

Article

# Can Biomass Quality Be Preserved through Tarping Comminuted Roadside Biomass Piles?

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Received: 1 August 2017; Accepted: 18 August 2017; Published: 23 August 2017

**Abstract:** Storage conditions play a vital role in maintaining biomass quality as a suitable bioenergy feedstock. Research has shown that biomass undergoes significant changes under different storage conditions and that these may influence its suitability for various biorefining and bioenergy opportunities. This study explores the effects of different tarp covers on the properties of stored-comminuted forest harvest residue from the Great Lakes St. Lawrence Forest. Characteristics of the biomass were evaluated upon harvesting and after one year in storage. The physical state of the different tarps used for pile coverage was monitored onsite. Results indicated that tarp material considerably affects micro-climatic conditions inside piles, yielding variation in the characteristics of stored biomass over the storage period. While plastic based tarps were easier to work with and lasted longer than paper-based tarps, the paper-based tarps were more breathable and resulted in less degradation of biomass. However, the paper-based tarps did not maintain their structural integrity for the full duration of the storage period. Moisture content of original biomass (48.99%) increased to a maximum of 65.25% under plastic cover after 1 year of storage. This negatively influenced the net heating value of the biomass, causing it to decrease from 8.58 MJ/kg to 4.06 MJ/kg. Overall, the use of covers was not considered successful in preserving the original quality of biomass but may enhance its quality for other biorefinery opportunities.

**Keywords:** biomass; storage; feedstock; forest; harvest residues; comminuted biomass; tarps; covering; biorefinery

## 1. Introduction

Forest biomass has gained attention as an alternative energy source to address unsustainable supplies of fossil based fuels [1]. A renewable resource, forest harvest biomass offers potential to enhance the sustainability of energy production as well as to greatly reduce greenhouse gas emissions from reliance on fossil fuels [2]. Bioenergy applications can further enhance the economic value of forest harvest operations, diversifying the forestry industry and creating new jobs in rural communities within the forestry and energy sectors [3].

Offsetting the shutdown of many Canadian pulp mills since 2005, the Canadian Forest Products Association, in cooperation with multiple partners, has introduced a “bio-pathways” program, intended to transform the Canadian forest products industry from its traditional applications to a global producer of bioenergy and bio-chemicals [4]. The market for diverse bioproducts presents opportunities to collaborate with other industries, which can further help maximize efficient use of

forest resources and create new job opportunities [5]. In order to leverage these opportunities, a strong supply chain must be established to ensure the quality of the biomass used for various applications.

Establishing a strong supply chain begins with a thorough understanding of the resource. Forest harvest residue biomass is typically produced as a by-product of industrial operations and is commonly comprised of tops, branches, bark pieces and foliage. It is generated as residue either during the harvest and extraction of merchantable logs from forest sites or when extracted logs are being processed. Traditionally, residues are either left on the forest floor as material for nutrient cycling and/or erosion control, or they may be piled at roadsides and burned. With rising interest in their application as bioenergy feedstocks however, they have become valued commodities in their own right. As such, there are government sponsored innovation initiatives underway to quantify, classify and characterize feedstocks with the aim of connecting them with compatible technologies and establishing supply chains to benefit Canadian operations [6].

Properties of forest-based residues are complex due to variation in species and component composition. This complexity may be further developed during supply chain operations such as storage. Converting forest harvest residue biomass into energy or bioproducts usually requires a period of storage, which may be considered a step in the material processing. Storage is a dynamic process in which many interconnected factors affect the state of the biomass. Extended storage may cause degradation, organic matter loss and changes in energy value and fibre quality, which can reduce the overall quality of the biomass and render it ill-suited to certain applications [7]. There are multiple factors involved in storage practices that may influence the changes that biomass undergoes. These include climatic conditions, pile geometry and structure, pile size, storage time, species composition, moisture content, season of harvest, and state of the biomass [7]. However, the effects of storage are not well understood and there are many contradictory findings to date. Since much of the reliable data on suitability for biorefining applications refers to the properties of newly harvested biomass, it is important to better understand the changes that biomass undergoes in storage in order to maximize its potential as industrial feedstock.

