# Monitoring Woody Biomass Chips Quality Change during Field Storage in Michigan

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## Abstract

Storage is a key component within the woody biomass supply chain, especially when year-round harvesting is impossible. To determine whether chipped biomass is a better form for in-woods storage than unchipped biomass, and to examine the effect of weather factors on wood chip quality, this study was designed and conducted at three study sites in Michigan. From July to December 2013, samples were collected twice a month and tested for moisture content (MC) and higher heating value (HHV). Results showed that during the 4-month field storage, unlike unchipped biomass, the small particle size and high degree of compaction in the wood chip pile caused biomass MCs to increase. Results also indicated that a smaller sized pile and higher initial MC could lead to a wetter middle layer in a wood chip pile. Owing to the high MC and microbial activity, declining trends in biomass HHV were detected. Whole tree chips were found to have higher HHV variation than pure stem wood chips because of the different content and types of lignin and extractives. Different positions within a wood chip pile did not affect the biomass HHV. Regression analysis showed that at Site 3, monthly cumulative rainfall was significant in predicting biomass MC in three models, and average air temperature was significant most of the time. However, none of the preselected variables were tested to be significant at the remaining two study sites because the biomass HHV change was small over storage time. Other more sensitive variables need to be considered in future studies.

Owing to increasing energy demands and the need to reduce greenhouse emissions, there is a strong necessity to decrease dependence on fossil-based fuels (REN21 2012, Zanchi et al. 2012). Biomass materials such as trees, grasses, and agricultural crops have thus become imperative alternative energy resources (US Department of Energy [USDOE] 2004). Among all of these materials, woody biomass is one of the most feasible choices because of its relatively low cost and high availability (USDOE 2004). Approximately 87 million dry tons (short tons) of wood residues and 64 million dry tons of forest harvest residues are produced in the United States every year, which accounts for approximately 2 percent of the total energy consumed (USDOE 2004, White 2010). In Michigan, there are over 1,400 forest products manufacturing facilities and 1,700 units that are working in the forest products manufacturing business, which implies a high availability of forest residues that can be used for bioenergy generation (Michigan Forest Products Council 2010).

Green biomass is usually directly processed into wood chips by mills or other wood-using facilities and is stored on-site before being transported to a power plant or a biofuel refinery (Lin and Pan 2013). Wood chip quality control during storage is a key consideration because woody biomass with a high, constant, and uniform fuel quality is always desired (Lehtikangas and Jirjis 1998, Afzal et al. 2010). Wood chip piles, compared with bundled and unchipped logging residues, pose more challenge such as dry matter loss, increment in moisture content (MC), and reduction in energy content (Fredholm and Jirjis 1988; Thörnqvist and Jirjis 1990; Jirjis 1995, 2001; Garstang et al. 2002; Afzal et al. 2010). Because of these concerns, the duration of wood chip storage is normally suggested to be less than 6 months. Kofman and Spinelli (1997) suggest that willow from short rotation coppice should be delivered immediately to heating plants after harvest to avoid difficulty in storage. In Michigan, the typical storage period of wood chips is around 60 to 70 days (Scott Robbins, Director of SFI & Public Affairs in Michigan Forest Products Council, personal communication, October 15, 2013). However, no study is available to validate these

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suggestions for wood chip storage in Michigan. In addition, a key yet unresolved issue is how to predict the MC in a biomass pile without frequent measurement (Erber et al. 2012). This is also the problem for biomass higher heating value (HHV) estimates, because all existing models to predict the HHV of woody biomass use independent variables such as fixed carbon content, volatile matter content, and ash content, which all require additional testing (Iyer et al. 2002, Channiwala and Parikh 2002, Parikh et al. 2005).

Several factors exist that can affect woody biomass MC. They are air movement in the pile, relative air humidity, and monthly cumulative rainfall (Jirjis 1995, 2001; Garstang et al. 2002; Afzal et al. 2010). Using these weather factors can be a possible solution to predict woody biomass MC and HHV. However, to our knowledge, no previous research has been documented regarding this type of predicting model. This study was designed and conducted in three different regions in Michigan. The detailed objectives of this study were (1) to monitor the change of wood chip characteristics including MC and HHV during a 4-month field storage period; (2) to examine the effects of storage locations and positions within a biomass pile on wood chip MCs and HHVs; and (3) to explore the quantitative relationships between wood chip MC and HHV and weather factors, including monthly cumulative rainfall (RF), average air temperature (T), and average relative air humidity (RH).

## Methodology

### Study sites and tree species

The first study site (Site 1) was located at Michigan State University (MSU) Forest Biomass Innovation Center, Escanaba (45.75°N, 87.06°W). The wood chip pile at Site 1 was established on July 14, 2013 with 33.14 green tons (short tons) of jack pine (*Pinus banksiana*) hog fuel generated from a cut-to-length harvesting and grinding operation. The pile was 15 feet long and 7 feet high.

The second study site (Site 2) was at the MSU Tree Research Center in East Lansing (42.74°N, 84.48°W). The wood chip pile at Site 2 was set up on July 19, 2013. It consisted of 25.87 green tons of pitch pine (*Pinus rigida*) wood chips resulting from a whole tree (WT) harvesting and chipping operation. The pile was 12 feet long and 6 feet high.

The third study site (Site 3) was at the MSU Kellogg Biological Station in Augusta (42.34°N, 85.35°W), and the wood chip pile was formed on July 31, 2013, with around 20 green tons of larch (*Larix decidua*) wood chips harvested using a WT harvesting system and chipping operation. The pile was 10 feet long and 6 feet high. The monthly weather conditions at the three study sites are summarized in Table 1.

The HHVs of the three species used in this study are 8,930 BTUs per dry pound for jack pine, 12,230 BTUs per dry pound for pitch pine, and 8,825 BTUs per dry pound for larch (Miller and Hansen 1951, Combustion Engineering, Inc. 1966, Harder and Einspahr 1976).

