

MOISTURE CONTENT OF BALED FOREST AND URBAN WOODY BIOMASS DURING LONG-TERM OPEN STORAGE

J. H. Dooley, M. J. Wamsley, J. M. Perry



ABSTRACT. *This article describes how the moisture content of baled woody biomass varied during long-term open-air storage under conditions in the Pacific Northwest region of the United States. Large rectangular bales of forest and urban biomass were produced beginning in August 2015 and periodically until June 2016. Weights were measured approximately monthly until the entire lot of bales was ground into fuel in December 2016. Because it was impractical to non-destructively obtain moisture content samples during the study, final moisture content was measured from the ground material. Estimated temporal moisture contents were back-calculated from the final dry weight and moisture content of bales. All bales dried considerably during the spring and summer months, achieving a minimum moisture content in the early fall of 15 to 29% (wb). Minimum early fall moisture content had no correlation with the initial moisture content at time of baling. The ending moisture content in December 2016 ranged from 44% to 57% (wb), with a mean moisture content of 53% (wb). Ending moisture content had no correlation with initial moisture content at the time of baling, but appeared to be related to the amount of fine versus coarse woody material in the bales. Bales of forest and urban woody biomass proved to be structurally stable during long-term storage to enable handling and final transport to a centralized grinding location.*

Keywords. *Density, Logging, Baling, Bioenergy, Biofuel, Bundling, Forest operations, Forestry, MC, Seasonality, Transport, Woody biomass.*

The bioeconomy, including bio-based products, biochemicals, and biofuels, depends upon a sustainable supply of lignocellulosic biomass feedstocks. Forest residues left on logging sites after commercial harvests, thinning, and other forest management activities have the potential to supply more than 100 million tons per year of biomass across the forests of the United States (U.S. Department of Energy, 2016). Sustainability regulations and forest management objectives typically require that a portion of the residual biomass be left on site to provide habitat, soil health, erosion control, and other benefits. However, large quantities of excess biomass are available for collection and delivery as feedstocks for the bioeconomy (Stokes and Watson, 1991; Turhollow et al., 2014).

Transportation costs for forest biomass that is collected and delivered to centralized storage sites or end users is highly influenced by biomass moisture content. Freshly harvested forest trees and biomass typically have a moisture content of approximately 50% on a wet weight basis (wb). The volume of fresh-cut material that can be transported on

highway-legal trucks is often limited by weight. Therefore, it is desirable to use natural-air drying to reduce the moisture content prior to collection and transport when possible.

Natural-air drying of forest residues has been studied in the U.S. and Europe for many years (Civitarese et al., 2015; Forbes et al., 2014a; Gautam et al., 2012; Johansson et al., 2006; Nilsson et al., 2013; Nurmi, 1999; Pettersson and Nordfjell, 2007; Routa et al., 2015, 2016; Stokes et al., 1993; Zamora-Cristales et al., 2014). The objective of these studies was to reduce transportation costs and improve the net energy content of chipped and ground biomass fuels that were to be used immediately after delivery to biomass-fired power plants.

In many cases, forest residues cannot be left on-site for months to dry naturally. Sites must be cleared of woody debris to enable fall and winter planting of new seedlings, or the material must be removed quickly after summer harvests to reduce risks of human and lightning caused wildfire. Harvests on public lands often require immediate removal of excess residues to restore viewsheds and access for hikers, recreation, and hunters. In this case, baling and bundling are effective options to densify forest residues for low-cost transport to centralized sites for storage and future processing.

