Relationship of species and season to sawmill by-product production: A case study

Brian K. Via*
Todd F. Shupe*

Abstract

The goal of this study was to investigate the effect of species and season on lumber and chip cost, sawdust, and chip weight. Logs were processed through a small sawmill for a 4-year period and board volume, chip weight, and sawdust weight were recorded. A total of 14 species, with a sample pool of 602 data points (43 data points per species lumber and chip groups), were available for model building. It was found that chip weight was not influenced by season for any one species. Conversely, for mixed species (n = 43), the period of processing had a considerable influence on chip weight. Since the season of production didn't influence chip weight for any one species, it is unlikely that a change in moisture influenced mixed chip weight. Instead, a shift in species composition over time was probably the cause of weight variation. Mill production capacity constraints were identified using the Pearson correlation coefficient. It was found that oak, pine, poplar, and mixed species all had negative relationships to one another. The negative relationships between these four species groups were attributable to the production capacity of the mill. All other low-volume species had, in general, a negative relationship to the major four species, although often not statistically significant. Hickory, beech, and birch were positively correlated with each other, which was probably a function of all three growing near one another and not a function of customer demand.

In the forest products industry, very rarely do manufacturers share production numbers with suppliers. As a result, procurement managers find it difficult to forecast log quantity and species needed by local mills and instead have to react to immediate market and environmental conditions during harvest. On the other hand, mills must balance production of lumber as a function of chip and lumber prices. Such independence between forest resources and manufacturing can be confounded for small sawmills that produce a range of products, from various species, and makes forecasting for log demand a challenging task (Kangas et al. 2000, Kallio 2001). Being able to predict which groups of species a mill might process at the same time would be useful for forest managers in prioritizing which species to harvest, but can only be done if manufacturers share production numbers. Also, when there is a correlation between the volume of two species produced per unit of time, manufacturers may reduce quality control costs by monitoring only one species. When it is cost effective, the mill can step up their quality control by monitoring both species and use multivariate T2 charting to detect outlying performance (Hawkins 1991, Wade and Woodall 1993, Lowry and Montgomery 1995).

The production of chip and sawdust residue is another factor important to small sawmills and perhaps forest procurement. Since pulpwood supplies are plentiful and increasing in availability, it is quite possible that the pulpwood industry may need less sawmill residue to support mill needs (MacPeak et al. 1987, MacPeak et al. 1990, Kennedy 1995, Barbour 2001). Such increase in availability of pulpwood has been coupled with more pulpmills closing down rather than opening up. Any change in residue demand would surely affect the behavior of small sawmills who rely on pulpmills and particleboard mills to purchase residue (Kibblewhite et al. 1991, Xu and Suchsland 1999).

When purchasing sawdust or chips, pulpmills or particleboard mills usually buy on a weight basis even though it may not be an accurate indication of value. Such variation in weight is assumed to represent density and volume variation. Any significant moisture variation is undesirable and will hinder the ability to yield a fair residue price (Dubois 1998).

The authors are, respectively, PhD Candidate and Associate Professor, School of Renewable Natural Resources, Louisiana State Univ. Agri. Center, Baton Rouge, LA (bvia1@lsu.edu; tshupe@lsu.edu). This paper (04-40-0192) is published with the approval of the Director of the Louisiana Agri. Expt. Sta. The authors would like to thank Dr. Jamie Barbour for his thorough review. This paper was received for publication in April 2004. Article No. 9876.
*Forest Products Society Member.

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However, for forest procurement, seasonal conditions can influence site availability for harvest and perhaps the moisture of the raw material (Felker and Guevara 2003). Any bias in harvesting due to seasonal differences in moisture may have an impact on tree or residue weight and is worthy of consideration.

Aside from density and moisture variation, chip and sawdust weight can also be a function of log diameter (Barbour 1999). Likewise, lumber grade distributions can change with log diameter (Stevens and Barbour 2000). As a result, it is important to report if log diameter varies significantly during the course of a study. For chips composed of a mixture of species, the variation in weight can be a function of differences in density between different species. Any change in species composition could result in a change in raw material properties. Species composition variation is a growing concern in the pulping industry because it directly adds variation to pulp yield and paper properties (Fuhr et al. 1998).

The goal of this study was to investigate the effect of species and season on the cost, volume, and weight for lumber, chips, and sawdust. Data were obtained on a monthly basis for 4 years. Costs were modeled by multiple regression to determine if species and season were important variables. All lumber, chip, and sawdust variables were tested for cross correlation using the Pearson correlation coefficient with the goal of identifying relationships between log species or log species and residue.