### Sample installation

Heavy-duty mesh firewood bags with a 1-$ft^3$ capacity were used to hold the samples. Each bag was filled with 1 pound of randomly selected wood chips and the bag was attached to a 5-foot-long string to facilitate sample collection. A front buck loader was used to establish the wood chip piles. The piles were defined to have three layers, including top part (TOP), middle part (MID), and bottom part (BOT). Each layer within a pile was about 2 feet high and contained of 75 randomly placed samples (Figs. 1 through 4). A total number of 225 wood chip samples were installed in each pile.

### Data collection and analysis

Preinstalled samples were collected twice a month starting from July 31 to December 2, 2013. On each sampling date, two random samples were taken from the BOT, MID, and TOP layers of the pile. The MCs of the sample wood chips were measured at the research stations of the three study sites, following ASTM E 871-82 (ASTM International 2003a). The HHVs of the sample wood chips were tested using an oxygen bomb calorimeter at MSU based on the standard described by ASTM E 711-87 (ASTM International 2003b). The monthly weather data, including RF, T, and RH, at these three study sites were obtained from the Michigan Agricultural Weather Network. The RF is the cumulative rainfall in the days prior to the sampling date. The T and RH were defined to be the average value of the

*Table 1.—Monthly weather conditions at the three study sites.*

| | Jul. | Aug. | Sep. | Oct. | Nov. |
|---|---|---|---|---|---|
| Site 1 | | | | | |
| Max temp. (°F) | 77.41 | 78.14 | 68.53 | 55.60 | 39.30 |
| Min temp. (°F) | 54.05 | 52.98 | 45.11 | 36.30 | 25.10 |
| Rainfall (in.) | 4.76 | 2.46 | 1.39 | 3.10 | 3.30 |
| Relative air humidity (%) | 72.00 | 71.55 | 76.30 | 75.45 | 72.80 |
| Site 2 | | | | | |
| Max temp. (°F) | 51.30 | 47.30 | 42.20 | 36.50 | 30.60 |
| Min temp. (°F) | 33.10 | 29.10 | 24.50 | 19.80 | 14.60 |
| Rainfall (in.) | 2.17 | 4.32 | 0.70 | 4.66 | 2.18 |
| Relative air humidity (%) | 67.75 | 68.15 | 68.90 | 71.05 | 68.10 |
| Site 3 | | | | | |
| Max temp. (°F) | 81.40 | 79.70 | 73.80 | 62.40 | 44.40 |
| Min temp. (°F) | 61.00 | 57.70 | 51.00 | 42.70 | 29.70 |
| Rainfall (in.) | 3.10 | 4.96 | 0.90 | 2.17 | 4.50 |
| Relative air humidity (%) | 71.25 | 71.90 | 70.45 | 73.95 | 69.15 |

Figure 1.—Wood chip pile during sample installation.

air temperature and relative humidity throughout the days before the sampling date.

The average MC of the sample wood chips at each position within a pile (sample size $n = 6$) was determined to be the average MC of the entire wood chip pile. A Kruskal-Wallis test at 5 percent significance level was used to detect whether the average MC of each biomass pile was statistically identical at each study site during the 4-month storage time (Higgins 2004). Kruskal-Wallis tests were also applied to examine the difference in the mean MCs and HHVs between different positions within a wood chip pile (Higgins 2004).

Multiple linear regression analysis with ordinary least squares estimator in STATA12 was used to explore the quantitative relationship between wood chip characteristics and weather conditions (StataCorp 2011). Wood chip MC and HHV were set as the dependent variables in the developed regression models, and local RF, T, and RH were preidentified as independent variables.

## Results

### Biomass MC change over storage period

The initial green basis biomass MCs were 29.4 percent (standard deviation [SD] = 8.7%) at Site 1, 27.8 percent (SD = 2.8%) at Site 2, and 52.9 percent (SD = 2.9%) at Site 3 (sample size $n = 6$ at each study site). After 4 months of field storage, the biomass MCs at Site 1, Site 2, and Site 3 increased to 39.3 ± 11.4 percent, 28.2 ± 13.3 percent, and 63.6 ± 4.0 percent, respectively (Fig. 5). Compared with the initial values, biomass MCs at the three study sites all increased.

At Site 1, the biomass MC increased from 29.4 ± 8.7 percent to 31.6 ± 14.0 percent on September 9, and then decreased to the lowest point at 19.0 percent on October 21.

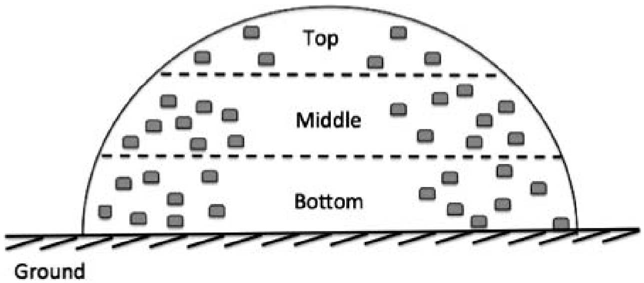


Figure 2.—Layout of wood chip bags in a pile (vertical section diagram).

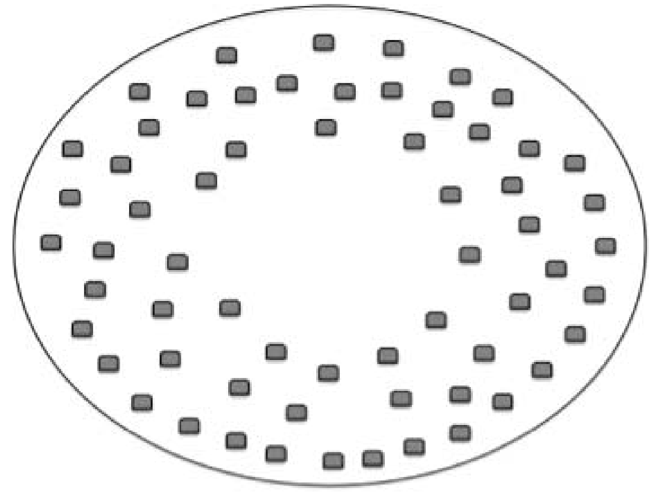

Figure 3.—Layout of wood chip bags in a pile (cross section view).

