00014	-	-	-	-	-	-	-	-
TPHA (-1/2)	5.411	5.411	5.411	5.411	-	-	-	-	6.055	-	-	-
TPHA	-0.000065	-0.000065	-0.000065	-0.000065	-0.0134	0.032	-	-	-	-	-	-
TPACC(-2)	0.17549	0.17549	0.17549	0.17549	-	-	-	-	-	-	-	-
C2	0.108	0.108	0.108	0.108	-	-	-	-	-	-	-	-
TPACC	-	-	-	-	29.7	14.3	-	-	-	-	-	-
UTM	-	-	-	-	-53.1	-	-	-	-	-	-	-
DBH*TPHA(-1/2)	-	-	-	-	-	-	1.263	0.4057	0.4057	0.1351	-	-
TPHA(-1/2)/(DBH2*TPACC)		-	-	-	-	-	5072.0	1395.0	-	560.5	-	-
1/(DBH2*TPACC)	-	-	-	-	-	-	5.988	5.988	5.988	5.988	-	-
DBH2/TPACC	-	-	-	-	-	-	-	-	-	-	0.000806	0.000806
RTHA	-	-	-	-	-	-	-	-	-	-	-	0.000138

* Dependent variable is indicated by Y = , e.g. (s) PMPTR = 0.091 + 0.000787 * DBH + 0.00014 * DBH^2 + 5.411 * $TPHA^{(-1/2)}$ - 0.000065 * TPHA + 0.17549 * $TPACC^{(-2)}$ + 0.108 * C2.

† TPPMH = trees per productive machine hour, PMPTR = productive minutes per tree, PMPTR = 60/TPPMH, DBH = average tree diameter at breast height removed, cm, TPHA = trees per hectare in the initial stand, TPACC = trees per accumulation, UTM = the ratio of unmerchantable to merchantable trees, RTHA = residual trees per hectare.

‡ (a) - (d) Ashmore et al, 1983, Hydro-Ax 411 with 41 cm shear head, row thinning in southern pine; (a) dbh 16.26 cm, operator can see > 20 m into the stand, (b) dbh 16.26 cm, operator can see < 20 m into the stand, (c) dbh > 16.26 cm, operator can see > 20 m into the stand, (d) dbh > 16.26 cm, operator can see < 20 m into the stand; C2 = 1 if feller-buncher backed out a tree length or more to dump, otherwise C2 = 0.

(e) - (f) Gingras, 1988; (e) John Deere 693 with 51 cm, Harricana shear head, clearcutting in jack pine, (f) Timbco 2518 with 51 cm, Tenco LDC-206 shear head, clearcutting in spruce.

(g) - (j) Lanford and Sirois, 1983, clearcutting in southern pine, (g) Franklin 170 XLN with 38 cm, Morbark shear head; (h) John Deere 544 with 38 cm Morbark shear head, (i) John Deere 544 with 51 cm Morbark shear head, (j) Hydro-Ax 511 with 51 cm Morbark shear head.

(k) - (l) Schroering et al., 1985, Franklin 105 with 30.5 cm, Tidewater DL-12 shear head; (k) row thinning and (1) selective thinning in a loblolly pine plantation.

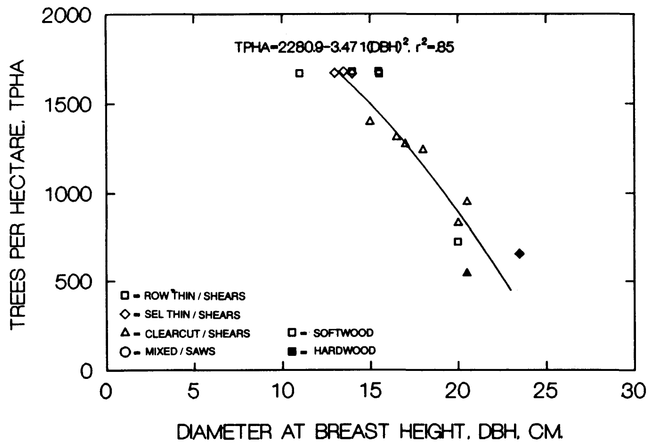

Figure 1–Trees/ha of the initial stand vs. average diameter at breast height removed in feller-buncher field performance studies.

