Changes in feedstock quality in willow chip piles created in winter from a commercial scale harvest

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Abstract

Storage and handling are important facets of biomass logistics because there are associated costs and biomass properties can change significantly as material proceeds through the supply chain. Thus, this aspect of biomass supply systems requires continued study. Shrub willow chips were harvested, and used to create six piles that each contained between 10 and 22 Mg (fresh biomass). Material was monitored for several months in temporary storage to assess changes in biomass quality (moisture, ash and energy content). Internal pile temperatures increased due to biological activity and conditions within a pile quickly differentiated based on location (shell, core, top, and side). Mean moisture content increased from 42 to 47% (mass fraction) between harvest and delivery of the chips, but ranged between 37 and over 60% over the next three months depending on pile location with the shell generally drier than the core. Mean ash content increased 1 to 2 percentage points (mass fraction) between harvesting, reloading and delivery to the trial location, but became more variable during storage. Higher heating values (HHV) were stable between 18.6 and 19.0 MJ kg⁻¹ over the six months, but lower heating values (LHV) ranged between 8.6 and 11.7 MJ kg⁻¹ and

mirrored changes in moisture content. There was minimal change in chip quality over two months, but quality became more variable over longer time periods. This period could be extended, and negative effects on chip quality could be mitigated, by improving storage methods, blending different types of chips, or employing pretreatments.

Highlights

- The ratio of outer shell chips and inner core chips affects overall pile quality
- Moisture content was higher in the pile shells compared to their inner core
- Ash content of chips increased most during handling and transportation of material
- Results suggest the time and pile configuration should guide sampling intensity
- Rapid methods of feedstock assessment may facilitate mitigating variability in future

Keywords - Short Rotation Woody Crops; Shrub Willow; Feedstock Quality; Feedstock Variability; Ash Content; Moisture Content

Abbreviations

FIFO, first-in first-out; HHV, higher heating value; ISO, International Organization for Standardization; LHV, lower heating value; LIFO, last-in first-out; SRWC, short rotation woody crops

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1. Introduction

In biomass production systems for bioenergy and bioproducts feedstocks may be harvested at different times during the year, but logistics and need for year-round demand may require that they be stored for extended periods of time [1–3]. Coming from many potential sources, woody feedstocks have variability in costs, quality, demand, and acceptance [4–6]. This perishable material is often stored in piles or bundles, and with varying levels of protection; thus, there is the potential for feedstock quality to change as it progresses through the supply chain [5,7,8]. Kenney et al. [5] especially highlight the importance of characterizing how changes in variability within the supply chain, and range of values for quality metrics, have on end-user processes.

Biomass sourced from shrub willow chips and other short rotation woody crops (SRWC) is a relatively high quality and has consistent mean energy and moisture content at the time of harvest [9] comparable to other biomass sources [5,10,11]. Several key attributes of SRWC and other biomass feedstocks (i.e. ash content, moisture content, and energy content) are a persistent concern because of their effect on costs, process efficiency, or materials handling [12–16]. Although there is room for improved flexibility of conversion and handling technologies [14], they are usually optimized for a limited range of variability in feedstock characteristics and do not respond well to large changes in feedstock characteristics, variability, and inconsistency which can create issues for handling systems, and refining or conversion

processes [14,17]. The variability of quality parameters as biomass progresses through the supply chain remains a concern [5].

A load of chipped willow biomass is most homogenous immediately after harvesting [9]. It begins to differentiate as soon as biomass is cut, continuing respiration and introduced microbial processes begin to degrade the material as it is stored in piles that begin to warm [2,18]. Microbial activity peaks between 35 and 40°C. If the chips produced begin to fall under 50mm size class they tend to be subject to less drying, lower gas permeability, and increased microbial activity; thus mass loss is greater, and the energy content as received (lower heating value – LHV) [19] are depressed. Depending on how the material is handled after harvest its quality can potentially be improved or degraded and the overall heterogeneity increases unless actions such as some pretreatment activities employed. Key feedstock properties that are subject to change appear to be moisture content, dry matter loss, ash content, and proportion of fines with regards to storage and transport.

Diverse options exist for structuring woody biomass supply systems based on mature industries like pulp and paper, but many challenges remain as the array of woody feedstocks expands, and the products that are made from this material. Information on different logistic components is needed to develop robust supply systems that provide biomass of consistent quality at an affordable price [20-22]. Previous studies have suggested that unprotected chips from short rotation woody crops (SRWC) such as willow can suffer mass loss over time [2,13]. Due to concerns for diminished quality, previous recommended storage periods for unprotected chips is two months or less [3,20].