The highest biomass MC of 39.3 ± 11.4 percent at Site 1 was reached on December 2. Biomass MC at Site 2 has the minimum fluctuation range compared with the other two study sites. The lowest biomass MC of 25.9 ± 0.9 percent was reached around the middle of the August, and the highest biomass MC of 31.8 ± 9.5 percent was reached in the middle of November. The biomass MC at Site 3 first climbed up to 56.4 ± 6.7 percent on August 12, followed by a decline to the lowest point of 51.0 ± 7.8 percent on October 7. The highest biomass MC of 63.6 ± 4.0 percent was reached on December 2.

During the field storage, the overall patterns of biomass MC change at the three study sites did not present a clear declining trend, but kept stable within a certain range and even increased toward the winter. These patterns indicated that storing woody biomass in the form of a wood chip pile did not effectively reduce the biomass MC.

### Effect of positions within a pile on biomass MC

The change of biomass MC within the pile at Site 1 is displayed in Figure 6. The initial biomass MCs were 26.4 ± 11.9 percent at the BOT, 26.1 ± 2.2 percent at the MID, and 35.8 ± 10.5 percent at the TOP. The ending values of biomass MCs at Site 1 were tested to be 46.8 ± 19.4 percent,

Figure 4.—Wood chip pile after sample installation.

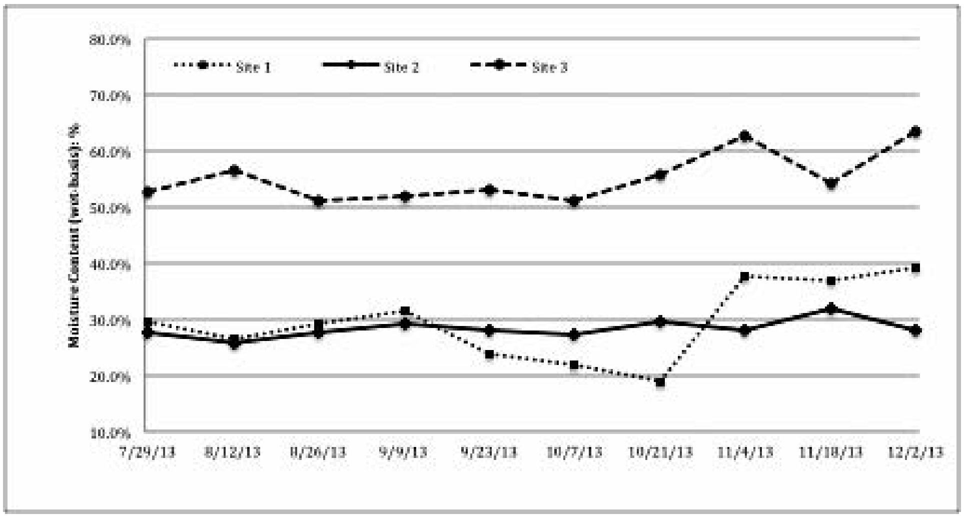


*Figure 5.—Wood chip moisture contents inside the piles measured on each sampling date during field storage at the three study sites.*

39.8 ± 5.9 percent, and 31.2 ± 0.8 percent at the BOT, MID, and TOP positions, respectively. The largest biomass MC change was detected in the bottom part within the pile, from 8.6 percent on October 21 to 57.3 percent on December 2.

At Site 2, the initial average biomass MCs at different positions within the pile were tested to be 24.9 ± 2.2 percent at the BOT, 27.8 ± 0.9 percent at the MID, and 30.6 ± 1.2 percent at the TOP (Fig. 7). At the end of the field storage period, the biomass MCs were 41.9 ± 1.1 percent at the BOT, 25.3 ± 15.0 percent at the MID, and 17.4 ± 5.4 percent at the TOP. The fluctuations of the biomass MCs at different positions were relatively small during the field storage compared with the other two study sites. There was no clear trend showing which position in the pile tended to have the largest variations in biomass MC change throughout the storage time (Fig. 7).

At Site 3, the initial biomass MCs within a pile were 52.4 ± 2.2 percent at the BOT, 52.0 ± 5.6 percent at the MID, and 54.2 ± 0.2 percent at the TOP (Fig. 8). The final MCs were 64.3 ± 1.9 percent at the BOT, 67.3 ± 2.3 percent at the MID, and 59.2 ± 1.7 percent at the TOP. Similar to the biomass MC change at Site 1, the largest biomass MC change was found in the bottom part of the pile.

According to the Kruskal-Wallis test, the mean values of biomass MC at different positions within a pile were statistically the same at Sites 1 and 2 (Site 1, $P = 0.716$; Site 2, $P = 0.418$), which implied that positions within a pile did not have a significant effect on biomass MC throughout the 4-month storage at these two study sites. At Site 3, however, biomass MC at the MID position was tested to be significantly higher than the other two positions within the pile during the field storage period ($P = 0.044$).

## Effect of weather conditions on biomass MC

At Sites 1 and 2, the relationships between biomass MC and RF were both determined to be insignificant ($P > 0.05$; Table 2). At Site 3, only the models using the RF data of 7, 6, and 5 days prior to the sampling date showed significant $P$ values, which indicated RF's significant impact on biomass