$$TPACC = 7.493 - 0.2609\ DBH,$$

$$r^2 = 0.685,\ se = 0.78 \quad (2)$$

The quadratic equation is:

$$TPACC = 14.10 - 0.976\ DBH + 0.01833\ (DBH)^2;$$

$$r^2 = 0.785,\ se = 0.65. \quad (3)$$

The regression equations indicate trends and may be useful in a methodology to adjust feller-buncher production estimates as a function of DBH. While the correlation between TPACC and DBH is reasonably good, perhaps it could be improved by normalizing DBH by shear (or saw) diameter (SHD).

Trees per accumulation is presented as a function of the dimensionless parameters (DBH/SHD), $(DBH/SHD)^2$, and $(DBH/SHD)^{2.5}$ in figures 3-5, respectively. The regression curves of Gingras and Ashmore in the figures are presented

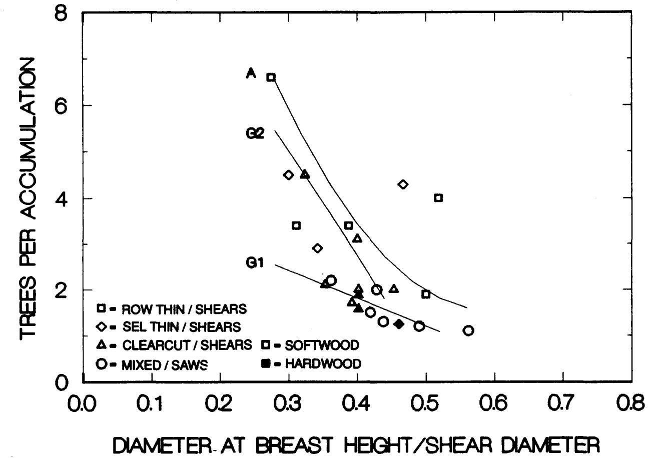

Figure 3–Trees/accumulation vs. average tree diameter at breast height removed/shear diameter in feller-buncher field performance studies: {A} Ashmore {G1} Gingras, Machine 1 {G2} Gingras, Machine 2.

in Appendix A. The rationale for dividing DBH by SHD is SHD represents the largest tree the feller-buncher can cut. The correlation of TPACC versus (DBH/SHD) is similar to but not appreciably better than that versus DBH. Most accumulating feller-bunchers operate in stands whose average DBH is 30-50% of SHD (fig. 3). Based on personal experience, the author hypothesizes that this range represents the practical operating limits for accumulating feller-bunchers. Therefore, a convenient rule of thumb for machine selection is to select a feller-buncher with SHD equal to two to three times DBH.

The rationale for using (DBH/SHD) (fig. 4) is $(SHD)^2$ may be proportional to accumulator area for many feller-bunchers and TPACC may be constrained by the area of the accumulator. A correlation of TPACC with DBH^2 /accumulator area would be interesting, but accumulator area is rarely reported in the research literature. The rationale for using $(DBH/SHD)^{2.5}$ in figure 5 is tree green weight is approximately proportional to $(DBH)^{2.5}$ for many tree species; e.g., for pine,

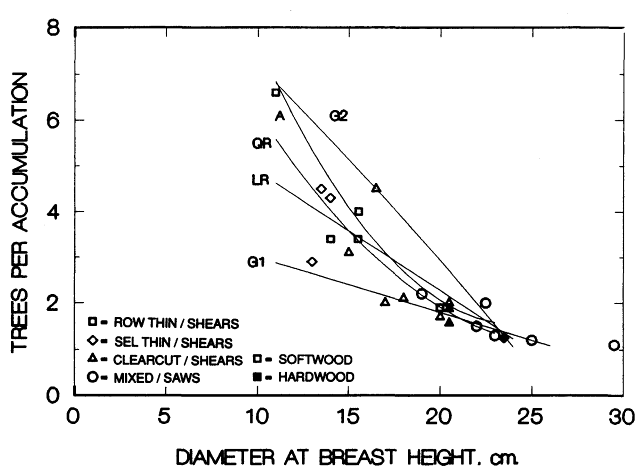

Figure 2–Trees/accumulation versus average tree diameter at breast height removed in feller-buncher field performance studies: {A} Ashmore {G1} Gingras, Machine 1 {G2} Gingras, Machine 2 {LR} Linear regression {QR} Quadratic regression.