Materials and methods

Processing

The selected sawmill was located in the northern portion of North Carolina in the United States. It produces an average of 8300 m^3 per year of both hardwood and softwood lumber including ash (*Fraxinus* L.), beech (*Fagus grandifolia*), birch (*Betula* L.), cedar (*Juniperus virginiana* L.), cherry (*Prunus* L.), hickory (*Carya* Nutt.), gum (*Nyssa sylvatica* Marsh. and *Liquidambar* L.), maple (*Acer* L.), pine (*Pinus* L.), poplar (*Liriodendron tulipifera* L.), red oak (*Quercus rubra* L.), walnut (*Juglans nigra* L.), and white oak (*Quercus alba* L.). The most common species processed by the mill were red and white oak, poplar, and pine. The other species were also produced but in notably less quantities (**Table 1**).

Species were organized in the logyard so that one species at a time could be cut. Typical products made by the sawmill were 5/4 and 4/4 (U.S.) lumber for furniture and flooring stock orders. Pallet stock and cants were also processed. A conventional sawing system was employed with logs manually positioned at the head saw on a dogging carriage. The aim of the sawyer was to optimize volume for pallet stock; the goal for furniture or flooring stock was to maximize volume and lumber visual grade. The set works for the head saw were hydraulic and a back stand indicator was used to determine the proper positioning.

After processing, the green lumber was stacked on stickers. A kiln was not available at the mill and the lumber was instead dried by distributors. Chips were conveyed from the manufacturing process to a truck bin such that the weight of the wet chips could be measured via a truck scale and shipped to a local buyer, often a pulpmill. Sawdust was also collected and measured on a weight basis. Chips and sawdust were measured for metric ton weight while volume was recorded for lumber produced. Values were available for a total of 43 months. A sample size of 602 total data points for lumber and residue were available for all lumber species combined (43 data points per species or species group) and was used to either determine coefficient significance or to eliminate variables not significant in predicting chip and sawdust weight, or mill cost.

Table 1. — Mean lumber, chip, and sawdust produced per month between years 1999 and 2002 (n = 43 months).

	Mean	Standard deviation
	(m^3)	
Lumber		
Ash (*A*)	9.7	34.9
Beech (*Be*)	0.1	0.5
Birch (*Bi*)	0.3	1.9
Cherry (*C*)	0.4	2.1
Hickory (*H*)	4.4	16.0
Gum (*G*)	0.5	3.3
Maple (*Ma*)	19.0	31.0
Mixed (*Mi*)	35.8	63.1
Pine (*Pi*)	144.0	186.9
Poplar (*Po*)	298.0	192.0
Red oak (*R*)	89.4	97.2
Walnut (*Wa*)	0.6	2.7
White oak (*W*)	78.1	107.8
Total	680.3	
	(metric tons)	
Chips		
Pine	93,875	106,184
Mixed species	48,878	47,433
Poplar	127,512	95,000
Oak	91,566	83,676
Sawdust	243,262	58,343
Total by-products	605,093	

Log, lumber, and chip inventory

Logs were organized by species in the logyard upon arrival. Mixed species logs were sometimes purchased and processed into mixed lumber, which also resulted in mixed chips (**Table 1**). The species of mixed logs were not recorded and they were marketed as mixed lumber and chips. The mixed species group usually did not contain the same species as single species groups, except for an occasional log of exceptionally small diameter. Instead, the mixed species group almost always consisted of anomalous species that were processed together since alone they did not yield any value. Otherwise, species were processed a group at a time so as to ensure proper identification during the sale. After processing, the lumber was stacked by species, measured for volume, and recorded on a daily basis. This daily figure was summed to yield a monthly figure at the sawmill. Daily values were not made available to investigators. Also, each load of chips per species was loaded onto a truck and sent to a papermill. Then 1 to 5 days later, the papermill received and measured the weight of chips in tons. The sawmill then recorded this weight. All pine chips were kept separate due to a higher dollar value paid by the papermill. The total weight of chips was also summed up 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.

Literature cited

Barbour, R.J. 1999. Relationship between diameter and gross product value for small trees. *In*: Proc. Wood Tech. Clinic and Show No. 27. Wood Tech. and Miller Freeman, Portland, OR. pp. 40-46.

__________. 2001. Log and lumber grades as indicators of wood quality in 20- to 100-year-old Douglas-fir trees from thinned and unthinned stands. Gen. Tech. Rept. PNW-GTR-510. USDA Forest Serv., Pacific Northwest Res. Sta., Portland, OR. 23 pp.

Dubois, M.R. 1998. A comparison of stumpage valuation methods for procuring wood used in linerboard production. Forest Prod. J. 48(10): 35-42.

Felker, P. and J.C. Guevara. 2003. Potential of commercial hardwood forestry plantations in arid lands - Economic analyses of *Prosopis* lumber production in Argentina and the United States. Forest Ecol. Manage. 186(1-3):271-286.