One challenge with biomass piles is that quality changes at different rates depending on the location within the pile. The interior of biomass piles develop heterogeneous conditions; thus, feedstock properties will not change evenly within chip piles [7,8,21]. Based on previous work, at a basic level, piles differentiate themselves into a shell (generally the upper 50-75 cm of surface chips on a pile) and core (chips under the shell and within the pile) [8,22–25]; which differ primarily based on temperature and aeration. A finer partitioning of zones might also include a base (chips in contact with the ground), and a cap layer comprised of chips on top of the pile [26,27]. A key goal for storage is to minimize temperature to reduce biological activity, and maximize airflow in order to maximize moisture loss. Storage research for chipped woody feedstocks in Europe over the past two decades suggest that the key mitigation practices are to limit the length of storage, or create anaerobic conditions; more recently, progress is being made on facilitating low-cost chip drying in piles [28].

While research concerning the storage and quality of wood chips in piles for large-scale depots or yards from the pulp and paper industry exists [7,23], there is limited information about likely short-term storage of willow biomass in small-scale operations that may involve small piles close to the points of production. Willow varies from pulp quality chips because bark, twigs and sometimes leaves are included in this biomass which can impact both the initial quality of the material and how it responds to storage conditions. There is information that demonstrates how the internal conditions of wood biomass piles differ in other industries, but much less information about how chip quality changes within in dedicated biomass systems. The objective of this study is to evaluate the changes in moisture, ash and energy content of

willow chips that were generated as part of a commercial scale harvest during winter and stored over a period of seven months.

2. Material and methods

2.1. Source of material

As part of a commercial-scale harvest [9,29], 21 loads of approximately 150 Mg of fresh willow chips, comprised of the cultivars SV1 (*Salix x dasyclados*) and S365 (*S. caprea*), were harvested on Feb 4, 2013 near Groveland, NY (42°42'09"N, 77°44'49"W). The harvester platform tested was an unmodified New Holland FR9080 harvester, equipped with a New Holland 130FB coppice header blowing chips into tractor-drawn collection vehicles, which transferred chips to waiting trucks for delivery to on-site storage at an unpaved landing within 1 km of the harvest site. The header cuts whole plants about 10-20 cm above ground level, and feeds them into the forage harvester using a system of rollers; given the time of year this material only included stems and bark, as leaves had fallen for winter. The length of cut selected by the operator was the largest setting ("33-mm") in order to maximize fuel economy and harvesting rate. Weather conditions were cold (-10 to 0°C), snowy (30-50 cm of snow on open ground), and windy (average 4 m s⁻¹; gusts up to 14 m s⁻¹). Additional site details of the harvesting operations are available in Eisenbies et al.[29].

Based on the source of the willow biomass from dedicated stands and a moisture contents over 35% (mass fraction) at the time of harvest [9] this material falls under the B1 grade of the ISO standard for graded wood chips [30]. Samples (2-4 kg) of fresh chips were collected from each truck load upon delivery to an on-site storage location. The sample was taken from within the chip mass of each truck load; Briggs et al. [31] showed that further

stratification of the sample from a truck bed was not necessary. Each sample was weighed at the time of collection to the nearest 0.1 g at the edge of the field on a scale (Mettler-Toledo PG 5002-S) in order to obtain the wet weight before the samples could dry in the sun or become wetter due to their proximity to other samples or precipitation. The samples were subsequently returned to the lab within 12 to 24 hours and dried at 60°C until they reached a constant weight. Moisture content was determined on a mass basis [32].

2.2. Establishment of experimental piles

Due to operational delays, the biomass was initially stored for four weeks in a single large pile of comingled loads at the on-site storage. Between March 4, and April 23, 2013, 85 Mg of fresh chips were ultimately transferred into semi-trucks using a bucket loader and delivered in four loads to Tully, NY (N 42.797, W 76.120) where six individual piles of sizes ranging between 10 and 26 Mg (fresh biomass) were established. Two piles were created on March 4, two piles on March 7, one pile on April 11, and one pile on April 23. Three 2-4 kg samples were taken from each load at the time of delivery from the front, middle, and rear section of the pile using a shovel. These samples were weighted and subsequently dried at 60°C until they reached a constant weight so that moisture content could be determined. Pile dimensions were determined by measuring the long and narrow dimensions of the base, top, pile height, and angle of repose. Pile volume was estimated for pile shapes that represent the shape of the geometric volumes as described in Hardy [33]. The ratio of core volume to total volume was determined by assuming a 45-cm depth to core. Given that the piles did not perfectly match the array of specific geometric shapes described, the closest match was used,

but other relevant shapes were also applied at each pile height in order to obtain a range of possible volumes.

