at the end of the month and made available. Likewise, the sawdust was purchased and weighed primarily by mills that use sawdust in fire boilers to generate extra energy.

Statistical analysis

Multiple linear regression was used to model the effect of species and season on cost, sawdust, and chip production. The full model, before any variable reduction, was:

$$Y_{ijklmnopqrstu} = \mu_{ijk...stu} + W_i + R_j + A_k + Be_l + Bi_m + C_n + H_o + Ma_p + Mi_q + Pi_r + Po_s + Wa_t + (Win_{0,1} + Sp_{0,1} + Su_{0,1} + Fa_{0,1}) + \varepsilon_{ijk...stu} \quad [1]$$

The abbreviations in Equation [**1**] are defined in **Table 1**. This full model (Eq. [**1**]) was investigated to predict sawdust and chip weight, and cost. C_p selection and backward stepwise selection were investigated as preliminary variable reduction tools (SAS 2001). C_p was defined as:

$$C_p = \frac{SSE_p}{MSE(X_1, \ldots, X_{p-1})} - (n - 2p) \quad [2]$$

where SSE_p = sum of the squares of error for the model fitted; $p - 1$ = potential X variables; $MSE(X_1, \ldots, X_{p-1})$ estimates the true error variance. C_p is the common statistical abbreviation for Mallow's C_p which is a diagnostic aimed at reducing the total means squared error of the regression model. For applied use, values of $C_p = p$ to $C_p < p$ will tend to yield models with limited bias and thus are a good model selection tool (Ronchetti and Staudte 1994, Neter et al. 1996). After groundwork testing of the data, C_p tended to yield better and more sensible reduced models than backward selection and was used to determine final models. However, the four indicator variables, winter (*Wi*), spring (*Sp*), summer (*Su*), and fall (*Fa*), were always left in the reduced model to explicitly demonstrate when season was not significantly influential. The number 1 was assigned to the corresponding season and a zero was applied to all other seasons for a given time period. The *p*-values, coefficients, and standard errors of the coefficients were then recorded and reported. Finally, the Pearson correlation coefficient was computed to resolve when variables were statistically related at the $\alpha = 0.05$ level (SAS 2001).

Results

Total production

There were two distinct groups of species manufactured at this mill, one of high production volume and one of lower production volume (**Table 1**). The white oak, red oak, poplar, pine, and mixed species were the four most commonly cut per unit of time. Poplar and pine were the two most frequently processed even though both oak species were just as common in area woodlands. The total amount of lumber produced in a month, on average, was 680 m^3, which classified this sawmill as a low volume producer (Nyrud and Bergseng 2002, Smith et al. 2004). Additionally, the number of employees was less than 20, which also classified this mill as a small manufacturer (Smith et al. 2003).

The standard deviation (SD) produced per lumber species was considerably different between species, with poplar and pine having the largest variation. As can be seen in **Table 1**, there was a positive relationship between mean lumber volume and volume variation across species. Within species, this relationship diminished, although the sample size was too low to determine with certainty. Beech, birch, cherry, gum, and walnut were rarely produced, which resulted in a narrow range for those dimensions during modeling.

The volume production of chips, as expected, followed the same order as lumber volume with poplar chips leading the way, then pine, then both oaks, and then mixed species (**Table 1**). The mixed species chips had the lowest variation between months while the pine chips exhibited the highest variation. When chip weight and sawdust were combined, the total weight of the by-products was 605,093 metric tons per month.

Multiple linear models

Cost was modeled for all independent variables (**Table 2**). The order of coefficients varied too much to determine if one species had a higher coefficient than another. The time of year unexpectedly had no significant effect on cost.

For sawdust weight (**Table 1**), the four seasonal indicator variables were more significant than any species with the exception of poplar, which had a slightly larger absolute t-value and nearly equivalent *p*-value. There were no significant differences between seasons as determined by the standard error. The standard error for the coefficients of pine, poplar, red oak, and white oak followed the same relative order as the variation of lumber produced in a month (**Tables 1** and **2**). In general, all species were statistically significant ($\alpha = 0.05$) in predicting sawdust weight despite vast differences in lumber production, which was expected since sawdust production should be proportional to the number of saw lines or lumber tally (**Table 1**).

When predicting pine chip weight, the volume of pine lumber produced was more important than season (**Table 2**). The prediction of mixed chip weight did not follow the same trend as pine weight. In other words, the time of production, and assumed harvest, had an important influence on total mixed chip weight.

