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Bundled Slash: A Potential New Biomass Resource for Fuels and Chemicals

Philip H. Steele · Brian K. Mitchell · Jerome E. Cooper · S. Arora

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Abstract Postharvest residues for southern pine species have not previously been quantified to compare volumes produced from both thinnings and clearcut volumes. A John Deere 1490 Slash Bundler bundled postharvest residues following a first thinning of a 14-year-old stand, a second thinning of a 25-year-old stand, and a clearcut of a naturally regenerated mature stand of 54 years of age. Regardless of stand type, nearly one-fifth of merchantable volume harvested was collected as postharvest residue. Initial bundle moisture contents were 127.3, 81.1, and 49.4% dry basis (db) for the first and second thinnings and mature stands, respectively. Bundle needles content was found to significantly influence the relative moisture contents of the bundles by stand type due to the high moisture content of needles compared to other bundle components. Bundles were stored outside and exposed to very hot and dry conditions and dried very rapidly to lowest moisture contents of 22.8, 14.5, and 13.5% (db) for first and second thinnings and mature stands, respectively. Response to moderating temperatures and higher precipitation resulted in rapid moisture content increase to 69.9, 46.2, and 38.1% (db) for the first and second thinnings and mature stand bundles by the end of the study. Temperature and precipitation and bundle percentage needles content all significantly influenced the rapid moisture content variations observed over the study periods.

Keywords Harvest · Residues · Bundles · Stand · Slash · Moisture content

P. H. Steele · B. K. Mitchell · J. E. Cooper (✉)
Department of Forest Products, Forest and Wildlife Research Center, Mississippi State University, Starkville, MS 39759, USA
e-mail: jcooper@cfr.msstate.edu

S. Arora
Mississippi Technology Alliance, Ridgeland, MS 39157, USA

Introduction

Postharvest Residues

Forest residues following harvesting have been shown to comprise a significant volume of total timber stand biomass. However, difficulty in recovering this biomass and low prices for this feed stock for its use in combustion have severely limited efforts to utilize this resource. In the USA, virtually 100% of this postharvest residue is unutilized. Previous research into recovery of US timber harvest residues peaked in the 1980s during the nation's last energy shortage. Relatively low fuel prices until 2005 made this resource an uneconomic feed stock as a result of the high costs of collecting and transporting the biomass. However, current high fuel costs and the current interest in conversion of lignocellulosic biomass to ethanol have increased interest in the potential recovery of post-timber-harvest residues as feed stocks for bioenergy products.

Nettles [1] performed a thorough review and summary of harvest residue volumes produced by stand type, and we are indebted to this researcher for his bibliography, from which we located most of the literature cited below. Past research on southern pine plantations was performed by Beardsell [2], which indicated that 44.7 oven-dry metric tons per hectare (ODMT/ha) was available following clear cutting. When hardwoods were present, postharvest residue volumes were significantly higher with 50 ODMT/ha for mixed species and 80.1 ODMT/ha for hardwood stands. For large-diameter bottomland hardwood stands, harvest residue volumes again increased significantly to 150.0 ODMT/ha [1, 2]. The residue volumes cited above were for clearcut timber stands.

Clearcut postharvest residue volumes were compared to thinning harvest residue volumes for UK upland spruce plantations with 44.7 ODMT/ha yield volume for clearcut and 18.0 ODMT/ha yield volume for thinned stands [1]. Watson et al. [3] quantified the energy–wood biomass available on two 22-year-old slash pine plantations and a 45-year-old natural stand of mixed slash and loblolly pine in Alabama. All stands were being clearcut for pulpwood. Two harvesting methods were applied, a one-pass system and a two-pass system. Mean residue harvest volume for the two plantation pine stands was 75.4 green metric tons per hectare (GMT/ha); for the natural mature stand the mean harvest volume was 61.5 GMT/ha.

A West Virginia study computed postharvest residue available when definition of acceptable biomass required pieces to be at least 1219.2 mm long and of rather large average small-end (122 mm) and large-end (182.9 mm) diameters. Mean length of all pieces was 3,658 mm, resulting in a mean volume collection of 32.7 m^3 per hectare [2]. A 1976 study of a maple-birch northern hardwood stand indicated that harvest residues were of relatively large diameter, with 50% having diameters exceeding 76.2 mm; 25% of the volume was greater than the minimum size for 470 mm pulpwood grade; 15% made the 2,540-mm pulpwood size class [4].