Piles were instrumented with temperature loggers (HOBO U12-008, Onset Computer Corp, Cape Cod, MA) that recorded hourly temperature for each probe location. Other studies [18,22] and recommended sampling protocols under development (ISO draft standards 18135, 14780), may partition piles into layers or grids. Only eight probes were available per pile; thus sampling and probe placement was based on a symmetrical scheme that was independent of pile size and simplified routine sampling (Figure 1). Temperature probes were installed ordinally (Top, N, SE, SW) to test for possible aspect differences. Probes were inserted into the pile 2/3rds of the height from the base; 45 cm for a shell sample, and one half the pile heights for the core sample. Probes were precisely installed by inserting a length of steel angle stock into the pile with the peak upward, taping a threaded nut to the probe, guiding probe and wire with a threaded rod along the inside of the angle stock pushing upward to create a void to correct depth, removing the angle, and unscrewing the threaded rod, leaving the probe at the required depth with minimal disturbance. Step ladders were laid on the pile sides for footing and to minimize disturbance while mounting the piles. Chip samples were collected on May 4, July 3, and August 8, 2013 near the probe locations but far enough away so that probes were not disturbed. Shell samples (1-2 kg) were taken using a shovel. Undisturbed core samples were obtained using a custom sampler that was augured to the same depth as the temperature probe for each location. The sampler (similar to a bucket augur) was designed to move into or out of the chip pile by turning the handle clockwise, a door in the side of a sample chamber was subsequently opened by turning the handle counter clockwise and held closed by returning to a

clockwise direction. A minimum of approximately 150 g was obtained from the core depths using a second coring as required.

[INSERT FIGURE 1]

2.3. Sample collection and processing

For samples taken from specific locations and depths that were too large to be ground, a stratified subsample for grinding was taken based on sampling guidelines for wood chips [19,31,34,35]; up to nine 10 to 15-cm³ scoops (three scoops from three layers) were carefully taken from a sample bag and combined. These were subsequently ground in a Wiley mill through a 0.5-mm screen for subsequent lab analyses yielding approximately 120 cm³ of sample. Ash content was determined by a dry-ashing method by placing a crucible with 2-g samples in a cold muffle furnace and raising the temperature slowly up to 550°C [36]. Higher heating value was determined using Parr 6200 Oxygen Bomb Calorimeter (Moline, Illinois) [19,37] (except for the July sampling date due to the lack of change between May and August). Lower heating value was calculated using moisture content and the formula described in section D2 of Annex D of the ISO standard [19].

2.4. Statistical analysis

To assess the quality parameters of chips prior to storage, the 21 individual loads of willow chips sampled at the time of harvest and the four individual loads at the time of delivery were compared using a contrast statement in the MIXED procedure in SAS 9.2 (SAS Inc.; Cary, NC).

Once the willow chip piles were established they became the experimental unit for this trial. The experiment was a 4 x 2 factorial design with four ordinal directions representing solar and wind exposure (Top, N Side, SE Side, and SW Side) and two depths (Shell, <45cm; Core, ~1 m). Willow chips were sampled on three different dates (mid-May, early-July, and mid-August) so a repeated measures analysis of a 4 x 2 factorial was analyzed using the MIXED procedure (model parameter = block position depth period position*depth position*period depth*period position*depth*period). Thus, the experimental unit was sample location within the pile; the individual piles, which had different sizes and slightly different shapes, were treated as a block effect. Parameter distributions were obtained using the FREQ procedure.

In order to approximate the quality of a load of chips once they are reloaded on trucks as compared to the ISO standards for class B wood chips we scaled the pile location means up based on the proportion of shell and core material. This was done by weighting the shell and core samples to the total volume of individual piles based on its physical dimensions and our best estimate of four shapes as described by Hardy [33] (i.e. irregular solid/trapezoidal, paraboloid, half-ellipsoid, half cylinder).