The study reported in this article is part of a Biomass Research and Development Initiative (BRDI) funded project at Humboldt State University. A set of paths of research working within the BRDI project are exploring ways to reduce the cost of in-woods processing and hauling of forest residues after commercial harvest on private timberlands. Open

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burning of slash piles and broadcast burning are being phased out due to concerns about smoke, risk of fire escapes, and thermal effects on soil quality. The industry-standard approach to removal of residues consists of in-woods grinding and hauling of bulk ground woody biomass in specialized trailers. Harvest units inaccessible to large in-woods hog fuel grinders and conventional fuel/chip trailers (aka stranded landings) may be treated by chipping and scattering back across a harvest unit. An alternative to in-woods grinding and a method to increase recovery of useful biomass from stranded landings is to bale the forest residues into high density prismatic bales for transport on agile flatbed trucks and trailers.

If forest residues are baled soon after harvest operations end and are transported to centralized storage sites for aggregation before just-in time grinding into fuel, the question arises about how the moisture content changes with storage time and seasonal climates. Only a few researchers have studied how moisture content varies with seasons and duration of storage of densified forest residues in bundles or bales (Pettersson and Nordfjell, 2007; He et al., 2015). He et al. (2015) at the University of British Columbia developed weather-based mathematical models to predict moisture content of aspen wood samples under field conditions for up to one year of storage. They found that the moisture content tracked with the model for both uncovered and covered materials. Pettersson and Nordfjell (2007) monitored the moisture content of densified bundles made from hardwood and softwood forest residues. They found that the bundles which were produced during the summer further dried into the fall and then gained moisture from rain and snow during the winter months. From a summer-low moisture content of 18% (wb), uncovered bundles rehydrated to more than 40% (wb) during the winter. The He and Pettersson studies both found only marginal benefit from covering. According to the Pettersson study, moisture content dropped to 18.2%-20.7% for covered compacted cylindrical bundles and 18.8%-24.9% for uncovered bundles during 9-12 months of storage. The raw forest residues had a moisture content of 28.6% prior to bundling. Pettersson concluded that relative humidity was a dominating factor controlling densified biomass moisture content. Forbes et al. (2014b) studied the effects of long-term storage for forest residue bundles that were subsequently chipped for fuel. Their bundles were stored along access roads prior to transport to maximize space efficiency at landings and to allow dry-down before transport. The bundles were stored for up to three years prior to chipping. The Forbes team found that moisture content varied extensively over the seasons, and that deterioration reduced the fuel quality and energy content over time. However, the fuel quality was still judged acceptable at the end of three years of storage prior to chipping.

LARGE RECTANGULAR BALES OF FOREST RESIDUES

Baling of forest residues into large rectangular bales is of current interest to supply feedstocks for solid and liquid biofuels (Bisson et al., 2013; Zamora-Cristales et al., 2015; Bisson and Han, 2016; Bisson et al., 2016). The net thermal energy of ground woody biomass used for biopower is

highly sensitive to moisture content. Thus, the price for forest-derived fuels is often inversely related to moisture content. Other solid biofuels such as pellets and briquettes requires dry feedstock (Mani et al., 2006). The cost of production is also quite sensitive to drying energy consumption. In all cases, the transportation costs for fuels or feedstocks can be reduced by reducing moisture content to fiber saturation or lower (Zamora-Cristales et al., 2015). Typical fiber saturation points for different species of wood vary around 30% (Forest Products Laboratory, 2010).

It is of interest to learn how baled woody biomass changes moisture content during long-term storage. Open storage of agricultural residues in bale yards at aggregation depots, bioenergy facilities, and centralized biomass processing sites is a common practice. Modern agricultural hay bale yards utilize raised gravel pads to separate bales from groundwater and soil moisture. Smith et al. (2013) concluded that soil moisture transfer may occur in bottom bales when stacked on soil such as at the edges of farm fields. While it might be preferable to tarp bales produced from low moisture summer-collected residues for short-term storage, an objective of the present study was to understand changes in moisture content of bale stacks during long-term storage under un-tarped conditions. Biomass depots and distributed storage sites may place bale stacks on pallets to eliminate direct soil contact and to enable handling.