With the exception of one of the studies cited above, very little research has been performed to quantify postharvest residues for thinned stands. None provide this quantification for thinned southern pine plantations. Managers of southern pine timber stands who contemplate the total utilization of the biomass available on their forests have no information on potential postharvest residues available following thinning treatments.

A major potential between-stand difference for loblolly pines is caused by the density and moisture content differences between juvenile and mature wood. The southern pines produce juvenile wood during an approximate 10-year period beginning with germination. The juvenile wood type has larger cell lumens, resulting in increased moisture content because more water is contained in the cells. Mean southern pine juvenile wood moisture content is reported to be

139% dry weight basis (db), compared to 98% (db) for normal wood [5]. Therefore, juvenile wood is expected to have 42% higher moisture content than mature wood.

The moisture content of wood products is of interest because green wood has a moisture content ranging from 50 to 100% (db) or more depending on the species and wood type involved. For green southern pine, the weight of water is generally equal to the weight of the dry wood matter. Therefore, drying wood prior to transportation is a method to substantially reduce transportation costs. In addition, green wood must often be dried prior to processing to bioenergy products. Heat from wood combustion is considerably higher for dry compared to green wood. Pyrolysis and gasification for energy require that wood be dried to between 5 and 10% (db) moisture content. Few wood biomass feed stocks dry naturally after harvest, and large amounts of energy must be expended to dry the wood prior to processing. Development of a natural drying method for postharvest biomass to be utilized for bioenergy products would benefit the economics of the product production process.

Southern pine needles contain 154% (db) moisture content, while stems and branches average 115.5% (db) [6]. Young pine trees have a significantly higher proportion of branches with needles attached than do older pines. This is particularly true for plantation pines that generally have much wider between-tree spacing than do naturally regenerated stands. With all else equal, harvest residue from younger stands, containing large volumes of juvenile wood and needles, should have significantly higher moisture content values.

Postharvest Residue Collection Machinery

Several specialized machines have been developed to collect postharvest residues with their challenging size and distribution characteristics. Designs implemented in 2001 were reviewed by Nettles [1]. These include the Nicholson–Koch "Mobile Harvester," Georgia Pacific's "Jaws III," the Canadian Forest Engineering Research Institute's "Recufor M," and TVA's topwood harvesters.

John Deere has recently developed the 1490 Slash Bundler to collect postharvest residues following both thinnings and clearcuts. The John Deere 1490 (JD 1490) was originally developed in Scandinavia as the Timberjack 1490D (TJ 1490D). In 2003, several stand types were harvested in the western USA with the TJ 1490D to determine volume yields and efficiencies [7]. Rummer et al. quote a Swedish study that found that the TJ 1490D produced 30–40 bundles per hour with the range of costs at \$8.66 to \$11.33/m^3 harvested [7]. On the multiple sites tested by Rummer et al. in their western US studies [7], the bundles per hour produced ranged from 5 to 24, with a mean of 14.5. Site difficulty, slash arrangement, and residue density influenced the per-hour bundle production by determining the feeding time. Moisture content of the bundles on the four sites, at which this variable was measured, ranged from 11.3 to 58.1%, with a mean value of 30.8%. The TJ 1490D collected only a percentage of available material. Residues that were too scattered, short, rotten, or unproductive of retrieval were left in the field. Collection rates for available residues were highly variable, with the respective rates for the six sites being 5, 16, 20, 33, 53, and 62% [7].

Objective

The objectives of this study were (1) to compare relative bundled postharvest slash yields by stand type and (2) to monitor moisture content changes over a 4-month period during outdoor storage of the bundles.

Procedures

Slash Collection Machine

A JD 1490 Slash Bundler was used to harvest the study sites. A photograph of this machine is shown in Fig. 1, harvesting slash on one of the study stand sites. The boom grappler is utilized by the operator to collect residues for input to the in-feed deck. Multiple compression rollers forward the material into the bundler packing unit. Two pairs of compaction frames grasp and slide the compacted bundle through the wrapping unit, where bundles are wrapped with twine. The wrapped bundle is passed through the bundler until it reaches a preset length, at which time a chain saw cuts the bundle transversely, allowing it to drop to the side of the bundler.