3. Results and Discussion

3.1. Pile volumes

Pile heights ranged between 1.4 and 2.4 m tall, 3 to 6 m on the short axis, and 4 to 10 m on the long axis, with a 40 degree maximum angle of repose (Figure 1). Pile biomass ranged between approximately 8 and 22 Mg (fresh) at the time of delivery from on-site storage to short-term storage; the first four piles were created from split loads (approximately 60:40); the total volume of the delivery trucks was approximately 70 m³. However, the range of volume

estimates based on Hardy [33] for applicable pile shapes differed by up to a factor of 4 for individual piles and thus care should be taken when choosing a pile shape. Despite the wide range of volume estimates, the ratio of core volume to total volume for any assumed shape was more stable; the mean ratio between core and shell chips ranged from 50:50 to 60:40 as the height of the pile increased (Figure 2). In contrast, wood yard chip piles such as those described in Ferrero [18] have larger core volumes that likely constitute more than 85% of the volume of the pile because of the way material is stacked after being unloaded from trucks. The material in our trial was not manipulated after pile creation.

[INSERT FIGURE 2]

3.2. Overall Pile Compliance

There were changes in chip quality associated with on-site storage at the harvest location, and delivery to the short-term storage sites in Tully. The mean ash content of these chips at the time of harvest was 1.9% (CV=18%), which increased to 2.7% (CV=29%) at the time of delivery ($P=0.0081$) (Table 1). A large proportion (77%) of the samples from the delivered chips met the ISO ash standard for B1 chips compared to a 100% pass rate for the freshly harvested chips [9]. Dirt clods were observed in the delivered loads of willow biomass suggesting contamination during the reloading and transportation process. The mean ash content commonly reported for willow ranges between 1.3-2.7% [38,39], although values for individual samples or sites have been observed to exceed 3% [9].

[INSERT TABLE 1]

The mean moisture content of the delivered chips was 47% (CV=9%) (mass fraction), which was 5% percentage points higher than the freshly harvested chips ($P=0.0521$). However, the maximum moisture content (53%) had only increased 2% percentage points compared to the freshly harvested chips. There was no difference in the HHV (18.9 MJ kg^{-1}) between the delivered and freshly harvested chips ($P=0.9445$), but the coefficients of variation increased slightly from 0.45% to 2.7%. The LHV mirrored the increase in moisture content. In spite of the fact these loads were delivered at different times, there were no significant differences between ash ($P=0.1008$), moisture ($P=0.9868$), HHV ($P=0.4334$), or LHV ($P=0.9368$) for the chips delivered between March and April.

3.3. Pile Temperatures

Temperature is a surrogate for biological activity in the various zones that develop where properties will change differently due to heating and ventilation [8,24,27]. Based on temperature, these piles reached a steady state in early to mid-July. Once all of the chip piles were established, the mean temperature rose throughout the study period reaching a peak temperature just below 50°C in the top core, and just below 40°C in the sides (Figure 3). Half of the daily temperature exceeded 40°C in the top shell and core, 30°C in the side core, 25°C in the side shell (Table 2). Specific moisture and temperature conditions favor different cohorts of fungi and other microorganisms; the resulting conditions may be desirable or undesirable depending on which organisms are active [27].

[INSERT TABLE 2]

Passive piles such as these ventilate by taking air in through the sides, and up through the center [26]. The degree of ventilation is a function of chip size and porosity. Air flow and humidity influence the internal temperatures of the pile. There was a slight gradient of 2-5° C in mean temperatures between the core and shell at the tops of the piles, and a more substantial gradient of 5-10° C on the sides. Overall, there was a 10-15° C difference between the tops and sides with considerably more variation amongst the tops from pile to pile; this was possibly due to pile size. Finally, there was very little difference amongst the sides or ordinal direction of the sides (i.e. N, SE, and SW). The temperature gradients appear similar to young, passively aerated compost piles as reported by Fernandes et al. [40].

Pile conditions were responsive to changes in ambient air temperature and humidity. Changes in pile temperature lagged behind changes in air temperature in the first half of the study (Figure 3). Temperature also rose and fell with ambient humidity, particularly during the first half of the monitoring period. Lower relative humidity (below 70-80%) appears to have facilitated airflow through the pile resulting in heat loss due to evaporative cooling.