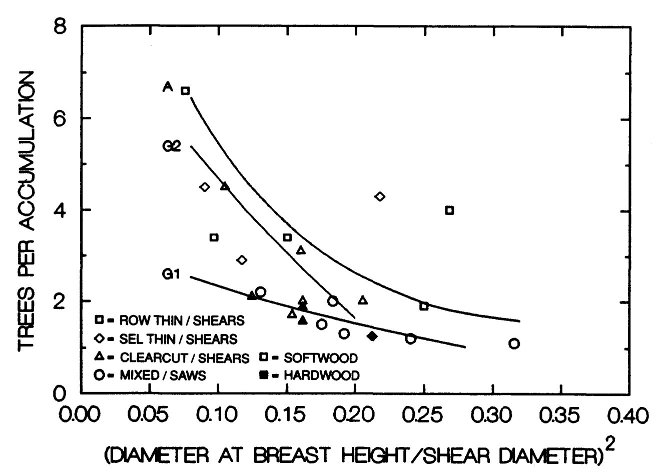

Figure 4–Trees per accumulation vs. (average tree diameter at breast height removed/shear diameter)^2 in feller-buncher field performance studies; {A} Ashmore, {G1} Gingras, Machine 1, {G2} Gingras, Machine 2.

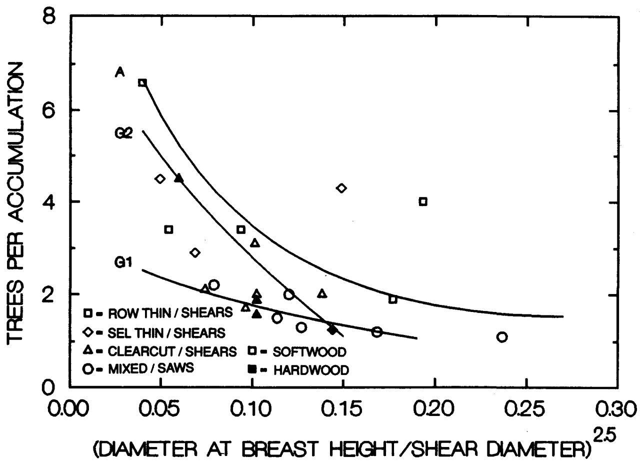

Figure 5–Trees/accumulation vs. (average tree diameter at breast height removed/shear diameter)$^{2.5}$ in feller-buncher field performance studies; {A} Ashmore, {G1} Gingras, Machine 1, {G2} Gingras, Machine 2.

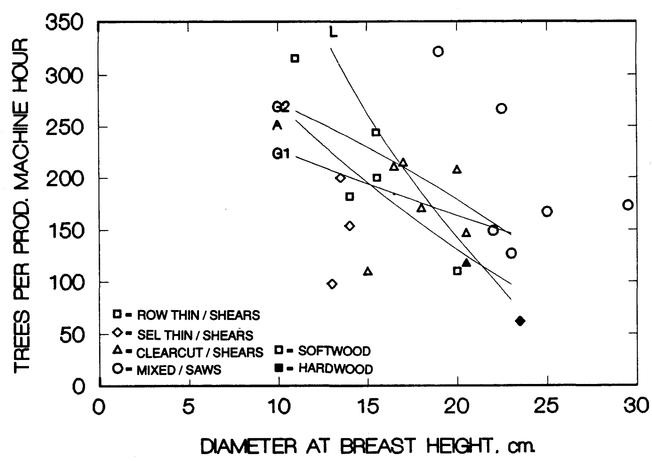

Figure 6–Trees/productive machine h vs. average tree diameter at breast height removed in feller-buncher field performance studies; {A} Ashmore, {G1} Gingras, Machine 1, {G2} Gingras, Machine 2, {L} Lanford.

$$\text{Weight} = 4.07\ (\text{DBH})^{2.48} \tag{4}$$

(Clark et al., 1985). Using this analogy, accumulating feller-bunchers tend to operate in stands whose average tree weight is between 5-20% of the machines' accumulated tree weight capacity (fig. 5).