Season was not influential in predicting poplar and oak chip weight. Likewise, sensible models were confirmed by the lowest C_p value. For example, when manufacturing poplar, one would expect only poplar and maybe season to predict total chip weight, as was the case when the C_p index was used for model selection (SAS 2001). When oak, poplar, and pine chip models were compared, the coefficients followed the same order of expected density, typical for species in that area. In other words, oak had the highest coefficient of 577 and 590, and the highest assumed density, while poplar yielded the lowest coefficient of 443 and lowest assumed density (**Table 2**). The ratio of the oak to poplar coefficients (599:434) was 1.38 which was similar to the published green density ratio of oak to poplar (0.56:0.40) and equaled 1.40 (Haygreen and Bowyer 1989). Such a similarity in ratio of coefficients used in predicting chip weight, versus the ratio of published density values for the same species, suggests that density was the main contributor to weight variation instead of moisture.

Between species and product relationships

Table 3 illustrates the relationship between species and by-products. The mixed species of lumber was positively correlated with beech and birch but was negatively correlated with red oak. Hickory lumber production was also correlated with beech and birch but was not correlated with the mixed lumber production.

Table 2. — Species parameter estimates for multiple linear regression model predicting monthly cost, sawdust, and pulp chip production from lumber quantity (m^3) and season.

Dependent variable	*r*	Independent variable	Parameter estimate	Standard error	t-value	*p*-value
Cost ($US)	0.69	Intercept	31609	16438	1.92	0.0626
		Season	--	--	--	NS[a]
		Pine	46.5	14.8	3.14	0.0034
		Poplar	67.3	13.7	4.9	0.0001
		Red oak	58.2	26.6	2.19	0.0356
Sawdust	0.87	Intercept	231073	38644	5.98	0.0001
		Winter	−161503	30164	−5.35	0.0001
		Spring	−168850	31035	−5.44	0.0001
		Summer	−157157	29887	−5.26	0.0001
		Fall	−154879	31550	−4.91	0.0001
		Mixed	213.7	79.2	2.7	0.0120
		Pine	152.9	46.3	3.3	0.0028
		Poplar	263.5	43.1	6.11	0.0001
		Red oak	357.1	81.0	4.41	0.0002
		White oak	291.1	81.5	3.57	0.0014
		Maple	484.3	173.5	2.79	0.0097
Pine chips	0.94	Intercept	−44944	39476	−1.14	0.2622
		Pine	530.0	34.7	15.29	0.0001
		Winter	88734	41142	2.16	0.0376
		Spring	56521	41501	1.36	0.1815
		Summer	57540	41011	1.4	0.1689
		Fall	51229	41684	1.23	0.2268
Mixed chips	0.77	Intercept	141934	32978	4.30	0.0001
		Mixed	429.0	83.1	5.17	0.0001
		Winter	−107314	34553	−3.11	0.0037
		Spring	−131074	34847	−3.76	0.0006
		Fall	−119228	34315	−3.47	0.0014
		Summer	−122428	34581	−3.54	0.0011
		Maple	433.9	167.1	2.60	0.0136
Poplar chips	0.90	Intercept	−4498.3	12154	−0.37	0.7132
		Season	--	--	--	NS
		Poplar	443.0	34.4	12.88	0.0001
Oak chips	0.91	Intercept	−6120.3	9071.9	−0.67	0.5038
		Season	--	--	--	NS
		Red oak	577.4	58.2	9.93	0.0001
		White oak	590.0	52.5	11.25	0.0001

[a]NS means the parameter estimate is not significant at the alpha = 0.05 level.

Poplar, pine, red oak, and white oak exhibited negative correlations with each other throughout the matrix. Thus, pine had a significant negative correlation with poplar and while not significant, pine had a negative correlation with both oak groups. Poplar was also negatively correlated with both oak groups. The exception was white oak and red oak, which were positively correlated.

The chips produced, as expected, were primarily dependent on their species classification. Thus, when more poplar, oak, and pine lumber was produced, so were the respective poplar, oak, and pine chips. Just as with the lumber, the oak chips negatively correlated with pine, poplar, and mixed species. In short, the whole matrix had a negative relationship to one another even though oak chips and mixed chips were not significantly related.

Poplar was the only species to significantly influence sawdust weight according to **Table 3**. However, in **Table 2**, this was not the case, where almost every species was important in predicting sawdust weight. While this seemed contradictory at first, the differences occur in the procedure used and will be discussed in the next section.