Fuhr, B.J., D. Henry, G. Leary, and G. Smith. 1998. Seasonal variations at a mechanical newsprint mill – Chip properties linked to the time of year. Pulp Pap. Can. 99(2):45-49.

Harlow, W.M., E.S. Harrar, J.W. Hardin, and F.M. White. 1991. Textbook of Dendrology. McGraw Hill, NY. pp. 501.

Hawkins, D.M. 1991. Multivariate quality-control based on regression-adjusted variables. Technometrics 33(1):61-75.

Haygreen, J.G. and J.L. Bowyer. 1989. Forest Products and Wood Science: An Introduction. Iowa State Univ. Press, Ames, IA. 500 pp.

Haynes, R.W. 1991. Monthly stumpage prices for the Pacific-Northwest. PNW Re. (436): U1-U1. USDA Forest Serv., Pacific Northwest Res. Sta., Portland, OR..

Kallio, A.M.I. 2001. Interdependance of the sawlog, pulpwood and sawmill chip markets: An oligopsony model with an application to Finland. Silva Fenn. 35(2):229-243.

Kangas, J., P. Leskinen, and T. Pukkala. 2000. Integrating timber price scenario modeling with tactical management planning of private forestry at forest holding level. Silva Fenn. 34(4):399-409.

Kennedy, R.W. 1995. Coniferous wood quality in the future - Concerns and strategies. Wood Sci. and Tech. 29(5):321-338.

Kibblewhite, P.R., A.D. Bawden, and M.C. Hughes. 1991. Hardwood market kraft fibre and pulp qualities. Appita J. 44(5):325-332.

Liukko, K. and T. Elowsson. 1999. The effect of bark condition, delivery time and climate-adapted wet storage on the moisture content of *Picea abies* (L.) Karst. pulpwood. Scand. J. Forest Res. 14(2):156-163.

Lowry, C.A. and D.C. Montgomery. 1995. A review of multivariate control charts. IIE Trans. 27(6):800-810.

MacPeak, M.D., L.F. Burkart, and D. Weldon. 1987. A mill study of the quality, yield, and mechanical properties of plywood produced from fast-grown loblolly pine. Forest Prod. J. 37(2):51-56.

__________, __________, and __________. 1990. Comparison of grade, yield, and mechanical properties of lumber produced from young fast-grown and older slow-grown planted slash pine. Forest Prod. J. 40(1):11-14.

Myers, J. and E.W. Richards. 2003. Supporting wood supply chain decision with simulation for a mill in northwestern BC. INFOR 41(3): 213-234.

Neter, J., M.H. Kutner, C.J. Nachtsheim, and W. Wasserman. 1996. Applied Linear Statistical Models. McGraw-Hill, Boston, MA. 1408 pp.

Nyrud, A.Q. and E.R. Bergseng. 2002. Production efficiency and size in Norwegian sawmilling. Scand. J. Forest Res. 17(6):566-575.

Persson, E., J. Filipsson, and T. Elowson. 2002. Roadside storage of Nor-way spruce (*Picea abies* (L.) Karst.) pulpwood: Effect on moisture content of climate conditions, felling season and exposure. Paperi Puu-Pap. Timber 84(3):174-178.

Roise, J.P., P.E. Whitlow, and E.L. Deal. 1999. Equations for predicting weight loss in stored pulpwood for North Carolina and Virginia. Forest Prod. J. 49(1):77-81.

Ronchetti, E. and R.G. Staudte. 1994. A robust version of mallows c(p). J. Am. Stat. Assoc. 89(426):550-559.

SAS Institute (SAS). 2001. SAS/STAT statistical analysis software. Version 8. SAS, Cary, NC.

Smith, P.M., S. Dasmohapatra, and W.G. Luppold. 2004. A profile of Pennsylvania's hardwood sawmill industry. Forest Prod. J. 54(5): 43-49.

__________, W.G. Luppold, and S. Dasmohapatra. 2003. Estimating the size of the hardwood sawmill industry in Pennsylvania. Forest Prod. J. 53(6):19-22.

Stevens, J.A. and R.J. Barbour. 2000. Managing the stands of the future based on the lessons of the past: Estimating western timber species product recovery by using historical data. Gen. Tech. Rept. PNW-GTR-528. USDA Forest Serv., Pacific Northwest Res. Sta., Portland, OR. p. 9.

Wade, M.R. and W.H. Woodall. 1993. A review and analysis of cause-selecting control charts. J. Qual. Tech. 25(3):161-169.

Xu, W. and O. Suchsland. 1999. Within-panel variability and selected property relationships of particleboard from single- and mixed-species processes. Forest Prod. J. 49(10):36-40.