This study has two moisture related objectives. The first objective is to understand how the moisture content of baled woody biomass is affected by season. The second objective is to study long-term moisture content of bales made at different times of the year with varying initial moisture contents. During long-term storage, it is expected that water content of baled woody biomass will closely trend with short-term rainy and dry weather patterns as found by the earlier Pettersson and Nordfjell (2007) and He et al. (2015) studies. Our expectation is that baled woody-biomass moisture content will track with seasonal climate conditions, peaking in the winter and achieving lowest moisture content in the late summer and that any varying initial moisture content will eventually converge on a narrow range of seasonally-controlled moisture levels.

METHODS AND MATERIALS

This study is part of a larger BRDI project that includes improvements to forest residue collection, sorting, handling, and processing. An improved method for sorting of residues into stems and finer tops/branches/brush was developed earlier in the project (Kizha and Han, 2016). Sorting out stems enabled their transport on conventional log trucks for grinding or chipping into high value fuels and feedstocks. Sorting reduced the amount of forest residues left for alternative handling, but the branches, tops, and brush were found to be very costly to handle and transport in bulk. Baling the small-diameter tree tops, branches, and brush fraction of forest residues is an attractive alternative to in-woods gathering with modified dump trucks and loaders, and grinding (Bisson et al., 2013, 2016). Beginning with field trials during the summer of 2015 and continuing through the spring of 2016,



Figure 1. Baling of forest residues on the Deschutes National Forest (Forest Concepts photo).

large rectangular bales of woody biomass were collected from each field trial for long-term assessment of moisture content and structural stability.

The Forest Concepts commercial prototype woody biomass baler was used to produce high density biomass bales from forest and suburban sites in western Washington. Design of a forest-specific version of the high-density baler was completed in 2015 and tested on active logging sites in California, Oregon, and Washington (Dooley et al., 2015a, b, c; Dooley et al., 2016). The baler is powered by a 54 kW (40 hp) engine-driven hydraulic power unit to compress biomass with up to 587,000 N (132,000 lbf). The baling platen is 1.22 m (48 in.) wide and 0.81 m (32 in.) tall, having platen area of 0.99 m² (1536 in.²). The resulting compression pressure on a charge of woody biomass is approximately 590 kPa (86 psi). Bales were manually tied with “440” polypropylene baler twine using 5-7 wraps as the bales were ejected. Finished bales had an average volume of 1.36 m³ (48 ft³) and a typical bulk density of approximately 350 kg/m³ (22 lb/ft³) at time of baling. Seasoned and dry solid Douglas fir density is considered to be about 512 kg/m³ (32 lb/ft³) for reference. Moisture content at time of baling ranged from approximately 25% to 50% (wb).

Stacks with two bales each were stored outside without cover at the Forest Concepts facility in Auburn, Washington. They were exposed to weather typical of western Washington and weighed at least monthly. Moisture content of the



Figure 2. Bales of forest residues and urban greenwood used in the study.

bales was impractical to assess over time due to the destructive sampling needed for lab analysis and impracticality of using agricultural bale moisture probes on woody bales. Moisture content was measured after grinding at the end of the study and back-calculated to each weighing event.

The bales were processed on 22 December 2016 into boiler fuel using a Universal Grinder machine at Rainier Wood Recyclers in Covington, Washington. Moisture content analysis was determined gravimetrically using a laboratory drying oven. Three replicate samples of the ground material from each of the seven two-bale stacks were collected and analyzed. The three samples collected for each stack were comprised of combined ground material subsamples of midpoints throughout the grinding process for the stack. The ending-point moisture content data was used to estimate the oven dry weight of each stack of bales. The moisture content of each stack over time could be estimated from the monthly wet-weight measurements. Based on evaluation of physical mass loss during storage due to handling in this study and previous work evaluating decay (Laitila and Routa, 2015), mass loss was assumed to be negligible as a percentage of the total mass.

Weather data for Auburn, Washington was obtained from the National Weather Service to correlate with bale moisture trends over time. Detailed modeling of short-term weather effects on baled biomass moisture content was not an objective of this study.