The JD 1490 Slash Bundler is a six- or eight-wheeled device weighing about 22,000 kg; its horsepower is 182.4. The machine's length is 6,200 mm. The maximum boom reach length is 10 m. Bundle length can range from 2,400 to 3,200 mm. Bundle diameter can range from 700 to 800 mm. The manufacturer's estimate of bundler productivity is 20 to 30 bundles per hour.

Study Harvest Sites

The site of the study was on timberlands owned by Potlatch. The sites were located in Bradley County in eastern Arkansas. Company personnel identified typical first thinning, second thinning, and mature stands on which to perform the representative bundling studies. The characteristics of the three stands harvested for this study are described in Table 1. The stands were contiguous blocks, with the first-thinning site comprised of 5.11 ha, the second-thinning site comprised of 3.59 ha, and the mature stand comprised of 3.53 ha. The mature site was harvested on July 20, the second-thinning site on July 25, and the first-thinning site on July 26.

Table 2 is the Potlatch characterization of the study stands by presence of hardwood vs. pine species and by pulpwood vs. saw log size timber. The first-thinning stand was comprised of 100% pine pulpwood with no saw timber size trees. Pine timber on this young tract had not had time to grow to saw log size; likewise, ingrown hardwood had not had time to reach a merchantable size. The second-thinning stand had a small component (4.4%) of hardwood pulpwood resulting from hardwood under story invasion. The same was true of the clearcut mature stand with only 2.6% of pulpwood size hardwood under

Fig. 1 Photograph of JD 1490 Slash Bundler on a study site showing use of boom grappler to feed biomass into the compression jaw, compression of biomass into a bundle, and exit of bundle from compression system after binding with twine

Table 1 Initial and postharvest characteristics of the three study stands.

Study site	Stand size (ha)	Stand age (years)	Initial stand volume (GMT/ha)	Initial basal area (m^2)	Postharvest basal area (m^2)
1st thin	5.11	14	297.7[a]	11.4	7.9
2nd thin	3.59	25	370.9[b]	8.2	6.9
Clearcut mature stand	3.53	Approx. 54	424.0[b]	7.2	0

[a] Volume estimated from 2003 prethinning inventory.

[b] Volume estimated from 2006 prethinning modeling.

story invasion. Pine saw logs in the second thinning comprised 66.7% of total merchantable volume, while for the clearcut mature stand, this percentage was 71.1%.

Slash Bundler Production Statistics

Production and cost determination for the JD 1490 were outside the objectives of the current study. However, a team led by Dr. David W. Patterson collected time and motion and cost data, which were published in a MS Thesis in 2006. The data shown in Table 3 are from this study [8]. These results show the bundles and tons per hour production rate and costs by stand type.

Sampling Method

A subsample of five bundles was selected at random from each study site and was weighed green on the same day as they were bundled. These 15 subsamples were covered and transported by trailer from Arkansas to the Department of Forest Products, Mississippi State University, Starkville, MS. Bundles were distributed on a mowed lawn with 1,524 mm of clear space separating all sides of each bundle from its neighbor to simulate aging in a harvested setting as closely as possible. Bundles were uncovered and with no shade from any source, such that they were fully impacted by sun and rain that occurred during the study.

Each stand type's five bundles were randomly assigned to monthly destructive determination of needle and stem volume and oven-dry moisture content. The period over which the moisture content of the bundles was monitored was 4 months, with sampling occurring at 30-day intervals over this period. The sampling schedule is shown in Table 4. At the beginning of each period, three bundles, one bundle for each stand type, were sampled and their needle and stem components quantified. For this study, stem wood was defined as all solid wood components that were not needles. This included small bole wood

Table 2 Components of study stands by timber species and pulpwood vs. saw log size.

Study site	Hectares harvested (ha)	Pine logs (GMT/ha)	Pine pulpwood (GMT/ha)	Hardwood pulpwood (GMT/ha)	Total merchantable (GMT/ha)
1st thin	5.11	0	64.7	0	64.7
2nd thin	3.59	43.7	19.0	3.0	65.7
Clearcut mature stand	3.53	89.2	33.1	3.2	125.5

Table 3 JD 1490 production rate in green tons and bundles per hour with estimated production cost per bundle.