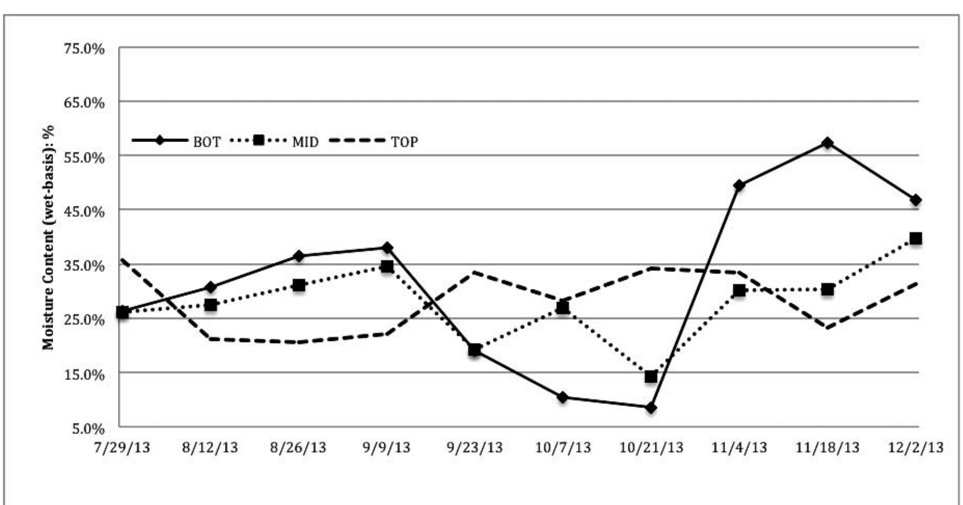


*Figure 6.—Wood chip moisture contents at different positions within the pile measured on each sampling date during field storage at study Site 1. BOT = bottom layer of the pile; MID = middle layer; TOP = top layer.*

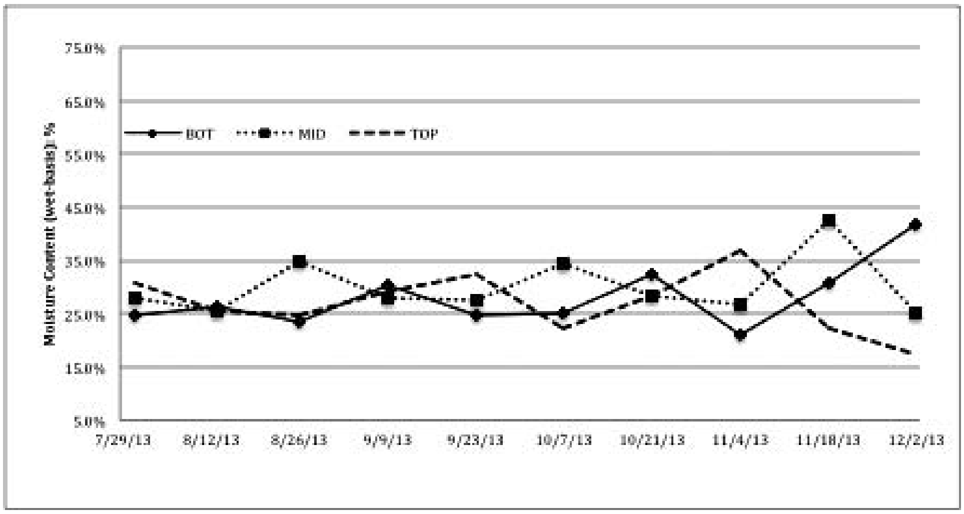


*Figure 7.—Wood chip moisture contents at different positions within the pile measured on each sampling date during field storage at study Site 2. BOT = bottom layer of the pile; MID = middle layer; TOP = top layer.*

MC. The positive coefficients of the independent variable RF implied that biomass MC would increase with the mounting RF during 5 to 7 days before sampling.

There was no significant relationship detected between biomass MC and RH at all study sites ($P > 0.05$), with only one exception using the 2 days RH data at Site 3 ($P = 0.016$; Table 2). This result suggested that RH was not an effective variable to estimate biomass MC.

As shown in Table 2, the *P* values of T were not significant at Sites 1 and 2. However, T is a significant variable to determine the biomass MC at Site 3. The negative coefficients of the independent variable T indicated that the biomass MC increase was associated with the drop of T.

## HHV change over the field storage period

Wood chip HHVs at the three study sites all decreased from the initial values during field storage (Fig. 9). At Site 1, wood chip HHVs decreased from 8,355.5 ± 352.1 to 7,404.6 ± 340.2 BTUs per dry pound, with a continuous declining trend. At Site 2, the wood chip HHVs constantly deceased from their original value of 8,422.0 ± 438.2 BTUs per dry pound to the lowest point of 7,618.2 ± 699.9 BTUs per dry pound in late September, and then slightly increased to 8,001.9 ± 132.0 BTUs per dry pound in early November. At Site 3, wood chip HHVs started at 8,579.5 ± 189.4 BTUs per dry pound and ended at 8,300.9 ± 436.7 BTUs per dry pound accompanied by the larger variations. The highest value of Site 3 wood chip HHVs of 8,634.2 ± 157.6 BTUs per dry pound was found in the middle of August, and the lowest value of 8,039.3 ± 272.3 BTUs per dry pound was detected at the end of August (Fig. 9). The decrease in biomass HHV caused by the field storage method in this study suggested that storing woody biomass in chip form could not necessarily ensure a high energy content of biomass.

## Effect of positions within a pile on biomass HHV

At Site 1, the average biomass HHVs at the BOT, MID, and TOP positions varied from 7,682.4 ± 21.8 to 8,213.7 ±

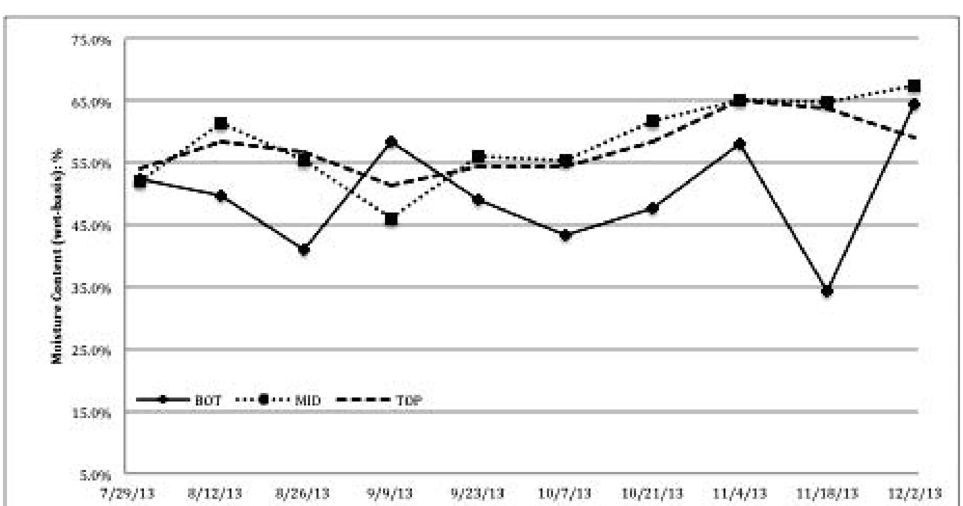


*Figure 8.—Wood chip moisture contents at different positions within the piles measured on each sampling date during field storage at study Site 3. BOT = bottom layer of the pile; MID = middle layer; TOP = top layer.*

