From tree cutting to pulping: the impact of storage time on pulp mill economics

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ABSTRACT: Variability in wood properties has a major impact on pulp quality and the cost associated with pulp production. Frequently, accounting data for green tons of wood across the mill scales and the tons of pulp produced suggest that the pulp mill has affected the pulp yield because the tons of purchased wood divided by the tons of pulp produced changes. The current work examines the impact of the time — from when a tree is harvested in the forest to the time it is brought across the scales at the mill — on accounting yield and operating cost. Percentage weight loss (assumed to be changes in moisture content) were determined for *Pinus taeda*, *Eucalyptus dunni*, and *Eucalyptus grandis* over a 12-week period in the winter and summer seasons. Wood samples were obtained immediately after being harvested. The percentage weight loss within the first 5 days of storage varied from 2% to 13%, depending upon species and season, and reached 36% after 11 weeks of storage. For a 1000 tons/day mill with a 55% pulping yield on o.d. fiber, the difference between using fresh-cut wood verses cut trees that have been stored for 11 weeks is 1130 green tons. Assuming the mill pays $45/green ton, the change in green log usage between fresh-cut and 11-week-old logs can cost the mill US$50,850 per day.

Application: A better understanding of variations in pulp yield may be beneficial to mill personnel in reconciling production and accounting data.

In today's manufacturing environment, the pulp mill superintendent is responsible for technical operation of the mill while maintaining all of the administrative and accounting practices mandated by senior management. One of these mandated goals is pulp yield, or the tons of green wood required to produce an o.d. ton of pulp. When the amount of wood required to produce a ton of pulp increases, the superintendent has to determine and explain what operational practices resulted in the increased wood demand and what steps will be taken to mitigate the increased wood consumption in the future. Often, the monthly changes in yield cannot be readily explained by changes in operational procedures.

The monthly changes in the wood handling and properties have a significant impact on the operating cost of the mill; therefore, maintaining proper control and understanding operational targets is important from an economic perspective. Unfortunately, the raw material is not particularly uniform. Extreme variability exists among different wood species and even within a specific wood species. Nonuniformity of these raw materials can result in variability in the pulp mill operation and in properties of the pulp produced. Wood age, genetics, and environmental factors affect pulp mill operational variables directly and indirectly.

The pulp mill superintendent is responsible for pulp yield, which is typically measured by taking the green weight of wood purchased at the gate and dividing it by the amount of pulp actually produced. Over the past several years, reported studies have shown that wood moisture, and hence pulp yield, exhibits a seasonal component [1,2]. Often, this seasonal component is not accounted for in the pulp yield goals established by management; thus, the superintendent has to account for changes from target even though the change occurs every year.

Watson and Stevenson [3] studied the effect of seasonal variation on the moisture content and chip size distribution produced in a mill. These variations interfere with the wood yield and affect the amount of cooking chemicals consumed. When higher-moisture cold or nearly frozen wood is processed, more fines and pins are produced; this is especially the case with pine [1]. Also, wood debarking varies according to the moisture content [1,2,4]. For eucalyptus, bark removal becomes easier when the wood has higher moisture content. Typically, eucalyptus bark is easy to remove up to about 20 days after the tree is cut. Eucalyptus passes through an intermediary period — between 30 and 120 days after being cut — during which it is extremely difficult to remove the bark. After the 120-day mark debarking generally starts to improve until about 180 days, when the tree becomes relatively easy to debark [5].

If the yield calculation is done using green wood, seasonal variations will result in monthly yield fluctuations [1–3]. These fluctuations will affect the wood cost to produce a ton of pulp and as result, the pulp mill superintendent will miss his or her yield target. Frequently, the yield calculation employed by accounting is based on fixed values that do not take seasonal variations into consideration.