	1st thin	2nd thin	Clearcut
GMT/h	9.2	9.6	6.4
Bundles/h	21.1	23.2	16.1
Cost per bundle	$9.53	$8.72	$2.56

pieces, limbs, and small stems. Needles were separated from small needle-holding stems during sorting.

Moisture Content Analysis

Prior to destruction, to determine needle and stem component volumes, each sample bundle was weighed in total. This allowed computation of the moisture content of the bundles based on this green bundle weight and the oven dry weights of the stems, needles, and residuals. For the destructive needle and stem volume and moisture content determinations, each sample bundle was divided into five equal sections along its length, and three of these sections were randomly selected for stem and needle separation. The specimen sections were crosscut from the bundle at section demarcation boundaries by chainsaw. These specimen sections had needle and stem components segregated, and the separated components were weighed green and then placed in a biomass drier at 103 °C temperature for 24 h to obtain oven-dry weights for both stems and needles from which oven-dry moisture contents were computed. Stem and needle component percentages were computed for each of the bundles that were destructively broken down to obtain representative stem and needle moisture contents.

Bundle weights for each period, following the initial green weights obtained on the harvest site, were determined at the MSU storage site. The bundles to be broken down for component analysis were weighed prior to breakdown. Because breakdown took from 4 to 8 days to complete, the bundle section weights changed over this period as they dried. This did not influence the oven-dry section weights and estimation of section components but did not allow acquisition of a true moist bundle section weight at period beginning. To correct for this error, bundle dry section weight percentages were applied to the start-of-period moist bundle weights to estimate the start-of-period moist section weights.

During destructive separation of stem and needle components in each bundle, a small component of residue was present that was comprised of material that could not be classified as either stem or needle component. These we termed residuals, and this component consisted of dirt entrained into the bundles during harvesting, small fractured

Table 4 Dates, with number of days following stand harvest, at which bundle destructive testing to determine moisture content by component types was performed.

Period	Date and (number of days) following stand harvest		
	1st thinning	2nd thinning	Mature
Initial	8/7/2006 (12)	7/27/2006 (2)	7/24/2006 (4)
1st	8/29/2006 (34)	8/25/2006 (31)	8/23/2006 (34)
2nd	10/2/2006 (68)	9/26/2006 (62)	9/22/2006 (64)
3rd	10/24/2006 (90)	10/27/2006 (96)	10/30/2006 (102)
4th	11/30/2006 (126)	11/21/2006 (121)	11/20/2006 (123)

The 4 months over which bundles were destructively tested were divided into five periods as defined in the table.

pieces of needles and stems, dirt incorporated into the bundles from ants building nests in them during storage, and a fungally deteriorated needle and bark component resembling compost.

Results and Discussion

Bundling on the harvested stands commenced as soon as possible following harvest. Bundles from all stands averaged 635 mm in diameter and were 3,048 mm in length. On July 20, the 3.52-ha, naturally regenerated mature stand was bundled to produce a total of 238 bundles, over 14.8 h, with a mean weight per bundle of 0.4 GMT. Total bundled weight for the mature stand site was 95.3 GMT or 26.9 GMT/ha. Bundling was performed on July 25 on the 3.6-ha second-thinning site, and 100 bundles, produced over 4.3 h with a mean weight of 0.42 GMT/bundle, were harvested. Total weight of all bundles was 41.5 GMT or 11.6 GMT/ha. One-hundred and sixty nine bundles, with a mean weight of 0.43 GMT/bundle, were collected over a period of 8.0 h from the 5.1-ha first-thinning site on July 26. These bundles weighed a total of 72.8 GMT or 14.3 GMT/ha.

Per-stand merchantable volume harvested and residue bundled in GMT/ha are given in Table 2. The percentage of bundled residue per initial stand volume and per merchantable ton is also given in Table 5. For the first-thinning stand, initial stand merchantable volume harvested was 64.7 GMT/ha and bundled residue was14.3 GMT/ha. Bundled residue was 4.8% of estimated stand volume, and bundled residue was 22.0% of harvested merchantable volume. The percentage that bundled residue comprised of the first-thinning stand is probably overestimated because the computation is based on a 2003 inventory. Substantial growth since this inventory may be expected to have taken place. Second-thinning results were 65.7 GMT/ha of merchantable volume and 11.7 GMT/ha of bundled residue. Bundled residue comprised 3.1% of the estimated initial stand volume and 17.6% of the harvested merchantable volume. The naturally regenerated clearcut mature stand had 125.5 GMT/ha of merchantable volume with about double the bundled residue of the thinned stands at 26.9 GMT/ha. Bundled residue was 6.3% of the estimated initial stand volume harvested and was 21.5% of the harvested merchantable volume.