Discussion

Total production

When white oak and red oak were lumped together, there was a negative correlation between the four highest volume species groups (i.e., oak, poplar, pine, and mixed). The completely negative covariance matrix was an indication that these four species established the manufacturing capacity of the mill. In other words, if one species was produced more frequently, then the other three species must have decreased due to production capacity. According to Kallio (2001), the upper production boundary for a manufacturing firm is often not considered during modeling of short-term forest and mill productivity. Although not always significant, the less commonly produced species were generally negative in relation to the top four species. As a result, the Pearson correlation coefficient proved to be an efficient way to delineate the role of each species on mill capacity. Such a tool may particularly be important since species density, moisture, and log diameter can affect production rates. Forest managers should consider this limitation during harvest of widely available and reasonably priced species. Over-cutting these species could saturate the market with temporarily unusable material, resulting in price decreases and this may be particularly true for a smaller country or land area where fewer manufacturers and species create an oligopoly.

The SD for lumber produced was positively correlated with the total mean volume of lumber produced across species. Such variance inflation with increased production needs to be considered when modeling the effect of forest harvesting on mill production. Increased variance inflation suggests the primary species for harvest, for a given region, has less certainty in forecasting. For this paper, variance inflation may be defined as the increase in volume or weight variation that oc-

*Table 3. — Pearson correlation coefficient for each variable combination. Top cell is r-value and bottom cell is probability > |r| where * = significant at 0.05 p-value level, ** = significant at 0.001 p-value level, and *** = significant at 0.0001 p-value level.*

	Ash	Beech	Birch	Cherry	Hickory	Maple	Mix	Pine	Poplar	Red oak	White oak	Pine chip	Mix chip	Poplar chip	Oak chip	Saw-dust
Ash	--	−0.04	−0.04	−0.04	0.08	−0.02	−0.02	−0.12	0.16	−0.10	−0.07	−0.19	0.34 *	0.22	−0.14	0.39 *
Beech		--	−0.04	−0.30	0.45 **	−0.10	0.52 ***	−0.12	0.005	−0.04	0.14	−0.13	0.14	0.04	0.12	0.06
Birch			--	−0.03	0.45 **	−0.10	0.52 **	−0.12	0.005	−0.04	0.14	−0.14	0.15	0.04	0.12	0.06
Cherry				--	−0.06	−0.06	−0.11	0.05	−0.23	0.22	−0.007	0.08	−0.15	−0.20	0.05	−0.10
Hickory					--	−0.05	0.20	−0.15	−0.09	0.22	−0.04	−0.15	0.10	−0.10	0.20	−0.01
Maple						--	0.14	−0.21	0.10	−0.13	−0.10	−0.01	0.33 *	0.04	−0.10	−0.09
Mixed							--	−0.15	0.10	−0.30 *	−0.04	−0.11	0.59 ***	0.10	−0.13	0.16
Pine								--	−0.32 *	−0.21	−0.24	0.92 ***	−0.14	−0.36 *	−0.13	−0.18
Poplar									--	−0.26 *	−0.43 **	−0.25	0.09	0.90 ***	−0.50 ***	0.55 ***
Red oak										--	0.31 *	−0.25	−0.25	−0.13	0.52 ***	−0.06
White oak											--	−0.31 *	−0.04	−0.39 **	0.62 ***	−0.14
Pine chips												--	−0.07	−0.32 *	−0.48 **	−0.18
Mixed chips													--	−0.07	−0.16	0.24
Poplar chips														--	−0.40 **	0.62 ***
Oak chips															--	−0.08
Sawdust																--

curred with increased production of a given species or product.

For lesser produced species, one needs to be careful of extrapolation since extrapolation beyond the range of the independent variables increases the risk for error in the prediction of the dependent variable. Extrapolation could occur if an unusually large amount of stems suddenly become available for harvest for a particular species and geographic location. Any nonlinearity in the non-modeled region could result in gross errors when using these multiple linear models. An over- or under-production of that species would in turn have an influence on the short-term forecast of the fiscal environment. On the other hand, extrapolation might be a useful function of the model if linearity in each dimension exists.

The variation in chip production of pine, oak, and poplar was as expected when compared to the lumber volume produced for these same species (**Table 1**). However, for the mixed chips group, a lower variation in chip weight than any single species variation occurred. This was unexpected since the mixed species group was expected to have a larger variation in log diameter and green density, which should in turn increase the variation in by-product volume. As a result, the lower variation in mixed chips produced for this study should be taken with caution since it is only applicable to this case study and the composition of the mixed species was unknown.