Hart and Samistraro [1,2] observed that seasonal variability in the moisture content of pine can change the yield per ton of pulp by as much as 0.5 tons of green wood for the production of the same ton of o.d. pulp, depending upon the average moisture content. The authors found that the summer-to-winter moisture variation for eucalyptus harvested in southern Brazil was about 1.7 percentage points. The increase in green wood directly results in increased operating cost for the pulp mill. Hart [1] noted that the moisture content of pine changed by 4.5 percentage points between the driest summer months and the wettest winter months in the southern United States.

Recently, changes in management and accounting practices have led to a forced reduction of in-process inventory in the forest and wood stockyards. Instead of stockpiling cut trees until they can be conveniently scheduled to be hauled into the mill, the in-forest yards are working on a more rapid turnaround time. If the mill purchases wood on a dry-fiber basis, this reduction of in-woods process inventory will not impact the mill at all; however, mills typically purchase wood on a green basis [6]. Green wood weight is the primary measure used in buying and selling wood for most wood-based industries.

This change in management practice to reduce in-process wood inventory was found to have an adverse impact on pulp mill yields. The amount of green wood required to produce an o.d. ton of pulp was found to increase at about the same time that the fresher wood was starting to be processed. The noted change in wood yield that correlated with the change in forestry management and harvesting practices led to a review of the impact of the time since harvest, weather conditions, and seasonality upon the moisture content of the wood entering the mill and its resulting impact on the calculated pulp mill yield.

One of the important wood characteristics, either in commercial transactions of forest producers or when the wood comes into a pulp and paper mill, is the moisture content. This characteristic depends on the species, site, cutting time, length, wood storage method, geographical location, and weather conditions [4,7]. The knowledge concerning weight, volume, moisture content, and quality becomes essential when pulp mill processing targets are affected by the green weight of wood entering the mill.

The balance of the wood moisture content and the environment depends, mainly, on the temperature and relative humidity of the air. After a tree has been cut, it has a high moisture content that slowly diminishes, up to the point when the wood reaches equilibrium with the environment to which it is being exposed. Free or capillary water initially evaporates from the cell lumens, then the adherence water contained in the cell walls starts to evaporate. This point, called the fiber saturation point (FSP), has been reported to average 28% for all species of wood [8]. Water is still contained within the fibers at the FSP and is part of the wood chemical composition. Stein [4] suggests that the rate of moisture (weight) loss is greatest within the first week after harvesting. He also suggests that after about the fourth week, wood moisture loss slows substantially.

The current work examines the impact of the time, from harvesting to processing in the mill, on the pulp mill yield. For this study, the impact of in-process storage time on the weight loss of *Eucalyptus grandis* (8 years old), *Eucalyptus dunni* (5 years old) and *Pinus taeda* (14 and 19 years old) was determined. The impact of wood moisture change with storage on the calculated wood yield and on pulp mill economics was also determined.

MATERIALS AND METHODS

The wood used in this work was obtained from two different locations in Brazil and from South Carolina, USA. The 8-year-old *E. grandis* was obtained from the Itapeva-SP region, Brazil; the 5-year-old *E. dunni* and the 12-year-old *P. taeda* was obtained from Rigesa's plantations located in Três Barras-SC,

	Pinus taeda		*Eucalyptus dunni*		*Eucalyptus grandis*		
	Winter	Summer	Winter	Summer	Winter	Summer	Unit
Bark (green weight)	288,0	401,2	208,6	729,1	853,5	367,8	g
Bark (dry weight)	154,3	204,4	126,7	298,2	348,6	142,1	g
Bark consistency	53,6	51,0	60,7	40,9	40,8	38,6	%
Volume of log without bark	4.786,6	6.180,5	2320,4	4011,9	4794,1	4165,1	ml
Weight of dry log without bark	1.768,2	2.440,4	1033,4	2066	2177,2	1393,4	g
Basic density	0,3694	0,3949	0,4454	0,515	0,454	0,335	g/cm³
Wood without bark (green weight)	4.551,5	6.055,4	2274,3	4174,8	4661,6	3159,3	g
Wood without bark (dry weight)	1.768,2	2.440,4	1033,4	2066	2177,2	1393,4	g
Wood consistency	38,8	40,3	45,4	49,5	46,7	44,1	%
Diameter (with bark)	200,0	183,9	145,1	155,8	168,5	140,2	mm
Diameter (without bark)	189,7	173,6	137,7	143,2	153,6	133,5	mm
Difference	10,3	10,3	7,4	12,6	14,9	6,7	mm