Table 2.—Multiple linear regression models for predicting biomass moisture content (MC) within biomass chip piles (7, 6, 5, 4, 3, 2, and 1 day prior to the field sampling date).[a]

| | Site 1 ($n = 10$)[b] | | | Site 2 ($n = 10$) | | | Site 3 ($n = 10$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | MC (%) = | $r^2$ | Prob > $F$ | MC (%) = | $r^2$ | Prob > $F$ | MC (%) = | $r^2$ | Prob > $F$ |
| 7 d | 97.3 | 0.407 | 0.108 | 39.66 | 0.372 | 0.005 | 68.93 | 0.845 | 0.007 |
| | + 0.72 × RF | | 0.790 | + 0.21 × RF | | 0.780 | + 2.19 × RF | | 0.022 |
| | − 0.34 × T | | 0.090 | − 0.06 × T | | 0.142 | − 0.27 × T | | 0.007 |
| | − 0.68 × RH | | 0.350 | − 0.11 × RH | | 0.409 | − 0.03 × RH | | 0.900 |
| 6 d | 62.75 | 0.239 | 0.230 | 36.92 | 0.297 | 0.008 | 70.46 | 0.841 | 0.006 |
| | + 1.53 × RF | | 0.760 | + 0.21 × RF | | 0.794 | + 2.60 × RF | | 0.031 |
| | − 0.29 × T | | 0.237 | − 0.06 × T | | 0.196 | − 0.24 × T | | 0.012 |
| | − 0.26 × RH | | 0.648 | − 0.07 × RH | | 0.592 | − 0.07 × RH | | 0.769 |
| 5 d | 60.69 | 0.209 | 0.251 | 39.66 | 0.322 | 0.006 | 77.34 | 0.852 | 0.002 |
| | + 1.79 × RF | | 0.750 | + 0.41 × RF | | 0.634 | + 2.65 × RF | | 0.029 |
| | − 0.26 × T | | 0.286 | − 0.06 × T | | 0.201 | − 0.27 × T | | 0.008 |
| | − 0.24 × RH | | 0.668 | − 0.11 × RH | | 0.421 | − 0.15 × RH | | 0.469 |
| 4 d | 59.84 | 0.296 | 0.186 | 34.93 | 0.246 | 0.032 | 96.54 | 0.777 | 0.003 |
| | + 0.86 × RF | | 0.747 | + 0.46 × RF | | 0.780 | + 1.44 × RF | | 0.243 |
| | − 0.31 × T | | 0.178 | − 0.06 × T | | 0.142 | − 0.30 × T | | 0.013 |
| | − 0.20 × RH | | 0.672 | − 0.05 × RH | | 0.409 | − 0.36 × RH | | 0.194 |
| 3 d | 59.84 | 0.216 | 0.903 | 9.19 | 0.381 | 0.599 | 91.91 | 0.867 | 0.000 |
| | + 0.86 × RF | | 0.436 | − 1.30 × RF | | 0.386 | − 2.37 × RF | | 0.076 |
| | − 0.31 × T | | 0.653 | − 0.06 × T | | 0.205 | − 0.31 × T | | 0.005 |
| | − 0.20 × RH | | 0.575 | + 0.32 × RH | | 0.228 | + 0.39 × RH | | 0.065 |
| 2 d | −13.83 | 0.249 | 0.786 | 25.96 | 0.319 | 0.224 | 115.39 | 0.88 | 0.000 |
| | − 2.29 × RF | | 0.752 | + 1.51 × RF | | 0.535 | + 0.46 × RF | | 0.728 |
| | − 0.04 × T | | 0.847 | − 0.05 × T | | 0.289 | − 0.29 × T | | 0.006 |
| | + 0.58 × RH | | 0.341 | + 0.07 × RH | | 0.821 | − 0.62 × RH | | 0.016 |
| 1 d | 22.55 | 0.111 | 0.460 | 22.37 | 0.427 | 0.036 | 105.26 | 0.765 | 0.003 |
| | + 17.55 × RF | | 0.739 | + 1.91 × RF | | 0.763 | − 0.42 × RF | | 0.205 |
| | − 0.16 × T | | 0.509 | − 0.09 × T | | 0.097 | − 0.13 × T | | 0.155 |
| | + 0.19 × RH | | 0.613 | + 0.16 × RH | | 0.312 | − 0.62 × RH | | 0.078 |

[a] RF = cumulative rainfall in inches; T = average temperature in °F; RH = percentage of relative air humidity.
[b] $n$ = the number of sample collecting dates at each study site.

14.0 BTUs per dry pound, 7,683.8 ± 106.9 to 8,633.5 ± 286.9 BTUs per dry pound, and 7,076.1 ± 6.3 to 8,756.4 ± 19.5 BTUs per dry pound, respectively (Fig. 10). At Site 2, the average biomass HHV changes at different positions (Fig. 11) were from 7,916.6 ± 75.6 to 8,796.2 ± 219.1 BTUs per dry pound at the BOT, 7,727.8 ± 175.6 to 8,775.9 ± 181.1 BTUs per dry pound at the MID, and 7,966.9 ± 215.1 to 8,813.4 ± 591.8 BTUs per dry pound at the TOP. At Site 3, the average biomass HHVs at the BOT, MID, and TOP positions changed from 7,181.7 ± 144.4 to 8,271.8 ± 117.2 BTUs per dry pound, 7,709.9 ± 357.4 to 8,629.8 ± 552.4 BTUs per dry pound, and 7,162.83 ± 122.6 to 8,717.67 ± 32.6 BTUs per dry pound, respectively (Fig. 12). Kruskal-Wallis tests showed that different positions within a wood chip pile did not cause significantly different HHVs (Site 1, $P = 0.827$; Site 2, $P = 0.255$; and Site 3, $P = 0.833$).