Major processes that effect change to stored forest harvest biomass include moisture evaporation, living cell respiration, biological degradation and thermo-chemical oxidative reactions [7]. Resulting changes in the characteristics of the biomass may include moisture content, energy value, ash content and dry matter content [8], which affect its value as fuel feedstock. Moisture content is particularly important for energy production since some of the energy generated during combustion must be used for the evaporation of the water, which leaves less usable energy from feedstock. This decreases the economic value of the biomass. Another consequence of higher moisture content in stored biomass is increased biological activity due to favourable environmental conditions for bacteria and fungi growth, the presence of which can present a health and safety risk [9]. Biodegradation can, in turn, contribute to increasing the internal temperature of biomass piles, which is another major concern during storage. Elevated temperatures promote exothermic chemical reactions that can cause the piles to self-ignite which results in organic matter losses, particulate and greenhouse gas (GHG) emissions and economic peril [7].

Covering storage piles with tarps is suggested to be an inexpensive air drying technique that has been shown to be feasible and enhance biomass quality in certain operations. Covering piles ensures their protection against rain and snow, thereby preventing the introduction of extra moisture into biomass stored outdoors. Investigating the characteristics of feedstocks from silvicultural cleanings and thinnings, Nurmi and Hillebrand [10] observed that roadside drying of covered wood harvested in January resulted in lower moisture content than uncovered wood. Roser et al. [11] found similar benefits of tarping bundles of stems in different climate regions of Europe. However, applying covers to biomass has the potential to trap heat and accumulate moisture inside, which may increase the risk of degradation within biomass piles. Studies on the response of wood particles to climatic variation provide evidence that ventilation in stored biomass may result in reduced dry matter losses [12]. To address this, Afzal et al. [8] demonstrated promising results in moisture reduction of comminuted

biomass using a breathable tarp cover in Eastern Canadian climatic conditions. Thus, covering storage piles with tarps, particularly those that allow for some degree of air permeability—may provide a means to lower the material's overall moisture content without significantly increasing the risk of degradation.

This paper examines the impact of two different tarp covers—moisture permeable versus moisture impermeable—on stored comminuted forest harvest residue properties in Eastern Canadian climatic conditions. Properties of interest include physical characteristics such as moisture content, bulk density and particle size, as well as thermo-chemical characteristics such as energy value, volatile matter, fixed carbon and ash content as well as elemental analysis. This study has three key objectives. Firstly, it aims to evaluate the overall biomass quality with respect to coverage during extended storage. Secondly, it aims to evaluate and compare the performance of different tarp covers by their effects on the various physical and chemical characteristics of biomass material. Finally, it aims to evaluate tarp performance by their durability and relative handling ease during tarping operations. Conclusions drawn from this study can be used to inform optimal storage strategies that maximize the desirable properties of biomass as a raw material for the purpose of direct combustion or thermal/biochemical conversion to novel forms of bio-energy and bio-materials.

## 2. Material and Methods

### 2.1. Operational Trial

JD Irving Ltd. (JDI) provided the storage site and FPInnovations (FPI) the experimental set-up for this study including pile formation and tarping operations. Samples of stored biomass were supplied to the Faculty of Forestry at the University of Toronto for characterization. Samples of biomass were obtained from piles covered with two different types of tarps as well as control piles (no tarp) at the beginning of the study and after twelve months of storage.