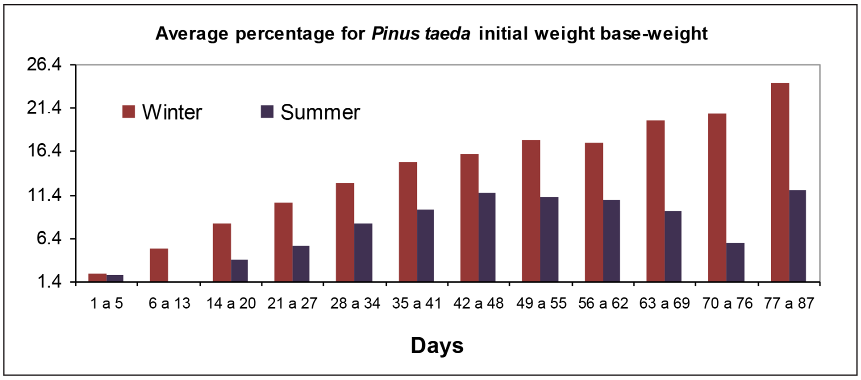
I. Basic density and moisture levels of wood and bark for each species.

Brazil. The Rigesa plantations are located at an altitude of 800 m, south latitude of 26º, and longitude of 50º [9]. The Rigesa plantations are located in a humid mesothermic climate with a harsh winter prone to frosts and hot summers with an average annual temperature of 17.1ºC (Cfb Köppen climate classification). Additional 21-year-old *P. taeda* trees were obtained from South Carolina.

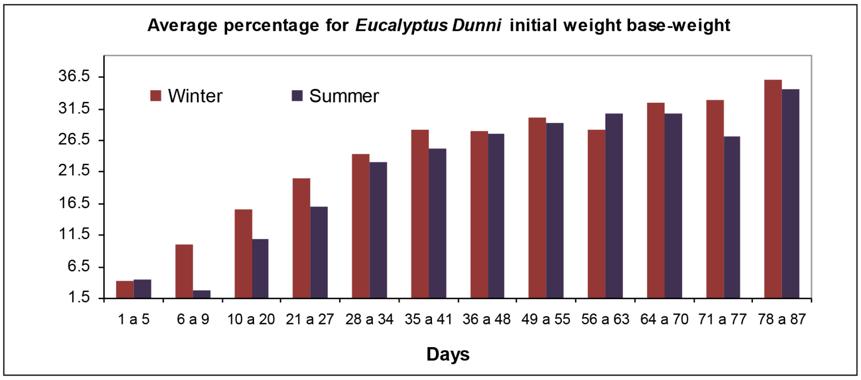
A number of randomized trees obtained from the same plantation were cut and processed for this study in both the summer and winter seasons. The trees were felled, cut into logs of 3-m lengths, and transported to the mill storage site on the same day. Once at the mill site, the logs were weighed, numbered, and left under the open sky exposed to ambient humidity and weather conditions.

The study in Brazil was performed twice during two distinct seasonal conditions. The first phase was performed during the winter, from August to November, and the second phase was performed during the summer, from December to February. The study in South Carolina study was conducted in each of the four different seasons. Each log was weighed after 5 days of storage, and then weekly for 11 weeks. The study was performed for 87 days during each of the seasons examined.