[INSERT FIGURE 3]

3.4. Moisture Content

Within the pile, there were significant differences in moisture content between shell and core samples ($P < 0.0001$) and by sampling period ($P < 0.0001$), but not by sun or wind

exposure due to ordinal direction (i.e. Top, N, SE, SW) ($P=0.3098$). As stated previously, moisture content increased between harvest and delivery to the Tully site by 5 percentage points ($P<0.0001$). Once the small piles had been established and could sit undisturbed, the moisture content of the core and shell differentiated within weeks (Figure 4). Shell chips quickly lost moisture and dried to levels equal to or less than at the time of harvest. Variability did not increase between harvesting ($CV=10\%$) and pile establishment ($CV=9\%$), and remained low in the shell throughout storage ($CV=4$ to 16%) (Table 1).

[INSERT FIGURE 4]

The trend for moisture content of the core was similar to the shell, but the mean moisture content was different. The peak mean moisture content of the core chips was 54% (mass fraction) in May and it decreased to 48% in July and 46% in August. The moisture content in the core was 7-9 percentage points greater than the shell throughout the study.

Piles were subject to the elements, but not subject to sampling after substantial rainfall events. There was a total of 12.7 (0.8 mm day^{-1}), 272 (5.5 mm day^{-1}), and 81.8 (2.8 mm day^{-1}) of cumulative rainfall preceding each of the May, July, and August sampling dates respectively. Each 10 mm of rainfall has the potential to raise the moisture content of the biomass about 1 percentage point (mass fraction) given the pile footprints and assuming 100% absorption. While pile heating and ventilation may facilitate moisture loss of chips throughout the pile, aeration and drying are likely fairly heterogeneous at scales relevant to the discrete chips samples locations within the pile.

By weighting the moisture content of core and shell samples by their proportion of pile volume based on Figure 2, the moisture content for a reconstituted load can be estimated. There were significant differences in moisture at the measurement locations within the piles between the three periods ($P=0.0164$) treating each pile as a separate load to be delivered to an end user. Chips piles, as a whole, were significantly drier in July (44%) and August (42%), compared to May (49%). However, the variability of moisture content increased in the core from the time of establishment through the three sampling periods (CV from 10 to 26%). Such results suggest that care should be taken sampling piles that have been stored for months due to the degree of differentiation that we observed. Specifically, as storage time increases the number of pile subsamples should be increased, and samples taken from shell and core locations. Results also indicate that care should be taken to ensure a fair degree of mixing occurs when chips are reloaded.

3.5. Ash Content in Piles

With this feedstock, ash is probably the most critical property to manage because once ash content has increased in chips, either from soil contamination or mass loss has occurred due to biological activity, it does not recover without an investment in some pretreatment activity. In this study, ash content increased between initial harvest and delivery by 0.8 percentage points, probably due to soil contamination during reloading and transportation as some clods were observed in the material. Once the material reached the study location in Tully for storage there were no significant differences in ash content between the three sample times ($P=0.3526$). Core samples had a mean ash content across all periods of 4.2%, although not significantly higher than the 3.7% of the shell ($P=0.1976$). However, the amount of variation

in the piles increased over time, coefficients of variation increased from 18% at the time of harvest to a range of 36-83% during pile monitoring (Figure 5, Table 1). Discrete samples had ash contents as high as 10% for both shell and core samples, probably the result of soil contamination, but may also be due to mass loss from higher microbial respiration. Regardless, the reported mean ash contents for a variety of bioenergy crops range from below 0.5 to just over 6% at the time of harvest [10], but the variability of other crops can spike to 15, 20, as high as 40% or more in some cases [5].

[INSERT FIGURE 5]

There were no significant differences in overall ash content between the three periods ($P=0.2026$); thus ash content did not significantly change during storage. However, the small and statistically insignificant differences in ash might have practical implications on the quality of the material based on ISO standards. As with moisture, the ash content of a composite load can be estimated by weighting the means for the core and shell samples by their proportion of pile volume. Chips piles, as a whole, had mean ash contents below 3.9% in May and July, versus 4.5% in August. Based on this result, these loads would no longer be compliant with the ISO standard for ash content [30] after 3-6 months of storage. However, the same implication identified with moisture content regarding sampling protocols and ensuring proper mixing of loads may be required during reloading to ensure the aggregate ash content remains within specification. It is clear that for ash content the chain of custody between harvest, storage, and

delivery is an important issue associated with biomass logistics, and can be difficult to track in a disrupted supply chain as with the delayed delivery of these chips.