The residual component of the bundles was relatively small at 6% or less of the total green bundle volume; the exception was one bundle with 15.3% residual volume that was particularly fungally deteriorated. The needle and stem components of the destructed bundles were oven dried and weighed following their separation into these components. Figure 2 gives stem, needle, and residual component oven-dry percentage volumes for each stand type. The first-thinning needle component comprised 22% of total bundle volume. At 12.7%, the second thinning had just over one-half the percentage of the needle volume of the first thinning. Needle volume component for the naturally regenerated mature stand was

Table 5 Per-acre harvested merchantable timber and bundled residue volumes and the percentage that bundled residue comprised of the initial stand and merchantable volumes.

Study site	Harvested merchantable volume (GMT/ha)	Bundled residue per initial stand volume (%)	Bundled residue (GMT/ha)	Bundled residue per merchantable ton (%)
1st thinning	64.7	4.8	14.3	22.0
2nd thinning	65.7	3.1	11.7	17.6
Naturally regenerated stand	125.5	6.3	26.9	21.5

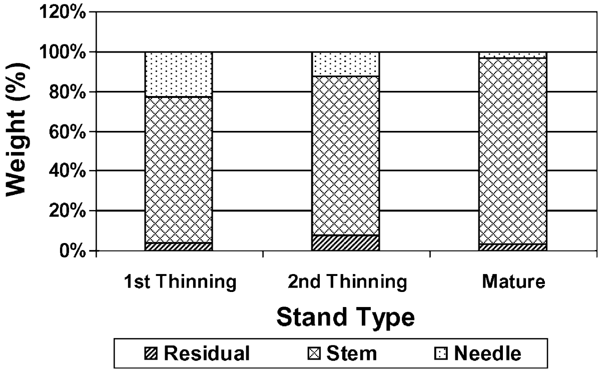

Fig. 2 Per-stand stem, needle, and residual volumes as a percentage of oven-dry bundle weight

a very low 3.4%, or about one-quarter of the needle volume of the first-thinning stand. These results correspond to the expectations discussed above that young stands would have higher needle volumes than older stands. Stem volumes are, by and large, the complement of the needle results because the residual component was a negligible amount of total bundle volume. The stem components of the bundles were 74.0, 79.6, and 93.0% of first-thinning, second-thinning, and mature-stand volumes, respectively.

Figures 3, 4, and 5 show the moisture content levels of the bundles by month over the 4-month study period. Average initial bundle moisture content value for the Fig. 3 first-thinning stand was 127.3% (db); the second-thinning stand initial moisture content value was 81.1% (db), while the mature stand value was 49.4% (db). Therefore, the first-thinning stand moisture content was 46.2% higher than that of the second thinning stand and 77.9% higher than that of the mature stand. These results appear to reflect the relative difference in magnitude of the juvenile wood prevalent and needles in the bundles by stand type. Both juvenile wood and pine needles contain higher moisture contents than stem wood and bark. The first-thinning material, at 14 years of age, was composed of a high volume of juvenile wood. Because research indicates that juvenile wood has a green moisture content of 139% (db), compared to a moisture content of 115.5% (db) for stem and branch wood, it was expected that the first-thinning and second-thinning stand bundles would have higher initial moisture contents compared to that for bundles from mature stands. In addition, as discussed above, bundles from younger timber should have considerably higher needle volumes, with a green moisture content of 154% (db), higher than any other component

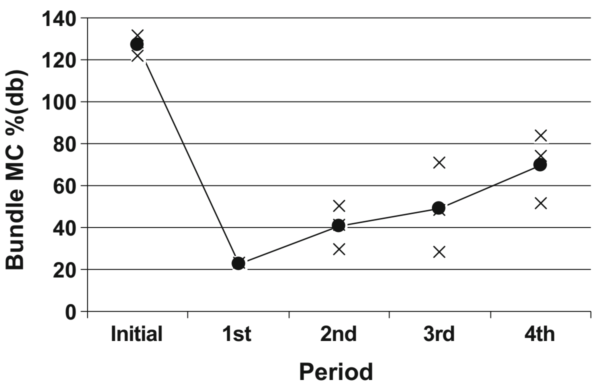

Fig. 3 Moisture content values by study period for the first-thinning stand. Means are shown as *black dots*, while observations are shown as *crosses*. For each period, three observations were made, with some observations hidden behind the mean value