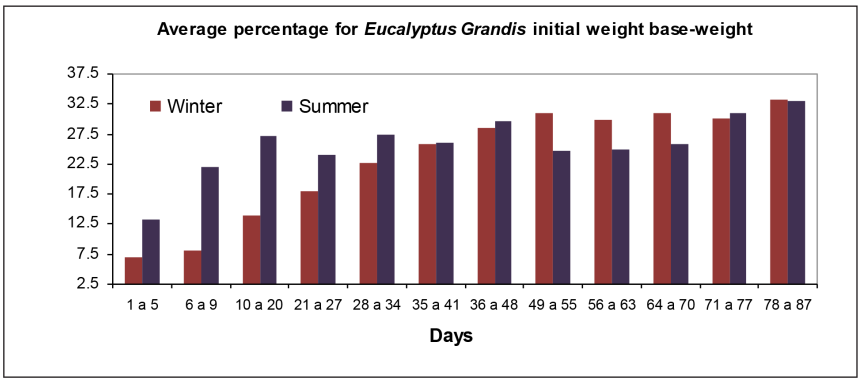
Representative transversal sample disks (bark + sapwood + core wood) were obtained from each of the species examined and the basic density (g/cm³) was determined by the water immersion method [10]. Disks were obtained from different diameter classes along the stem of the tree. The disk diameters were measured with and without bark, debarked, and then immersed in water until saturated. The initial moisture content of the wood and bark was determined by oven drying at 105°C. The basic density values of each species and the moisture contents of the wood in the green state are shown by species and season in **Table I**.



1. Weight loss over the winter and summer periods for **Pinus taeda*.***



2. Weight loss over the winter and summer periods for **Eucalyptus dunni*.***



3. Weight loss over the winter and summer periods for **Eucalyptus grandis*.***

RESULTS AND DISCUSSION

Basic density

The *E. grandis* was found to have a lower basic density than the *E. dunni*. It was also determined that the calculated basic density for *E. grandis* used in this study was lower than reported literature values. In general, *E. grandis* wood basic density has been reported to range from 0.458 g/cm³ [11] to 0.507 g/cm³ [12]. The work of Gonzaga found *E. grandis* to have a relatively low basic density compared to several other eucalypt species [11]. The basic density for *E. dunni* has been reported in the literature to range from 0.444 g/cm³ to 0.486 g/cm³ [12]. The basic density values of the *E. dunni* samples in the current work were about the same as those reported in the literature.

Moisture loss upon storage

Figures 1, **2**, and **3** show the cumulative weight loss by species for both the summer and winter studies during the first 5 days and during the 11weeks (87 days total) for each of the three species. The cumulative weight loss was calculated to take into consideration the amount of weight loss in the specific week and the initial

Season	Diameter Class (in.)	Days Since Felling[a,b]							
		14-17	21-23	28-29	35-36	42-44	48-50	55-58	69-72
Fall	6	6.5 (a)	11.5 (a)	14.4 (a)	*	17.6 (a)	23.7 (a)	24.4 (a)	26.2 (a)
	8	6.6 (a)	11.5 (a)	14.6 (a)	*	17.6 (a)	21.3 (a,b)	23.3 (a,b)	25.5 (a)
	10	6.3 (a)	10.9 (a)	13.6 (a)	*	16.0 (a)	18.8 (b)	19.4 (a)	20.8 (a)
Winter	6	3.3 (a)	7.1 (a)	8.5 (a)	9.9 (a)	11.0 (a)	13.5 (a)	15.8 (a)	17.2 (a)
	8	2.8 (a)	4.8 (a)	5.7 (a)	7.1 (a)	8.4 (a)	10.3 (b)	12.3 (b)	14.9 (a)
	10	3.0 (a)	5.3 (a)	5.8 (a)	7.1 (a)	8.1 (a)	9.7 (b)	11.3 (b)	11.3 (a)
Spring	6	7.6 (a)	12.3 (a)	15.4 (a)	19.1 (a)	22.9 (a)	24.5 (a)	28.0 (a)	27.6 (a)
	8	6.9 (a)	10.4 (a)	12.8 (a)	17.3 (a)	20.5 (a)	21.9 (a)	22.8 (a)	23.6 (a)
	10	7.0 (a)	10.7 (a)	14.1 (a)	18.7 (a)	22.9 (a)	25.3 (a)	26.8 (a)	25.9 (a)
Summer	6	14.6 (a)	17.9 (a)	21.5 (a)	22.1 (a)	21.8 (a)	21.0 (a)	22.6 (a)	19.3 (a)
	8	18.1 (a)	20.6 (a)	24.6 (a)	25.7 (a)	26.5 (a)	26.3 (a)	26.9 (a)	23.1 (a)
	10	14.3 (a)	16.4 (a)	19.2 (a)	20.6 (a)	22.9 (a)	18.4 (a)	19.9 (a)	19.5 (a)