3.6. Energy Content

The HHV remained above 18.6 MJ kg^{-1} from harvest to delivery and through storage ($P=0.4253$) (Figure 6). This result includes a lack of significant differences between the shell and core samples ($P=0.5398$). However, variability associated with values from discrete locations increased; the coefficients of variation increased from a minimum of $<1\%$ to a maximum of 4% (Table 1). The decrease in HHV from 18.9 to 18.6 MJ kg^{-1} was concurrent with increases in ash content. Increases in HHV for specific observations that contribute to the increased variation are associated with increases in energy density as lower energy density sugars are consumed by microorganisms and high-energy compounds are left behind [41].

[INSERT FIGURE 6]

In contrast the mean LHV was significantly different in the core (9.3 MJ kg^{-1}) compared to the shell positions (11.3 MJ kg^{-1}) ($P<0.0001$). The changes in variability of LHV (Table 1) are concurrent to the changes in moisture content (Figure 7) [19,22]. Thus, as the piles generally dried with time, mean LHV for composite loads significantly improved from 9.6 to 10.8 MJ kg^{-1} between the May and August sample periods ($P=0.0153$).

[INSERT FIGURE 7]

3.7. Implication

The longer biomass remains in storage and the more times it is handled, the more variable it becomes. Some of the variation in this experiment was associated with the operational realities of biomass handling and transportation; which highlights the importance of chain of custody to biomass quality. These chips were not handled well. The contractor transporting the chips was not practiced with biomass crops; soil was probably introduced because the unpaved loading area was not smooth or care was not taken to leave a buffer of chips on the ground. It can be a challenge to control the flow of biomass and integrate it into local shipping logistics particularly when demand is uncertain and other commodities are competing for logistic resources. This study, as well as others in the literature, clearly shows the need to establish best practices for storage and handling, the need for monitoring throughout the chain of custody.

The variability of characteristics associated with large scale biomass crops over time and growing seasons has been identified as an important barrier to the large scale commercialization [5]. The influence of shell chips on the overall quality of short term piles may be underappreciated and underrepresented by pile sampling protocols, particularly with regards to the degree that chips in the shell may have better quality. The increasing variation in characteristics within a pile and the composite loads that are created from piles suggests that these issues need to be better understood and managed during operations [5, 45-47]. Developing and deploying tools for rapid quality assessments of feedstock quality (e.g. portable near infrared spectroscopy [42], prompt gamma neutron activation analysis, and x-ray fluorescence [43]) would be beneficial in monitoring quality along the supply chain and for

389 facilitating the blending of material to ensure that a consistent quality biomass is delivered to
390 end users. Information about not only the means for quality parameters, but also the changes
391 range of values over time, is important because such data will have important repercussions for
392 cost modeling and uncertainty analysis [44,45].

393 Shrub willow biomass has a stigma for being lower quality feedstocks among some end
394 users; particularly with regards to high ash and moisture, because of the multiple stem nature
395 of the plant and associations with some willow tree species. Freshly harvested willow biomass
396 crops have a consistent quality that is comparable to hardwoods in energy content and most
397 other ways with the possible exception of ash content of debarked chips [46], but is still
398 compliant with ISO standards for class B wood chips [9,30]. Moisture content of willow biomass
399 crops at the time of these harvests was lower and more consistent than commonly described
400 [13,47–50]. However, these values can change during subsequent handling and storage,
401 particularly in a moist temperate region like the Northeast U.S. Regardless, even when stored in
402 passively aerated, unprotected piles, mean moisture content will apparently fall with time.

403 Keeping ash content within a target standard, such as the ISO limit of three percent,
404 seems to be the primary challenge for crops like willow biomass; without precautions, it only
405 increases as chips are stored and handled. In the case of this study, loads had acceptable
406 properties with the exception of ash content. The issue of high ash content does not preclude
407 acceptance by an end-user who ultimately decides what constitutes acceptable quality.

408 Observably, it is generally best for biomass to head straight to the biorefinery or to
409 some sort of preprocessing depot where improvements to the feedstock quality can occur, or
410 at the minimum some stability achieved. Previous recommendations are that unprotected

storage be limited to two months [3,20]; our results support that recommendation with the caveat that piles were created in the spring and monitored into the summer. Piles created during the winter months when outside temperatures are lower may last longer without changes in biomass quality. However, more research is needed to determine how flexible that recommendation may be; best storage practices may require a seasonal component in relation to the length of time material can be stored. The initial quality of the material put into storage will also have an impact [9]. In general piles should be kept as cool and dry as possible, and steps should be taken to facilitate drying; other methods such as compaction are also employed with very large piles [23,51].