The two outliers with trees/accumulation ≅ 4 that appear in figures 3-5 were reported by Schroering et al (1985). The feller-buncher was a Franklin 105 with a 30 cm Tidewater shear and a large accumulator area. The apparent outliers are legitimate data points explained by the detailed design features of the machine. Undoubtedly, design features account for some of the variability in trees/accumulation. Also, if the Franklin 105 had been equipped with a larger shear, which are more popular, the performance would have been more in line with other feller-bunchers.

Operator technique also affects trees per accumulation. Greene and McNeel (1988) reported that average trees/accumulation varied markedly for different operators. Gingras (1988) reported that operator performance and accumulator performance have a determinate influence on the average number of trees per accumulation. The quantitative effect of operators is not easy to determine. The typical study observes the performance of one operator on one machine. When more than one operator has been observed on the same machine, performance is often confounded by tree size and stand density. Several authors have suggested the need for more definitive studies on operator performance, (Lanford and Sirois, 1982; Greene and McNeel, 1988).

Trees Per Productive Machine Hour

Harvested trees/productive machine hour (TPPMH) for various average tree DBH removed is shown in figure 6. Each data point represents the production of a specific machine with a specific operator in a specific timber stand. Four theoretical curves showing TPPMH as a function of DBH are shown; two for Gingras, one for Ashmore, and one for Lanford. They were obtained using the equations for TPPMH presented by the authors and summarized in Table 2. Equation 1 was used in every case to eliminate TPHA as a variable. The equations in Appendix A were used to eliminate TPACC as a variable in the Gingras' equations and the Ashmore equation. Lanford did not present an equation for TPACC as a function of DBH; equation 2 was used as a reasonable estimate. To ignore the variation of TPACC with DBH was considered unrealistic.

The theoretical curves in figure 6 indicate an approximately linear relationship between TPPMH and DBH for a specific feller-buncher and operator. The effect of DBH on TPPMH can be estimated using this linear relationship. For example, a JD693 carrier with a Harricana 51 cm shear head fells and bunches 200 TPPMH in 20 cm DBH stands, what will its production be in a 15 cm DBH stand? Use the slope of the G1 curve for this feller-buncher (≅ -6 TPPMH/DBH) to obtain the desired production estimate of 230 TPPMH. The approximate slopes of the curves are -6, -10, -13, and -25 TPPMH/DBH for G1, G2, A, and L, respectively. G1 and G2 are tracked machines; A and L are wheeled machines. Tracked machines may be less sensitive to DBH effects, but data are insufficient to prove it.

Conclusions and Recommendations

The United States and Canadian research literature on feller-buncher production determined from field studies was reviewed. A data base was developed from the literature composed of the field studies which reported trees/productive machine hour (TPPMH), trees/accumulation (TPACC), trees/ha (TPHA), and DBH. TPACC is frequently not reported. The data base should be expanded to include all field studies that report TPPMH and DBH and analyzed to determine information gaps; e.g. more studies of sawheads and hardwoods are indicated. Simulation and tabulated results should be included in the data base and compared to field study results. Future research studies should report TPPMH, TPACC, TPHA, and DBH. TPPMH should be the preferred dependent variable over productive min/tree. Research reporting standards may be needed to promote a consistent literature.

TPPMH is significantly affected by TPACC, TPHA, and DBH. TPHA and DBH were related using the literature database. Equations for TPPMH and TPACC have been determined for selected feller-bunchers. For these, TPPMH is an approximately linear function of DBH, with slopes ranging from -6 TPPMH/DBH to -25 TPPMH/DBH. Modeling techniques to predict TPACC and TPPMH as a function of DBH for other feller-bunchers should continue. Operator effects need more study and may require sophisticated experimental designs.

Based on the data and personal experience, accumulating feller-bunchers should be considered for use in stands with DBH=15-30 cm and shear or saw diameter should be two to three times DBH.

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Appendix A. Trees Per Accumulation Equations

Equations for trees per accumulation (TPACC) as a function of DBH are presented as they appear in the literature and in nondimensional form for use in the body of this article.