[a]Within seasons, only periods shown to be significantly different in ANOVA tests were compared using t-separate pairwise tests. Differences were significant at the .05 level of probability.
[b]Diameter classes followed by the same letter (a and/or b) are not significantly different within the same period.
*Not measured.

II. Average percentage weight loss by diameter class, days since felling, and season for* Pinus taeda *cut in South Carolina.

weight loss to show the percentage weight loss in relation to the initial harvest time.

During the first few days after a tree is cut, a significant amount of moisture is lost to the atmosphere. When a mill purchases wood on a green basis, this rapid weight (moisture) loss generates benefit for the mill if the tree is not processed though the mill scale house; reduced transportation and raw material costs result. Changes in forestry management practices that have significantly decreased the time between tree cutting and delivery to the mill have resulted in the mill purchasing and transporting more water.

The weather conditions for the evaluation periods were characterized in the winter months (August, September, October, November) by an average minimum temperature of 2.3ºC with two frosts and average precipitation of 125 mm, including the highest index of precipitation of the year in October. There were 33 rainy days in total. In the summer months (December, January, February) the average minimum temperature was 12.3ºC, with average precipitation of 199.6 mm and 50 rainy days.

Moisture loss was greatly influenced by seasonal changes. *P. taeda* was especially affected during the summer; there was no wood weight loss due to particularly heavy rainy periods. Figs. 1–3 show significant wood weight loss during the winter for the *P. taeda* compared to the summer, corresponding to 24.3% at the end of the evaluated winter period and 12.0% during the summer. The large difference in wood weight loss was directly attributed to the rainy period in the summer. The eucalypt species were not as significantly affected by the rainy period.

The *E. dunni* and *E. grandis* woods had weight loss totaling 36.1% and 33.3%, respectively, over the 87-day evaluation period. As with the *P. taeda* species, the greatest weight loss for both eucalypt species occurred during the winter months.

Season	Days Since Felling[a]							
	14–17	21–23	28–29	35–36	42¬–44	48–50	55–58	69–72
Fall	6.5(a)	11.3(a)	14.2(a)	*	17.1(a)	21.3(a)	22.4(a)	24.2(a,d)
Winter	3.0(b)	5.7(b)	6.7(b)	8.0(a)	9.2(b)	11.2(b)	13.1(b)	14.5(b)
Spring	7.2(a)	11.1(a)	14.1(a)	18.4(b)	22.1(c)	23.9(a)	25.9(a)	25.7(a)
Summer	15.7(c)	18.3(c)	21.8(c)	22.8(b)	23.1(c)	21.9(a)	23.1(a)	20.6(d)

[a]Numbers within a column sharing a common letter (a, b, or c) are not significantly different at the .05 probability level.
*Not sampled.

III. Average percentage weight loss across diameter classes for trees stored with their crowns intact for* Pinus taeda *cut in South Carolina.

Species	Season	Initial Moisture (%)	Pulp Yield (green tons of wood/o.d. ton pulp)			
			Day 0	Day 5	Day 34	Day 87
Pinus taeda	Summer	59.7	4.51	4.37	4.03	3.83
	Winter	61.2	4.67	4.51	3.89	3.38
Eucalyptus dunni	Summer	50.2	3.67	3.52	2.98	2.71
	Winter	54.6	4.00	3.81	3.10	2.79
Eucalyptus grandis	Summer	55.9	4.12	3.53	3.06	2.90
	Winter	53.3	3.89	3.61	3.09	2.82

IV. Impact of in-woods storage on the pulp yield, measured as green tons of wood per ton of pulp assuming a 55.0% yield on o.d. wood entering the digester.