If biomass from single pass cut and chip harvesting systems is to be stored longer, either protection measures or alternative harvesting methods should be considered. For protection, biomass may be covered by tarps or stored under a fixed cover. Compaction to inhibit air exchange and biological activity is another strategy, but there are risks for spontaneous combustion for chip piles above a certain size [7]. Alternative harvesting methods where SRWC biomass stored as stems, billets, or bales can maintain quality longer compared to chipped biomass [3,22,52,53]; however, that introduces additional processing steps and costs; biomass harvested and chipped in a single operation should be cheaper to produce [54].

One goal that has been proposed is to create a uniform feedstock supply system to decrease the variability and improve the properties of multiple biomass feedstocks into a single stream [5,54]. Several strategies could be employed to extend the usable lifespan of stored chips. First, mixing or blending feedstocks is an emerging approach. Formulated feedstocks may even improve desirable properties such as energy content [55]. This may entail simple

strategies where LIFO (last in, first out) and FIFO (first in, first out) inventory management are used to combined older biomass with fresher material [51]. If rapid quality assessments were available, mixing/blending could also be effective in attenuating marginal properties by combining low and high-quality feedstocks at a rate that keeps the overall signal within acceptable ranges. The distinction here between blends, which are carefully formulated, and mixes which are more arbitrary should be noted with regards to some sampling schemes that could be employed.

Successful operational drying of chips is desirable for storage periods greater than two to three months; but research has struggled with how to accomplish this with chipped biomass with out significant costs [3,8,22,28]. There are numerous low-cost or no-cost objectives that have been tried; succinctly these include increasing porosity, decreasing fines, and improving ventilation [20,24,56]. Using pile configuration that maximize the surface area of the pile is a low-cost possibility, but has not received much attention [7]. There may be a seasonal component to pile configuration. A leaf-on pilot study of willow biomass crops suggested that the cores of piles created in summer were drier than the shells [57]. For biomass where longer-term storage is planned, increased particle sizes (e.g. billets or whole stems) will limit fines which will enhance air flow through the pile and moisture loss, and limit mass loss due to microbial activity; however, such material requires additional processing and additional costs to meet size requirements of end users.

Another possibility is pretreatments that enhance or stabilize material. For example, cleaning loads of ultra fine material ($< 0.2\text{mm}$) will lower ash content and improve the feedstock quality [58]. Processes such as hot water extraction can serve as a pretreatment. The

extracted chip byproduct has reduced ash and been shown to be advantaged for pulping, wood pellets, and reconstituted wood products, but it accepts wet feedstocks, and the byproducts are a uniform low-ash feedstock and an marketable aqueous solution containing easily fermentable sugars [41]. Preliminary tests with post hot water extraction material suggest that these chips can be stored for a longer period of time with little loss in quality because the hydrophillic hemicellulose component of the material has been removed.

4. Conclusions

Willow biomass properties became more variable the more it was handled and the longer it was stored. Properties differentiated as conditions in the shell, core, tops, and sides differentiated. Mean pile temperatures rose consistently over the course of the study and reached a steady state between 25 and 45 degrees C depending on pile location. There was almost a 5 degree difference between core and shell locations, and a 10-15 degree difference between the top and sides. Mean moisture content increased from 42% to 47% (mass fraction) between harvest in February and deliveries between March and April. Moisture content decreased over the three-four months after the piles were established such that there was no significant difference in mean between the stored piles and fresh chips, but the material was more variable and differentiated by location. Ash content steadily increased and became more variable through each phase of this study. By the end of the study the mean ash content exceeded the 3% ISO standard at a load scale, but within the piles some locations were still compliant. One issue was soil contamination after loading. Mean energy content HHV was stable between 18.6 and 19 MJ kg⁻¹, but variability increased over time. Mean LHV ranged

between 8.6 and 11.7 depending on location and period within the pile, and differentiated based on changes in moisture content within the pile.

The differentiation in the characteristics of the willow chips in the outer shell and the inner core of the pile has implications for overall quality of the material. Due to the small pile size, the ratio of core to shell volume was between 50:50 and 60:40, which was lower than the 85:15 ratio typical of larger wood yard piles. Managing the size and shape of the pile to manipulate this ratio to maintain chip quality is one approach that should be explored.