RESULTS

Figure 3 shows stack weights for bales of woody biomass made by Forest Concepts’ prototype baler from 19 August 2015 to 22 December 2016. The start of new stack numbers is an indication of the dates of field testing that produced new biomass bales that were added to the study. Stacks 1 and 2 were baled from very dry (about 23%-25% moisture content) logging slash on Washington’s Snoqualmie Pass during an exceptionally dry weather period. Other materials were baled at various suburban locations near sea level in October 2015, and March, May, and June 2016. Weight measurements of stack 3 consisted of a single bale that was later combined with a new bale to be renamed stack 4. Back-calculated moisture calculation in figure 4 only extended to measurements of the two bale experimental unit of stack 4.

DISCUSSION

It is readily-apparent that the amount of rainwater that seasonally accumulates in baled woody biomass is very large during the winter months under western Washington climate conditions (high rainfall and humidity, with no long-term freezing and little snow). Even though the baled woody biomass had very high moisture content by late winter, the bales dried rapidly beginning in early spring and through the summer months. It is interesting to note that the stacks made in August 2015 gained 453 kg (almost 1,000 lb) of water from rainfall during the winter per stack. We do not know how much of the water gain was free water (at the surface of particles and held by surface tension where particles contacted

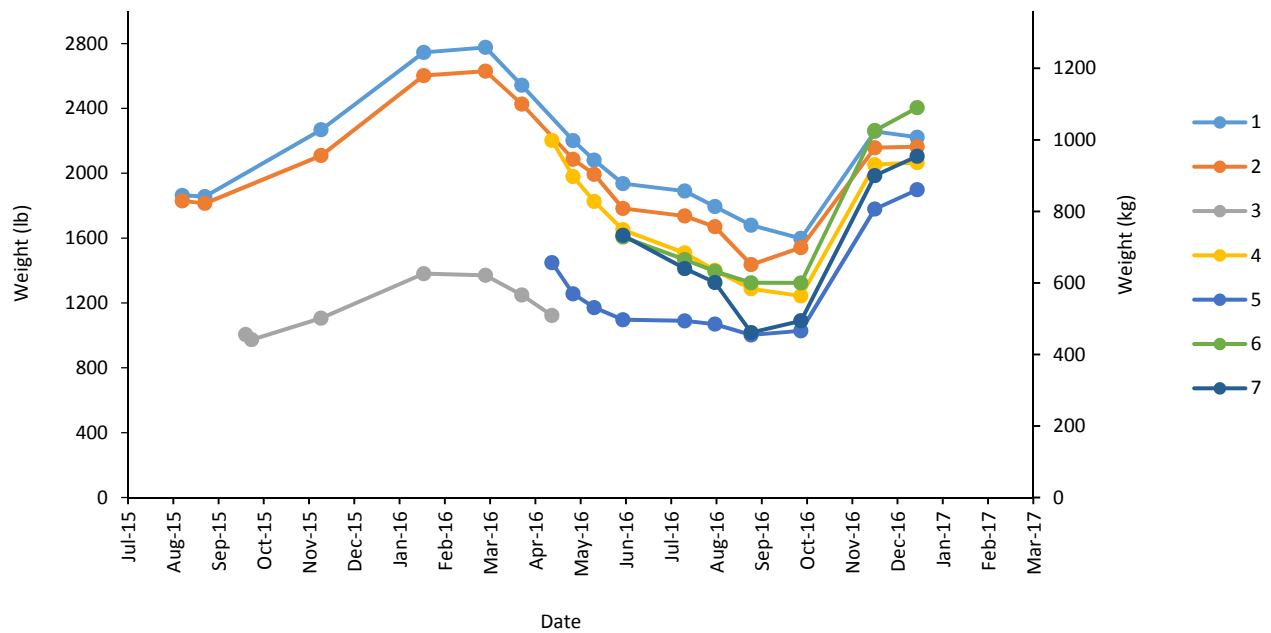


Figure 3. Stack weight measurements of woody biomass from Forest Concepts baler. Stack 3 consisted of one bale and all other stacks consisted of two bales.

each other) and how much was absorbed by the wood. The bale stacks dried almost back to their as-baled weight by the week of 5 June 2016 and below their as-baled weights as of early September 2016.