E. grandis, during the months that correspond to summer (December to March), displayed significant moisture loss in the first 20 days and virtually stabilized in the following weeks. During the winter, there was a gradual increase in moisture loss, with a smaller response after 36 days. The moisture content in this species was around 5.0% higher in the logs cut in the summer. As for the *E. dunni*, its behavior was similar in the winter and summer, with slower weight loss after 50 days.

In addition to the work performed in Brazil, a study was conducted with 19-year-old *P. taeda* obtained from the Redwood Unit Plantation in South Carolina. The study was conducted with felled trees cut to a 10 cm (4-in.) top and trees with the tops intact. This study covered all four seasons of the year and was conducted with 81 trees with diameter classes of 6-8 in. and 10 in., with 24 trees per diameter class. The weight loss was significantly different in the different seasons of the year. The trees without a top experienced the maximum weight loss percentage after 4 weeks in the fall, 10 weeks in the winter, 8 weeks in the spring, and 3 weeks in the summer. For the trees with tops, the highest loss percentage was 25.9% over 7 weeks of storage in the summer. **Table II** shows the weight loss for those logs cut to only 10 cm at the small end, and **Table III** shows the weight loss for logs with the tops intact. The presence of crowns did not alter the rate of or final equilibrium moisture content of the logs.

Stein stated that a study was conducted that examined the presence of bark upon moisture loss in 7-year-old, 2.2-m-long *E. grandis* logs in two different regions [4]. The highest weight losses were realized after 3–4 months of storage. At the end of 168 days after the logs were cut, a 30.0% moisture loss was realized. Only after 3 months of storage did the wood with bark have greater weight loss than the debarked wood. This study concluded that there was meaningful moisture loss up to the 3 months after the tree was cut. After this period, the drying rate was slower and weight loss was more closely associated with biological degradation instead of moisture loss.

Impact of moisture cycles on pulp mill economics and yield

The practice of storing cut logs in a forest woodyard or stockpiling them in a harvested log storage area before shipping to the mill can be very advantageous for the pulp mill, in terms of economics and pulp yield. If the calculation of wood yield is performed using green wood, the moisture loss cycle reported earlier causes large variations in the wood yield and in the raw material cost required to produce a ton of pulp. **Table IV** shows the impact of storing logs 5–87 days after cutting on the green yield obtained in the pulp mill. The data in Table IV were calculated assuming a constant pulp yield of 55.0% based on o.d. fiber. As shown, simply storing wood for 5 days after cutting before bringing the logs across the mill

Species	Season	$/o.d. Ton Pulp Change*		
		Day 5	Day 34	Day 87
Pinus taeda	Summer	6.41	21.75	30.64
	Winter	7.33	35.21	58.10
Eucalyptus dunni	Summer	7.10	31.41	43.12
	Winter	8.86	40.76	54.56
Eucalyptus grandis	Summer	26.59	47.83	54.83
	Winter	12.96	35.92	48.25
*Change determined as reduced cost from wood cut and delivered across the pulp mill scales on the same day.				

V. Impact of changes in moisture content on the cost of 1 o.d ton of pulp assuming a wood cost of $45/green ton and a 55.0% pulp yield on o.d. fiber.

scales can result in a green yield change of 0.14 green tons of *P. taeda* per ton of pulp in the summer and 0.16 green tons in the winter. For *E. dunni*, the yield change was 0.16 green tons in the summer and 0.20 green tons in the winter. The yield change for *E. grandis* was determined to be 0.59 green tons in the summer and 0.29 green tons in the winter.

If one assumes a wood cost of $45 per green ton across the mill scales, the then operating cost per ton of fiber produced can be significantly affected simply by the time elapsed between the cutting of a tree and the passing of tree across the mill scales. **Table V** shows the change in cost per o.d. ton of pulp produced resulting from the green yield changes shown in Table IV. Looking at the largest yield change between 0 days of storage and 87 days of storage, the impact on fiber cost can be more than $50 per ton of pulp for all three of the species examined.