## Effect of weather conditions on biomass HHVs

Multiple linear regression models using least squares estimator were developed to predict biomass HHV during the field storage using local weather data including RF, T, and RH as independent variables. Because the impact of weather factors on biomass HHV change normally takes longer to be detected, the weather data used to predict biomass HHVs were selected from the 14, 10, 7, and 3 days before the field sampling date.

The $r^2$ value of the biomass HHV predicting models at Sites 1 and 2 ranged from 0.553 to 0.900 (Table 3). At Site 3, the regression models' $r^2$ values are 0.525, 0.410, 0.265, and 0.268. In developed multiple linear regression models, most of the time preidentified independent variables including RH, T, and RF were verified to be insignificant ($P > 0.05$). The most significant contributing factor in the models was the constant values.

## Discussion

Based on the research results, the chipped biomass MC increased after 4 months of field storage at all the study sites. This finding was consistent with the results provided by Afzal et al. (2010), who observed a biomass MC increase of around double the initial value. This observed wood chip MC change pattern is different from the findings in the previous study using unchipped biomass, which showed a continuously declining trend in biomass MC during a similar storage period (Lin and Pan 2013). The main reasons for the difference are the smaller particle size and higher degree of compaction in the wood chip pile, compared with an unchipped biomass pile (Afzal et al. 2010). The small chip size and high compaction resulted in less space for air movement and therefore lower drying rate within the chip piles, thus causing irregular and increasing MC during the field storage (Jirjis 1995, 2001; Garstang et al. 2002).

The biomass MCs at different positions within a pile were consistent at Sites 1 and 2 during storage. At Site 3, wood

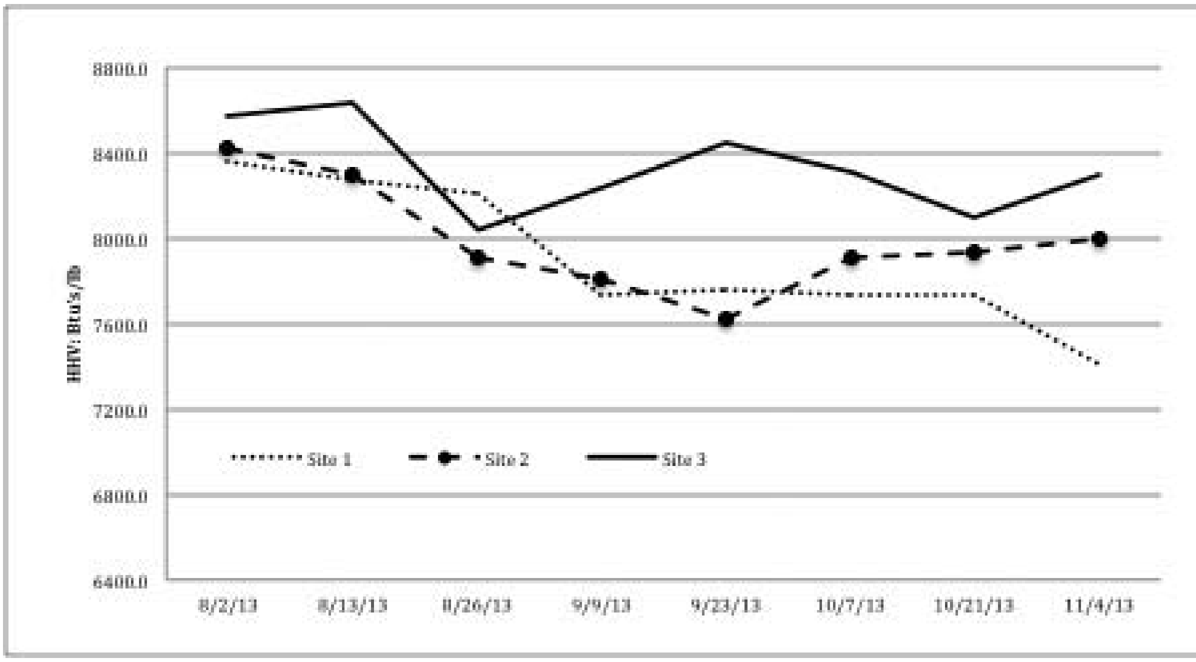


*Figure 9.—Wood chip higher heating values (HHVs) inside the piles measured on each sampling date during field storage at the three study sites.*

chips in the MID layer were significantly much wetter than those in the TOP and BOT parts. The low biomass MC was usually found in the central part of the biomass chip piles because of the heat generated in this position (Garstang et al. 2002, Afzal et al. 2010, Eriksson 2011). This self-heating problem will be mitigated when the height of the pile is less than 30 feet (Garstang et al. 2002, Solomon and Luzadis 2008). In this study, the piles were around 6 to 7 feet high, which was not high enough to generate heat and cause significantly lower biomass MC in the MID part compared with other positions in the pile. In addition, the high initial average biomass MC (52.9%) and the relatively slow air movement rates at Site 3 also contributed to the considerably wetter biomass MC in the MID part of the wood chip pile.

At Sites 1 and 3 the change of biomass MC at the BOT positions was noticeably different from other parts within the pile. These results implied a risk that when chipped biomass was field stored in a small-size pile, the positions within the pile may have a strong impact on the biomass MC change. In contrast, the unchipped biomass was less affected by environmental factors and positions within a pile, thus leading to uniform MC in the biomass pile (Gigler et al. 2000, Lin and Pan 2013).