ASHMORE Equation, Hydro-Ax 411

Trees per accumulation is given by,

$$\begin{aligned} TPACC &= 19.50 - 1.49\,(DBH) + 0.031\,(DBH)^2, \\ &\quad \text{if } DBH \le 24 \text{ cm}, \\ TPACC &= 1.50, \text{ if } DBH > 24 \text{ cm.} \end{aligned} \tag{A1}$$

where
TPACC = trees/accumulation, and
DBH = tree diameter at breast height, cm.

Equation A1 is descriptive of a Hydro-Ax 411 with a 41 cm, high-speed feller-buncher head doing a row thinning.

Use the following identities,

$$\begin{aligned} DBH &= 41\,(DBH/SHD) = 41\left[(DBH/SHD)^2\right]^{1/2} \\ &= 41\left[(DBH/SHD)^{2.5}\right]^{0.4}, \end{aligned} \tag{A2}$$

where SHD = shear or saw diameter, cm.

Substitute equation A2 into equation A1 to obtain equations for TPACC as a function of DBH/SHD, $(DBH/SHD)^2$, and $(DBH/SHD)^{2.5}$.

$$\begin{aligned} TPACC &= 19.5 - 61.1\,(DBH/SHD) + 52.1\,(DBH/SHD)^2 \\ &\quad \text{if } DBH/SHD \le 0.585, \\ TPACC &= 1.5 \text{ if } DBH/SHD > 0.585. \end{aligned} \tag{A3}$$

similarly,

$$TPACC = 19.5 - 61.1 \left[(DBH/SHD)^2\right]^{1/2} + 52.1\,(DBH/SHD)^2, \text{ if } (DBH/SHD)^2 \leq 0.342.$$

$$TPACC = 1.5 \text{ if } (DBH/SHD)^2 > 0.342. \qquad (A4)$$

and

$$TPACC = 19.5 - 61.1 \left[(DBH/SHD)^{2.5}\right]^{0.4} + 52.1 \left[(DBH/SHD)^{2.5}\right]^{0.8},$$

$$\text{if } (DBH/SHD)^{2.5} \leq 0.262.$$

$$TPACC = 1.5 \text{ if } (DBH/SHD)^{2.5} > 0.262. \qquad (A5)$$

GINGRAS EQUATION, MACHINE 1, JD 693

Trees per accumulation is given by,

$$TPACC = 4.36 - 0.12\ DBH - 0.00052\ UTPHA, \qquad (A6)$$

where UTPHA = unmerchantable trees/ha.

Eliminate UTPHA as a variable by substituting in the average value reported by Gingras (UTPHA = 200), then

$$TPACC = 4.26 - 0.12\ DBH \qquad (A7)$$

Equation A7 is descriptive of a John Deere 693 with a 51 cm Harricana shear head doing a clearcut.

Modify A7 by above procedures to obtain,

$$TPACC = 4.26 - 6.12\,(DBH/SHD), \qquad (A8)$$

$$TPACC = 4.26 - 6.12 \left[(DBH/SHD)^2\right]^{1/2}, \qquad (A9)$$

and

$$TPACC = 4.26 - 6.12 \left[(DBH/SHD)^{2.5}\right]^{0.4}. \qquad (A10)$$

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Trees per accumulation is given by,

$$TPACC = 9.0 - 0.34\ DBH + 0.00084\ TPHA, \qquad (A11)$$

where TPHA = initial stand trees/ha.

Use equation 1 to eliminate TPHA in equation A11.

$$TPACC = 10.9 - 0.34\ DBH - 0.00292\ DBH^2 \qquad (A12)$$

Equation A12 is descriptive of a Timbco 2518 with a 51 cm, Tenco LDC-206 shear head doing a clearcut. Modify equation A12 by above procedures to obtain,

$$TPACC = 10.9 - 17.34\,(DBH/SHD) - 7.59\,(DBH/SHD)^2 \qquad (A13)$$

$$TPACC = 10.9 - 17.34 \left[(DBH/SHD)^2\right]^{1/2} - 7.59\,(DBH/SHD)^2, \qquad (A14)$$

and

$$TPACC = 10.9 - 17.34 \left[(DBH/SHD)^{2.5}\right]^{0.4} - 7.59 \left[(DBH/SHD)^{2.5}\right]^{0.8}. \qquad (A15)$$