Proper accounting of these variations may also result in a savings of pulping chemical consumed. Frequently, fixed moisture content is applied to the digester and a set chemical charge is added based upon this moisture content. In most cases, the amount of applied alkali (white liquor) is set higher than required to account for wood with lower moisture content periodically entering the digester. In practice, this assumed moisture content is changed roughly twice per year to account for gross seasonal swings [1]. If an accurate online moisture measurement were available, it would be possible to add the proper amount of white liquor and thus reduce the total amount of chemical consumed in the pulping process.

The cost to transport the stored wood also is of interest. When a mill obtains eucalypt logs that have been stored for several weeks (roughly 28 days or longer) in the field before being transported to the mill, the net weight of logs will be reduced by 25.0%–30.0%. If fresh-cut logs are transported directly to the mill scales, then the mill will pay higher freight costs plus pay for 25.0%–30.0% extra water that will not produce a single additional ton of pulp. As for *P. taeda*, this study suggested a 17.8% weight loss in the winter and an 11.0% weight loss in the summer after a 50-day storage time. Storage of logs either with or without crowns was found to not have a large influence on the moisture loss associated with in-woods storage.

Of note, the current study only evaluated the impact of moisture loss due to storage. No attempt was made to determine the relative amount of wood decay resulting from biological activity during the storage of logs over a long period. Several reports have suggested that wood can easily be stored for at least 45–90 days before experiencing large amounts of weight loss due to biological activity [4,13]. Thus, bacterial decay should not have played a major part in the reported weight loss. In addition, visual examination of the logs during the weekly weighing process did not note significant levels of wood decay.

CONCLUSIONS

For the transport of wood and its use in the pulping process, the in-field storage of logs for a period of at least 28 days for eucalypt species could reduce the water content about 22.0%–25.0% during the winter and 23.0%–28.0% during the summer. The reduction in water in the wood going across the mill scales can result in a change in the calculated pulp yield of 0.7–1.0 ton of green wood per o.d. ton of pulp produced. The economic benefit of this change in green yield is roughly $30–$40 per ton of pulp produced.

The moisture changes resulting from in-process storage of cut wood before crossing the mill scales was found to be quite substantial. These moisture changes resulted in large changes in the calculated wood yield determined as tons of green wood consumed per ton of pulp produced. Often, just a few days' variation of the in-process storage time before entering the mill will result in substantial changes in the calculated yield and result in significant monthly changes in the pulp mill monthly yield numbers. Because mills do not have a good understanding of the moisture content of the logs entering the mill, any attempt by the pulp mill superintendent to account for yield changes of 0.1 ton green wood per o.d. ton of pulp produced is relatively futile. **TJ**

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ABOUT THE AUTHORS

Over the past several years, the pulp mill superintendents in several of our mills have have had difficulties attempting to reconcile actual pulp yields with the pulp yields predicted from accounting data. The current effort represents an attempt to explain, through the correlation of data, which variables directly influence the consumption of wood from the mill and which variables are characteristics of the wood itself that influence the cost of mill-produced pulp. These variables are represented by the economic analysis performed in the study.

Previous efforts to determine changes in accounting versus actual yield were focused on seasonal variations in the raw materials. The current work examines the impact of the time from tree felling until the time the tree is brought across the millyard scales.

An extensive amount of coordination was required between the mill and forestry personnel to obtain fresh-cut wood samples and immediately get them into the mill and weighed. Once the logs were in the mill, it was important to ensure that the samples were weighed in the same manner and at the prescribed time for an entire year. Diligent attention to the established procedures was essential to successfully complete this work.

The amount of moisture loss in the first 2 weeks after harvest was far greater than we had expected to see. The fact that all of the wood tended to reach about the same moisture content over time, regardless of the season or weather conditions, was also somewhat surprising.

The next step is to attempt to work with the wood procurement and accounting departments to better understand the material that they are actually supplying to the mill and to understand the impact of their actions on mill operating costs.

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