Modeling

The cost of total logs per month was modeled without accounting for time dependent variables like inflation, housing starts, or secondary manufacturing demand. It was thought that perhaps the mixture of species would provide enough variation to yield strong predictive models. However, the variables only accounted for approximately 50 percent of the variation for cost of logs for a given month (**Table 2**). For log cost, only pine, poplar, and oak were significant predictors, although mixed species was almost significant. This was expected and was, once again, the result of the asymmetrical production numbers for these species relative to the lesser produced species.

The time of season was not important in predicting monthly log cost after manufacturing. This was unanticipated since weather fluctuations were expected to influence log supply. For example, in the Pacific Northwest of the United States, seasonal variation was found in monthly stumpage price data (Haynes 1991). It is probable that the chip weight variation for the mill was so great that a sample size greater than 42 months was needed to detect differences, while for Haynes (1991), the variation was reduced due to the averaging of many mills, thus making detection of seasonal influence more likely.

All species statistically shared a nearly equal part in predicting sawdust weight despite vast differences in lumber volume per species, indicating that sawdust production is simply a function of sawkerf or volume of lumber produced. The magnitude of variation for each coefficient (**Table 2**) was positively correlated to the SD of lumber produced for that species (**Table 1**), emphasizing the need to account for variation in wood procurement forecasting.

The season of production did not influence pine chip weight, while for mixed chips the season was important. Significance in mixed chips may be attributable to wider variation in density and/or moisture that probably occurs across species. Neither pine nor oak chip weight was influenced by season, indicating that seasonal variation does not play a significant role within a species but is important between species for chip and sawdust weight (**Table 2**). Since moisture variation did not exhibit significance for any other single species group, it was plausible that species composition, and hence density, changed in the mixed species group, which explains the significant weight variation. Such results agree with a similar study of a mechanical newsprint mill where seasonal variation in strength properties was attributed to variations in species (Fuhr et al. 1998). Another factor may have been an interaction between season and log storage time because logs with partial bark removal will dry out rapidly, particularly in the summer (Liukko and Elowsson 1999, Persson et al. 2002). Roise et al. (1999) quantified that a 10 percent loss in weight can occur in only 3 weeks during the summer. Myers and Richards (2003) found that for colder regions, the time of season forces mill managers to maintain high inventories to ensure adequate supply. After consideration of these possibilities and after discussions with the mill, the change in species composition was the most likely candidate to influence weight variation.

Material and product relationships

It was discussed earlier that poplar, pine, red oak, white oak, and also the mixed (unidentified species blend) were the most produced. The production of lower volume species was often a function of the major four groups regardless of whether statistical significance occurred or not in **Table 3**. The exception was hickory, beech, and birch, which were positively correlated to one another in lumber volume. When asked, the mill did not know of this subtle relationship. According to local forest procurement, these three species commonly grow in the vicinity of one another, with hickory and beech being fairly shade tolerant and often in the same stand. Likewise, on sandy loam soils, beech, birch, and maple commonly grow in a single stand (Harlow et al. 1991) even though maple showed no relationship to beech and birch for this study. Additionally, the mill likely saw more beech and birch from log suppliers on the west end of the mill, according to species maps (Harlow et al. 1991), which would make collective harvesting of these two species more likely. As a result, the high correlation between beech, birch, and hickory in production did not appear to be a function of demand pressure from lumber buyers.

We looked for an explanation of why only ash and poplar were significantly correlated with sawdust weight in **Table 3**, when it was obvious in **Table 2** that almost all species were needed to predict the weight of sawdust. The elucidation was straightforward after careful consideration. What the linear model in **Table 2** suggests is that almost all species together, or in combination, are needed to predict sawdust weight even though most species by themselves would not be successful in predicting sawdust weight.

Conclusions

The most important outcome from this study was that within a species, the season of manufacture did not significantly influence chip or sawdust weight while for mixed species, the season was significant. The significant mixed species weight was probably attributable to a variation in species mix throughout the year. Also, even though mixed species chip weight appeared low in variation when compared to pine, oak, or poplar chips, the interpretation was confounded since lumber volume variation increased as cubic volume of lumber increased. As a result, the additional variation in mixed species weight due to seasonal differences should be considered by buyers of chips and sawdust for value-added products. Also, the Pearson correlation coefficient method was useful in defining production constraints for each species. Finally, a positive relationship between hickory, beech, and birch lumber volume was found, which was most likely attributable to these three species growing in mixed or neighboring stands.

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