In September 2009, fifteen piles of comminuted forest harvest residue biomass weighing on average 200 oven dry tonnes (odt), were built in the bush at roadside near Sussex, New Brunswick. The piles were built following harvesting and flail chipping operations (bark, branches and leaves removed from stems). The piles were comprised of roughly 81% softwood species (Balsam Fir and Black Spruce) and 19% hardwood species (Poplar, Birch and Maple). Average pile dimensions were approximately 22 m × 15 m × 5 m (L × W × H). A typical pile is depicted in Figure 1 below. The flail chipping operation employs a unique silvicultural system where the harvested tree is skidded to road side and delimbed and debarked by a flail chipper. The tree enters the flail chipper and proceeds through a series of chains that remove limbs and bark from the stem. The residue material is deposited into piles at the roadside, eventually to be used as hog fuel by the mill. The merchantable stem proceeds through a chipper and is blown directly into a transport van destined for the pulp mill.

Out of fifteen piles of biomass assembled for the trial, six piles were covered with plastic-based Interwrap [13] tarps, six were covered with paper-based Walki [14] tarps and three were left uncovered to serve as control piles, providing three treatments. The Interwrap tarps are made of plastic and are 100% recyclable. The tarps used in this study are commonly used for wrapping lumber products for storage outside. The weight of the tarp used in this study is 38 kg with an average density of 70 g/m<sup>2</sup>. Multiple tarps were sewn together for the purpose of the trial. Each modified tarp covered an area of 540 m<sup>2</sup>. The Walki tarp are composed of 2 layers of wet strength kraft paper overlaid with a polypropylene net material to resist tearing. The Walki tarp comes in rolls 4 m wide, by 250 m long and weighs 296 kg. The average density of the tarp is 246 g/m<sup>2</sup>. The manufacturer cautions that this tarp should not be used to cover material for more than a year, after which time it may start to degrade.



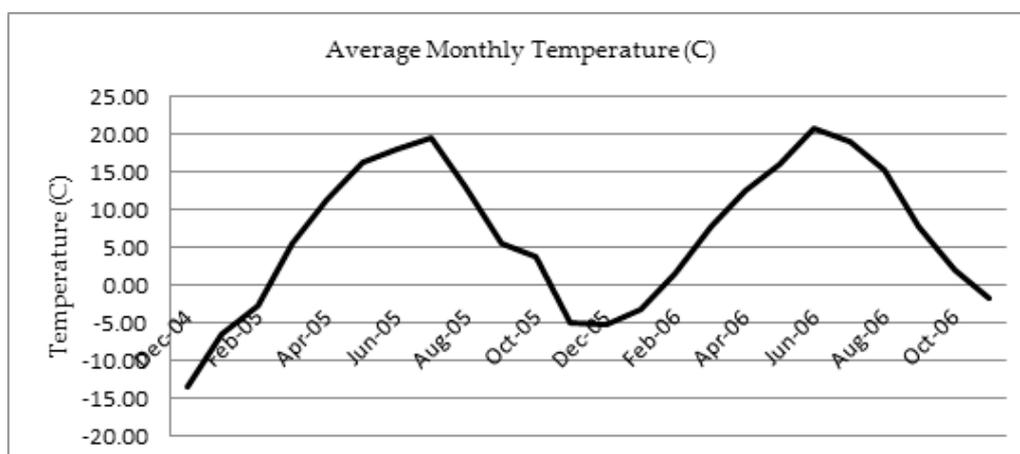
**Figure 1.** Pile of comminuted forest harvest residue at initial pile construction.