The equilibrium relationship between biomass MC and ambient environment can be affected by weather factors such as T, RF, and RH (Jirjis 1995, 2001; Garstang et al. 2002; Afzal et al. 2010). The developed multiple linear regression models indicated that T was the most significant variable to predict the biomass MC. The models also implied that the biomass MC increments in the wood chip

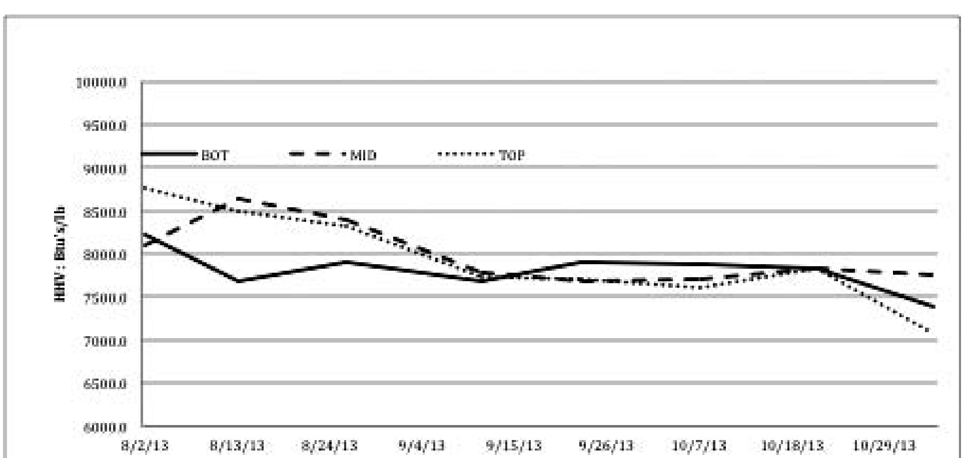


*Figure 10.—Wood chip higher heating values (HHVs) at different positions within the piles measured on each sampling date during field storage at study Site 1. BOT = bottom layer of the pile; MID = middle layer; TOP = top layer.*

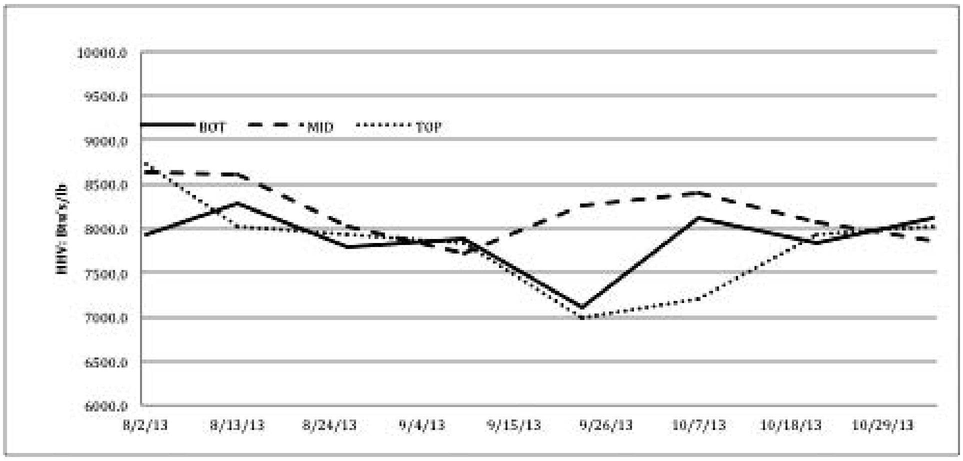


*Figure 11.—Wood chip higher heating values (HHVs) at different positions within the piles measured on each sampling date during field storage at study Site 2. BOT = bottom layer of the pile; MID = middle layer; TOP = top layer.*

piles were related to the sharply decreasing temperature during early fall. Therefore wood chips are recommended to be used during the early fall to avoid regains in moisture.

In this study, the average HHVs of the biomass at each site stayed in a range comparable with the reported HHVs of the major species (Fig. 9). Decreases in biomass HHVs were observed at all study sites, which was consistent with many other studies (Jirjis and Theander 1990, Jirjis 2005, Afzal et al. 2010). The reason for biomass HHV decline was the high MC remaining in the piles, which enhanced the microbial activity and resulted in lower HHVs (Hudson 1992, Gautam et al. 2012). Microbes, such as mold fungi, wood-decaying fungi, and blue stain fungi, will start to consume the woody biomass by aerobic degradation and then produce heat, carbon dioxide, and water (Eriksson 2011). Most of the time the microbes attack cellulose and hemicellulose; they degrade lignin as well (Eriksson 2011). Noticeable variations in biomass HHVs were observed at Sites 2 and 3 (Fig. 7). The wood chips at these two study sites were all produced from whole trees and consisted of branches, barks, and chunk wood. In this mixture of wood chips produced from different parts, the content and types of lignin and the extractives are expected to be substantially diverse, which can directly lead to the diversity in biomass HHV (White 1987, Melin 2008, Telmo and Lousada 2011, Burkhardt et al. 2013). Meanwhile, the decomposition rates are also found to be faster in the branches and barks compared with the chunk wood part (Slaven et al. 2011). The variations found in biomass HHV decline, therefore, can be committed to the different chemical compound contents and varying decomposition rates of the wood chips. This finding implies that the biomass HHV of whole tree wood chips are more erratic and difficult to predict during the field storage.

The effect of positions within a pile on biomass HHV was insignificant at all study sites. The biomass HHV change was mainly governed by microbes' activity, which was strongly correlated with temperature and MC inside a pile (Solomon and Luzadis 2008, Afzal et al. 2010). Suchomel et al. (2011) reported that the temperature inside the pile was mainly dependent on the ambient air temperature and was not affected by positions within the pile. At Site 3, although the middle part was wetter, no effect on biomass HHV was observed as a result of the higher MC. This result indicated that the impact of MC inside the wood chip pile on biomass HHV change is not significant during a relatively short field storage period.

The change in biomass HHV during field storage was unclear in other studies (Afzal et al. 2010, Eriksson 2011).