Recognizing the widely disparate ways that biomass can be handled and conditions it can be subjected to, this work highlights several needs for future research. In particular, methods for rapidly assessing moisture content and ash content need to be developed and a wider array of storage conditions need to be assessed. Passive, low-cost, methods for maintaining quality need to be assessed (i.e. pile configuration, seasonal storage, chip sizes) to extend the usable lifespan of stored chips. Rapid assessments would provide the means to evaluate these methods as well as methods to mitigate diminished quality due to storage by mixing with high-quality or fresher material. Previous recommendations for unprotected storage are up to two months. If rapid assessment technologies were to become available, the usable lifespan of chips could be extended.

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656 Table 1 Means and coefficients of variation for ash content, moisture content (mass fraction),
657 higher heating value (HHV) and lower Heating Value (LHV) from harvest, delivery, and three
658 sample periods.

Period	Dates	Ash Content		Moisture Content		HHV		LHV	
		----- Percent ----- (CV%)				----- MJ kg ⁻¹ ----- (CV%)			
Harvest	Feb 4	1.9 b [#] (18)		42 (10)		18.9 (<1)		11.3 (6)	
Delivery	Mar 4-Apr 23	2.7 a [#] (29)		47 (9)		18.9 (3)		10.0 (9)	
		Shell	Core	Shell	Core	Shell	Core	Shell	Core
Period 1	May 4	3.6 (46)	4.2 (58)	43 b* (16)	54 a* (10)	18.9 (2)	18.8 (4)	10.9 a* (12)	8.6 b* (13)
Period 2	July 3	3.2 (36)	4.0 (45)	40 b* (4)	48 a* (26)				
Period 3	August 8	4.3 (83)	4.9 (53)	37 b* (9)	46 a* (20)	18.7 (4)	18.6 (4)	11.7 a* (8)	10.0 b* (16)

659 # letters indicate significant differences between harvest and delivery

660 * letters indicate significant differences between shell and core

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664 Table 2 Percent of daily mean temperature at discrete pile locations at or exceeding given
665 temperature thresholds
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Exceeds	Top of Chip Pile		Side of Chip Pile	
Temperature (°C)	Shell	Core	Shell	Core
	percent of mean temperatures (percent of discrete temperatures)			
20	100 (97)	100 (98)	82 (82)	97 (95)
25	100 (95)	100 (96)	61 (58)	78 (81)
30	98 (91)	100 (93)	45 (33)	56 (57)
35	92 (74)	96 (76)	0 (10)	39 (30)
40	51 (52)	64 (55)	0 (0)	0 (7)
45	26 (30)	40 (39)		0 (6)
50	0 (17)	0 (20)		0 (0)
55	0 (6)	0 (18)		
60	0 (0)	0 (8)		
65		0 (0)		

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Figure Captions

Fig. 1 Generic cross section of a pile profile showing sample and temperature probe locations for monitoring the shell and core of the piles at the top and in the side of the pile at three ordinal locations

Fig. 2 Mean and range of core volume percentages (black line and gray field) for different pile shapes assuming a 45-cm thick shell. Approximate pile heights ranged between 1.4 and 2.4 m, and base dimensions between 3-6 m on the short axes, and 4-10 m on the long axes. Solid points represent observed core percentages for the "best" estimated pile shape. Hollow points are the biomass estimates associated with the right axis

Fig. 3 Temperature of shell/core and top/side locations in six willow chip piles (Above). Vertical error bars indicate the 95% confidence interval at the beginning and end of the study period. (Below) Mean, daily, ambient air temperature and relative humidity at the pile location

Fig. 4 Distributions of moisture content (mass fraction) for core and shell samples taken from six piles for May 4 (top), July 3 (middle), and August 8 (bottom), 2013. Points with horizontal error bars indicate the mean moisture content of harvested chips and delivered chips and two standard deviations

Fig. 5 Distributions of ash content for core and shell samples taken from six piles for May 4 (top), July 3 (middle), and August 8 (bottom), 2013. Points with horizontal error bars indicate the mean ash content of harvested chips and delivered chips and two standard deviations

Fig. 6 Distributions of gross calorific content dry (higher heating value) for core and shell samples taken from six piles for May 4 (top), and August 8 (bottom), 2013. Points with horizontal error bars indicate the mean HHV of harvested chips and delivered chips and two standard deviations

Fig. 7 Distributions of calorific content as received (lower heating value) for core and shell samples taken from six piles for May 4 (top), and August 8 (bottom), 2013. Points with horizontal error bars indicate the mean LHV of harvested chips and delivered chips and two standard deviations

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