## 2.2. Sampling

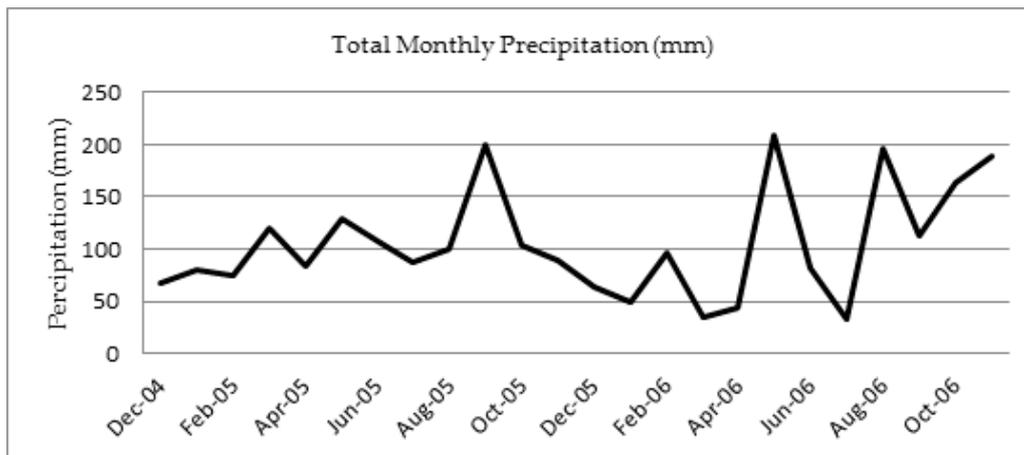
Sampling occurred at two intervals during the course of this study. Initial sampling occurred when the piles were established in September 2009. An excavator with grapple was used to collect the samples. Five samples were taken from one pile of each treatment (control, plastic-based tarp and paper-based tarp) in September 2009. Samples were sealed in polyethylene bags and frozen at the FPI lab in Montreal and then sent to the Faculty of Forestry at the University of Toronto. Samples were returned to the freezer on arrival. These samples will be referred to as ‘original’ throughout the paper.

In February 2010 (after six months), an on-site evaluation was conducted to assess the integrity of the tarps. Three piles (1-control, 1-plastic-based and 1-paper-based) were designated for long-term follow-up and left untouched for one year before sampling.

For the post-storage follow-up, the remaining three piles (uncovered, plastic tarp, paper tarp) were sampled in August 2010. Four samples were taken from each pile treatment at depths of approximately 1 m, 2 m, 3–3.5 m, and 4–4.5 m. Samples were frozen and sent to the Faculty of Forestry at the University of Toronto for characterization. Testing results from original samples were used for comparison with their counterparts from the one year stored material. The average monthly temperatures duration of the trial is shown in Figure 2. The total precipitation (snow and rain) is shown in Figure 3.



**Figure 2.** Fredericton, New Brunswick region average monthly temperature over one year.



**Figure 3.** Fredericton, New Brunswick region total precipitation over one year.

Dataloggers were used to monitor temperature within the piles throughout the study. One datalogger was inserted into each pile. Attached to each datalogger were 4 thermocouples which were positioned at different locations within the pile. The dataloggers received a reading every 5 s for intervals of 2 h. After each 2-h interval, the dataloggers recorded the average, maximum and minimum temperature values.

### 2.3. Characterization

Biomass characterization included evaluation of moisture content, particle size distribution, bulk density, energy value, ash content, volatile matter percentage, fixed carbon percentage and elemental analysis. Procedures were based on standard test methods such as American Society for Testing and Materials (ASTM) and European Committee for Standardization (CEN/TS) as well as on peer-reviewed literature. Moisture content was determined on an as-received (unfrozen) basis as specified in ASTM E871-82 [15]. Three samples of 20 g each were taken from each sample bag (of approximately 5 kg) for moisture content determination. Size distribution of the biomass samples was determined first by hand sieving to separate wood chips that were too large for mechanical sieving. Air dried biomass was placed on a screen which was then shaken horizontally until the chips had been separated by size. Chips that passed through a hand sieve with screen openings smaller than 4.75 mm were then mechanically sieved using a vibrating screen. Circular openings in the screen had a width of 12.5 mm squared. Chips that passed through the screen were designated as small fractions while those that did not were designated as large fractions. The material separated into each category was weighed and calculated as a percentage of the total oven dry mass. Bulk density was determined based on air-dried volume and oven dry mass, as specified in CEN/TS 15103 [16], by pouring the biomass into a vessel of known volume and determining the mass of the biomass which filled the vessel. It must be noted that this is not a measure of the actual compressed bulk density in the pile, but rather an uncompressed bulk density giving a relative measure of the particle spacing and a proxy for particle size measurement i.e. the lower the bulk density, the larger the particle size.