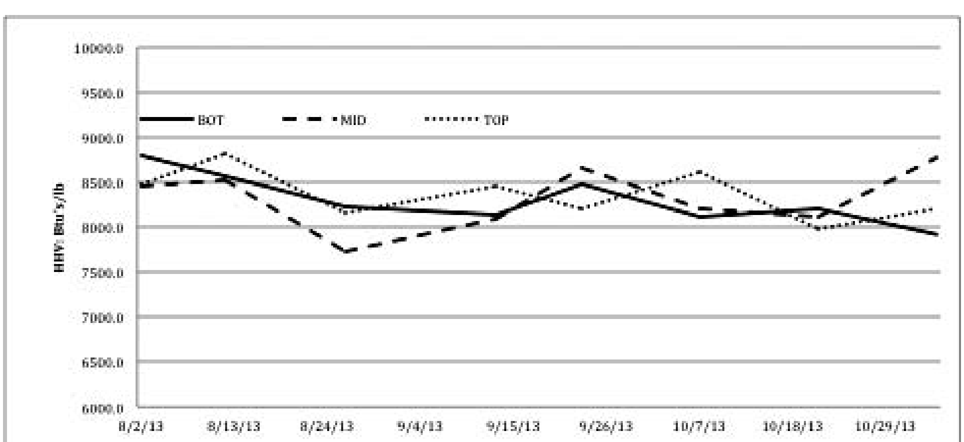


*Figure 12.—Wood chip higher heating values (HHVs) at different positions within the piles measured on each sampling date during field storage at study Site 3. BOT = bottom layer of the pile; MID = middle layer; TOP = top layer.*

Table 3.—Multiple linear regression models for predicting biomass higher heating values (HHVs) within wood chip piles (14, 10, 7, and 3 days before the field sampling date).[a]

| | Site 1 ($n = 10$)[b] | | | Site 2 ($n = 10$) | | | Site 3 ($n = 10$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | HHV (BTUs/lb) = | $r^2$ | Prob > $F$ | HHV (BTUs/lb) = | $r^2$ | Prob > $F$ | HHV (BTUs/lb) = | $r^2$ | Prob > $F$ |
| 14 d | 10,437.16 | 0.775 | 0.019 | 14,369.93 | 0.617 | 0.019 | 6,105.12 | 0.525 | 0.416 |
| | + 166.19 × RF | | 0.383 | − 100.43 × RF | | 0.410 | + 62.17 × RF | | 0.436 |
| | + 16.33 × T | | 0.085 | − 6.22 × T | | 0.540 | + 19.43 × T | | 0.239 |
| | − 4,773.35 × RH | | 0.250 | − 8,627.73 × RH | | 0.185 | + 1,235.44 × RH | | 0.894 |
| 10 d | 10,944.23 | 0.756 | 0.032 | 12,813.08 | 0.665 | 0.071 | 2,214.78 | 0.41 | 0.703 |
| | + 116.23 × RF | | 0.285 | + 420.67 × RF | | 0.049 | + 3.53 × RF | | 0.964 |
| | + 0.89 × T | | 0.969 | + 3.21 × T | | 0.859 | + 22.66 × T | | 0.249 |
| | − 40.69 × RH | | 0.238 | − 77.75 × RH | | 0.295 | + 65.68 × RH | | 0.383 |
| 7 d | 6,945.02 | 0.756 | 0.034 | 9,999.31 | 0.629 | 0.004 | 6,448.38 | 0.265 | 0.227 |
| | − 212.38 × RF | | 0.417 | − 287.95 × RF | | 0.125 | − 0.55 × RF | | 0.995 |
| | + 16.95 × T | | 0.209 | − 12.60 × T | | 0.255 | + 16.49 × T | | 0.466 |
| | + 2.97 × RH | | 0.906 | − 15.77 × RH | | 0.53 | + 11.30 × RH | | 0.820 |
| 3 d | 7,399.9 | 0.9 | 0.002 | 9,497.95 | 0.553 | 0.199 | 8,370.7 | 0.268 | 0.027 |
| | − 5.26 × RF | | 0.703 | − 243.80 × RF | | 0.609 | + 125.38 × RF | | 0.494 |
| | + 19.17 × T | | 0.014 | − 2.89 × T | | 0.811 | + 2.90 × T | | 0.817 |
| | − 249.05 × RH | | 0.092 | − 17.73 × RH | | 0.842 | − 10.37 × RH | | 0.738 |

[a] RF = cumulative rainfall in inches; T = average temperature in °F; RH = percentage of relative air humidity.
[b] $n$ = the number of sample collecting dates at each study site.

In this study, none of the preselected variables were tested to be significant in predicting biomass HHV because the decrease of biomass HHV was relatively small within the 4-month field storage time. In future studies, some more sensitive independent variables need to be considered in predicting biomass HHV.

## Conclusions

This study monitored the MC and HHV change of piled wood chips during 4 months of field storage at three different locations in Michigan. The small particle size and high degree of compaction in the wood chip pile caused increases in biomass MCs at all study sites, which suggested that storing woody biomass in chip form is a less efficient storage method compared with storing unchipped woody biomass. There was no significant variation found in biomass MC between different positions within a wood chip pile at Sites 1 and 2. At Site 3, the wood chips in the middle part of the pile were found to have a significantly higher MC than in the other positions. The main reason was the small size of the pile, which reduced the heat generated inside the pile. When the initial wood chip MC is high, a chance of inconsistent MC exists at different positions within the biomass pile.

Unlike unchipped woody biomass, decreasing trends of biomass HHV were detected during the storage at all study sites because of energy loss caused by the high MC and microbial activity in the wood chip pile. The biomass HHVs were determined to be statistically the same at different positions within a pile. In addition, owing to the different chemical compositions and decomposition rates of bark and white wood, no clear trend was detected in biomass HHV change in whole tree biomass chips, meaning the fuel quality of whole tree wood chips was more difficult to control than wood chips generated from log length.

T was the only significant variable in predicting biomass MC of field-piled wood chips in certain situations, and most of the time RF and RH were insignificant. It is recommended that wood chips in Michigan should be used before the temperature starts to drop to avoid taking on moisture. For prediction of biomass HHV, all preselected predicting variables were tested to be insignificant. Monitoring biomass MC and HHV change over longer field storage periods will reveal more detailed and accurate relationships between biomass quality and weather factors.

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