Although others, as discussed earlier, have constructed detailed predictive models to estimate seasonal moisture content for agricultural and woody biomass, we explored

only the correlation between easily-obtained rainfall records and bale moisture content. Figure 4 shows the three-month moving average of rainfall for Auburn, Washington, overlaid on a chart of the moisture content (MC) calculated from final moisture content and sample weight measurements for the bales of woody biomass included in figure 3 above.

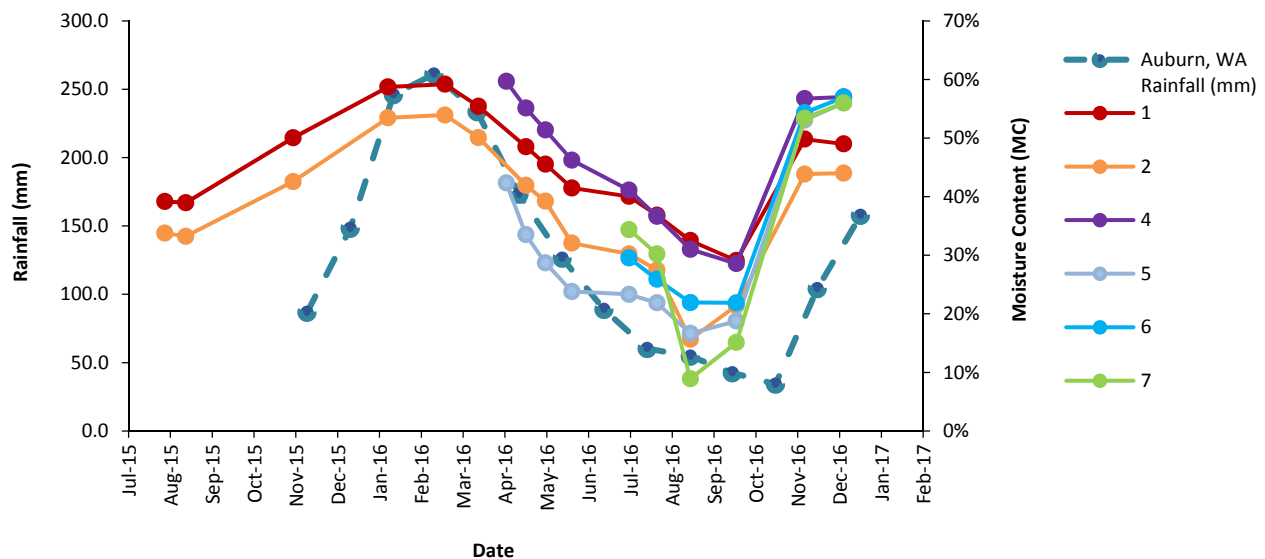


Figure 4. Three month moving average of rainfall for Auburn, Washington, and moisture content calculated from final moisture content and sample mass measurements. Three month moving average based on precipitation data from NOAA Global Summary of the Month for Auburn, Washington. April, May, and August of 2016 contained two separate dates of data measurements. Legend numbers 1-7 represent corresponding stack numbers 1-7.

Daily, monthly, and moving-average precipitation trends were plotted to consider suitable prediction of bale weight trends. Fairly long-term moving averages appeared more suitable for prediction. The rate of change for moisture in baled woody biomass has a fairly slow time constant and is expected to react relatively slowly to weather changes.