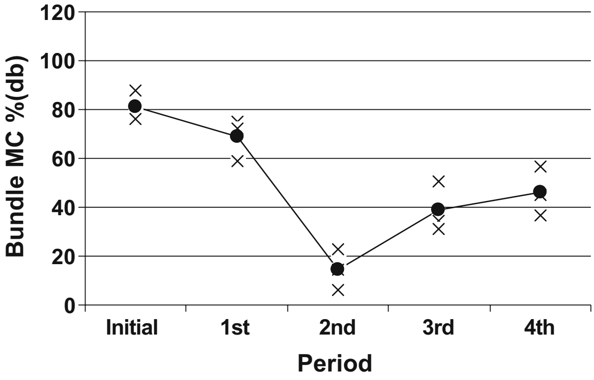

Fig. 4 Moisture content values by study period for the second-thinning stand. Means are shown as *black dots*, while observations are shown as *crosses*. For each period, three observations were made, with some observations hidden behind the mean value

shown by research to be the bundles. Therefore, bundles from first- and second-thinning material were expected to have higher moisture content from these two influences. Quantification of the actual relative needle volumes contained in the respective stand bundles confirmed our expectation that bundles from younger stands would have considerably higher needle volumes. The percentages of needles in the bundles were 22.7, 12.7, and 3.2% for first thinning, second thinning and mature wood stands, respectively.

To test our hypothesis that needle volume was an influential factor in high initial moisture content, Eq. 1 was estimated with initial moisture content (IMC) as a function of percent needle volume in each bundle (PN). Percentage needle volume (PN) was found to be highly significant at the 0.0001 level, supporting our hypothesis that magnitude of bundle needle volume influenced initial bundle moisture content.

$$\mathrm{IMC} = a + \mathrm{PN} + e \tag{1}$$

IMC	initial bundle moisture content
a	the intercept term
PN	the percentage total bundle weight comprised by needles
e	the error term

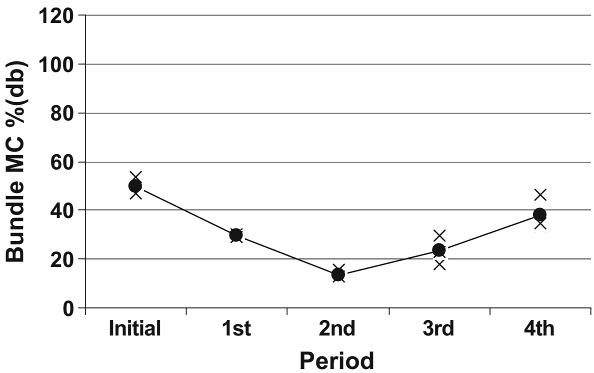

Fig. 5 Moisture content values by study period for the mature stand. Means are shown as *black dots*, while observations are shown as *crosses*. For each period, three observations were made, with some observations hidden behind the mean value

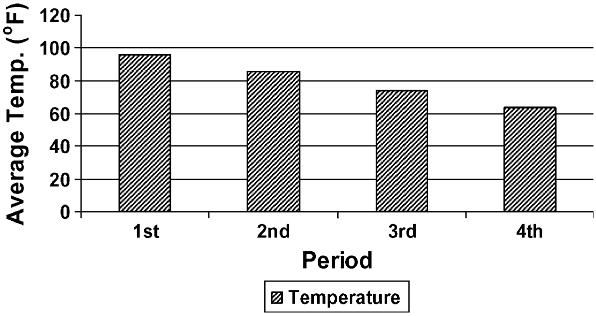

Fig. 6 Average temperature for each monthly period

Figures 3, 4, and 5 show that the study bundles dried very rapidly during what was a very hot and dry first monthly period extending from late July to late August. Bundles from each stand type lost moisture rapidly over this first period, with the first-thinning stand decreasing by 104.5 percentage points to 22.8% (db) moisture content. The second thinning and mature stand bundle moisture content values decreased to 68.7 and 29.6% (db), for respective percentage point decreases of 12.4 and 19.8%.