Observations of the trend lines for the forest residues bales (stacks 1 and 2) that are primarily made from branches and tops, with intact needles, suggest that bales with larger roundwood content react slower to seasonal changes, but follow similar paths as the more vegetative material included in stacks 5, 6, and 7. However, this study was too small to provide definitive correlations.

A co-objective of this bale moisture study was to provide information about the stability and integrity of baled woody biomass during repeated handling. All of the stacks of bales were moved by forklift from their outdoor storage location to a warehouse for each weighing event and then trucked approximately 20 km (12 miles) on public highways for final grinding. The oldest material was moved at least 16 times during the study. At the time of grinding, all bales were intact and sufficiently stable for trucking.

RECOMMENDATIONS FOR FUTURE STUDIES

The study reported in this article addressed a very narrow technical and operational question about the stability of baled woody biomass under high rainfall conditions typical of western Washington. Many other woody biomass bale related questions have been posed during the more than six years of field trials using a prototype baler.

The structural stability, mass loss, and grinding properties of baled woody biomass need to be studied across the forested regions of the country, particularly to add data from wet and dry climates of the northern latitudes and the humid subtropical climates of the southeastern United States.

Since the primary value of baled branches, leaves, and tree tops is as fuel, quality stability and losses during long-term storage should be studied. Ash content, energy content, and other important traits can be found by subjecting samples to proximate and ultimate analyses periodically during storage. Sampling strategies for bale stacks would need to be carefully considered to ensure the resulting data is representative and not unduly destructive to subsequent sampling events.

Transportation and grinding of frozen baled woody biomass during the winter needs to be studied if baled woody biomass is to be considered for just-in-time delivery for bio-energy on a year-around basis. Transportation of frozen bales may result in less shedding of fine materials than summer-transported bales. Grinding energy may be higher for frozen baled material than for loose frozen biomass due to the amount of energy needed to tear bales apart.

Stack heights and arrangement of bales in stacks needs to be studied across a range of biomass species, bale densities, and piece sizes to develop guidelines for bale storage yard operations. Use of pallets to separate the bottom bale from direct ground contact and to facilitate handling needs to be

compared to storage systems that use conventional agricultural hay equipment for handling and direct placement of baled biomass on gravel haystack pads.

As with other hay and forest residue storage research programs, studies of the effects for stack tarping or barn storage in comparison to open storage need to be conducted. Similarly, development of predictive moisture content models based on species, harvesting methods, piece size distribution, climatic data and biomass physical properties could be a long-term research objective.

CONCLUSIONS

This article reports the results of the first long-term assessment of moisture content and structural stability for woody biomass baled into prismatic large rectangular bales. The study was conducted in the Pacific Northwest near Seattle, Washington under open-air conditions. The experiment had two objectives. The first was to learn the relationship between material moisture content and seasonal climate conditions. The second was to assess bale structural integrity during long-term storage of up to a year.

Bales were stacked two high on pallets to enable handling, periodic weighing, and to conduct mid-term and end-point transportation tests. Bale integrity remained good during the entire study.

All bale stacks dried considerably during the spring and summer months, achieving a minimum moisture content in the early fall of 15% to 29% (wb). Minimum early-fall moisture content after 4 to 13 months of storage had no correlation with the initial moisture content at time of baling. The ending moisture content in December 2016 ranged from 44% to 57% (wb), with a mean moisture content of 53% (wb). Ending moisture content also had no correlation with initial moisture content at the time of baling, but appeared to be somewhat related to the amount of fine versus coarse woody material in the bales. Bales of forest and urban woody biomass proved to be structurally stable during long-term storage and handling to enable final transport to a centralized grinding location.

Now that we have demonstrated the potential for long-term storage and transport, future studies are encouraged to evaluate mass-loss during long-term storage as a function of material type, and to evaluate potential benefits from covered storage or seasonal tarping. Further study of baling of forest residues in an industrial setting and handling with an agricultural hay squeeze or other hay-bale handling machinery are also encouraged to incorporate questions of stability and integrity of bales.

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