Over the second and subsequent periods, the first-thinning stand moisture content increased steadily to 69.9% (db) in the fourth period from its lowest moisture content [22.8% (db)] at the end of the first period. Bundles from the second thinning and mature stands, however, followed a somewhat different pattern, losing moisture over the second period to lows of 14.5 and 13.5% (db), respectively, at the end of the second period. The moisture contents of the second thinning and mature stands then steadily increased through the final period to 46.2 and 38.1% (db), respectively. These results showed that the first-thinning stand not only began with bundles containing much higher moisture content but lost moisture at a much faster rate than did the bundles of the other stand types. In addition, the first-thinning stand gained moisture at a faster rate when its moisture content began to increase. Likewise, the second-thinning stand lost moisture at a faster rate than did the mature stand; moisture content also increased at a faster rate for the second-thinning stand compared to the mature stand when their moisture contents began to increase. The difference in initial moisture content has already been identified as the difference in proportion of higher-moisture juvenile wood and needles in younger stands. Following initial drying, the juvenile wood moisture content would not be expected to increase in moisture content at a significantly faster level than the rest of the bundle components. However, the small size of the needle components of the bundles renders them very sensitive to moisture content changes. We believed it likely that the rapid bundle moisture content variations over time probably stemmed from the major difference between the

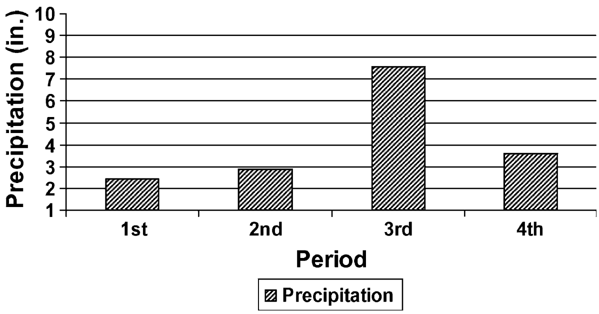

Fig. 7 Total precipitation by monthly period

bundles of each stand type: the percentage needle volume that each contained. These values differed considerably at 22.7, 12.7, and 3.2%, respectively, for the first, second, and mature stands. Below, we will test the hypothesis that the speeds of bundle moisture content change were related to the relative volume of needles in the bundles from each stand type.

Figures 6 and 7 show the average temperatures and mean precipitation amounts by period during the 4-month study. Figure 4 shows that the weather was extremely hot and dry during over the first and second periods, with a mean temperature of 35.3 °C during the first period and a mean temperature of 29.9 °C during the second period. This was accompanied by low precipitation of 63.5 and 73.7 mm during the first and second periods, respectively (Fig. 7). The very high temperatures and low rainfall during these periods explain the rapid moisture content losses from initial green to lowest moisture content of 104.5 (at the end of the first period), 66.6 (at the end of the second period), and 35.9 (at the end of the second period) percentage points for the first- and second-thinning and mature stands, respectively.

After the first period's high temperatures and low precipitation, temperatures began to moderate, and rainfall increased over subsequent periods. These weather factors appear to have combined to result in the increased moisture content values following the first period for the first-thinning stand and after the second period for the other two stand types.

The discussion above of the results in Figs. 3, 4, 5, 6, and 7 appear to indicate that weather, in the form of rainfall and temperature, expectedly influenced bundle moisture content to a high degree and that the changes varied considerably by stand type. As discussed above, we hypothesize that the volume of needles contained in each bundle, highly influenced by the weather, was the major factor responsible for the rapid fluctuation of bundle moisture content during the study. To determine the influence of the temperature, precipitation, and needle volume variables on bundle moisture content over time, a regression model (Eq. 2) containing these variables was developed.

$$\begin{aligned}\mathrm{MC} = a + \mathrm{PN} + \mathrm{PREC} + T + \mathrm{PN} * \mathrm{PREC} + \mathrm{PN} * T + \mathrm{PREC} * T \\ + \mathrm{PN} * \mathrm{PREC} * T + e\end{aligned} \tag{2}$$

MC	moisture content for periods 1, 2, 3, and 4
a	the intercept term
PN	the percentage total bundle weight comprised by needles
PREC	the total precipitation by period
T	the mean temperature over the period
*	interaction between the connected variables
e	the error term

Equation 2 results showed that precipitation (PREC) and needle percentage (PN) variables were highly significant at the 0.0001 level, while temperature was significant at the 0.03 level. None of the interaction terms were found to be significant variables. Percent needles (PN) contained in the bundles had the highest influence on moisture content, with a sum of squares (SS) value (44,565) more than five times as large as the 8,233 SS for precipitation. Temperature (*T*) had a lower SS value of 1,798.

These results indicate that the most influential factor influencing bundle moisture content was the weight of the needles present in each bundle. Precipitation and temperature significantly impacted moisture content, as would be expected, but had less impact as needle volume decreased.

This study's findings regarding the influence of bundle needle content, temperature, and precipitation are obviously only specifically relevant to slash bundling practiced during the hottest monthly weather in the south followed by storage into the fall when cooler temperatures and higher precipitation prevail. It is expected, however, that bundle needle content would have considerable influence on bundle moisture content values over time regardless of time of harvest and storage. Needles are, by far, the smallest lignocellulosic component in the bundles, and it makes sense that this small component will adsorb and desorb moisture readily as a result of precipitation and temperature variations during outdoor storage.

Summary

Postharvest loblolly pine residues were bundled with a JD 1490 Slash Bundler on Potlatch timberlands in eastern Arkansas. A first and second thinning and a clearcut of a naturally regenerated mature stand were performed on stands of 5.11, 3.59, and 3.53 ha, respectively. Bundled residue from these stands constituted 22.0, 17.6, and 21.5% of merchantable volume harvested for first and second thinning and mature stands. Bundles were stored outdoors over a 4-month period to simulate aging at the harvest site. Results showed that relative needle volume decreased as stand age increased with needle volumes of 22.7, 12.7, and 3.2% for the first- and second-thinning and mature stands, respectively. Bundles were monitored for moisture content variation over the 4-month study period. Initial green bundle moisture content values for the first- and second-thinning and mature stands were 127.3, 81.1, and 49.4% (db). The relative moisture content values were found to be significantly influenced by percentage needle content in the bundles due to the high moisture content of needles relative to other bundle components.

Temperature was very high and precipitation very low during the first period of the study. The high temperature and low precipitation were responsible for the decrease in bundle moisture contents to their lowest values of 22.8, 14.5, and 13.5% (db) for first- and second-thinning and mature stands, respectively. Temperatures moderated and rainfall increased over the remaining periods, causing a consistent rise in all bundle moisture content to 69.9, 46.2, and 38.1% (db) for the first- and second-thinning and mature stands, respectively, by the end of the study. A regression model was estimated that showed that temperature, precipitation, and percentage bundle needle volume all had significant influence on the rapid variation in moisture content over the study periods.

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References

1. Nettles, W. R. (2001). *Improving the utilization of logging residues*. Thesis, Department of Forestry, Mississippi State University, Mississippi State, MS.
2. Beardsell, M. G. (1983). *Integrated harvesting systems to incorporate the recovery of logging residues with the harvesting of conventional forest products*. Thesis, Department of Forestry. Virginia Polytechnic Institute and State University, Blacksburg, VA.

3. Watson, W. F., Stokes, B. J., & Savelle, I. W. (1986). Comparisons of two methods of harvesting biomass for energy. *Forest Products Journal*, *36*(4), 63–68.
4. Mattson, J. A., & Carpenter, E. M. (1976). Logging residue in a northern hardwood timber sale. *Northern Logger and Timber Processor*, *24*(9), 16–29.
5. Zobel, B. J., & Sprague, J. R. (1998). *Juvenile wood in forest trees*. Berlin: Springer-Verlag.
6. Koch, P. (1972). *Utilization of the southern pines, vol. 1*. USDA Forest Service, So. For. Expt. Sta., US Govt. Printing Office, Wash., DC.
7. Rummer, B., Len D., & O'Brien, O. (2004). *Forest residues bundling project: New technology for residue removal*. USDA Forest Service Forest Operations Unit, Southern Research Station CD Unnumbered Report.
8. Earl, J. A. (2006). *Slash bundler performance in southeastern Arkansas*. Thesis, Department of Forest Resources, University of Arkansas, Monticello, AR.