The Higher Heating Value (expressed in MJ/kg), which is the maximum amount of energy that can potentially be recovered on complete combustion of biomass samples, was determined by a Parr 1108 adiabatic oxygen combustion bomb calorimeter, using instrument operating instructions [17] and ASTM D2015-77 [18]. Ash content of biomass samples was assessed using a muffle furnace as per ASTM D1102-84 [19] and CEN/TS 14775 [20]. Percentages of volatiles and fixed carbon were determined by Thermo Gravimetric Analysis (TGA). Elemental analysis was conducted by the University of Toronto Department of Chemistry's Analytical Laboratory for Environmental Science Research and Training. A CHN analyzer was employed to determine carbon, hydrogen and nitrogen content. Oxygen content

was then determined by subtraction from 100%. Content of each element was calculated reported on an oven dried mass basis. The detection limit of this method is 0.3%.

### 3. Results

#### 3.1. Tarping Operation and Tarp Durability Evaluation

Plastic-based tarps were lighter ( $70 \text{ g/m}^2$  vs.  $246 \text{ g/m}^2$ ), more flexible and cover a greater area per sheet than the paper-based tarps. Additionally, the plastic-based tarps could be folded into an easily transportable bundle (38 kgs) relative to the paper wrap, which comes in rolls of 296 kgs. Due to their weight, the paper rolls require a roll dispenser to lift them and two workers to pull a layer of tarp over the pile. The paper-based tarps also require many layers to adequately cover a pile. On average, seven layers each 4 m wide were required, making it a physically demanding job for the workers. Using paper-based tarps also requires an excavator to follow the workers with the roll dispenser. From an operational perspective, the paper tarping operation took twice as long as the plastic tarping operation. Specific to covering large forest harvest residue piles, the tarping operation was less labour intensive and simpler when employing the plastic-based tarps as compared to the paper-based tarps, Figure 4.



**Figure 4.** Tarping operation using, (a) plastic-based tarp and (b) paper-based tarp.

After six months in use, a field evaluation of the two types of tarps revealed superior performance of the plastic tarp to the paper tarp. After six months of exposure to sun, rain, wind and snow, the plastic-based tarps retained their waterproof properties and remained intact all around the piles, as shown in Figure 5. The paper-based tarp showed signs of severe degradation and in some locations had completely lost their protective value, as shown in Figure 6. The degradation of the paper-based tarp on the top of the pile might be explained by Buggelen's wet lens theory [21]. According to Buggelen, a pile of biomass will expel hot/moist air through its top like a chimney as it draws in fresh air from its sides. As noted in this trial, the paper-based tarp on the sides of the piles, where the temperature is not expected to dramatically increase, and there is less snow and rain accumulation, remained in good condition through the six month period, while the tarp at the top of the pile was thoroughly degraded.



**Figure 5.** Plastic-based tarps after six months.



**Figure 6.** Paper-based tarp after six months.

### 3.2. Biomass Characterization

A comparison of the characteristics from biomass samples taken at the time of pile formation with those taken after long-term (1-year) storage was performed, as shown in Table 1. The moisture content and bulk density for the original material is an average of four samples from each of three random piles with three replicates per sample ( $n = 36$ ). The post-storage moisture contents are calculated from one pile at five different depths and three replicates ( $n = 15$ ). Post-storage values were averaged from the different strata samples within a treatment. To assess the differences across time and between tarp treatment, a two-way analysis of variance followed by Tukey's Honestly Significant Difference (HSD) test using R statistical computing software [22] was used. The results are summarized in Table 1.

**Table 1.** Properties of comminuted biomass including original material and samples after 1 year storage with no tarp, plastic-based tarp and paper-based tarp.

Parameter	Original Material	Post-Storage Control	Post-Storage Plastic Tarp	Post-Storage Paper Tarp
Pile Moisture Content (ar)%	48.99 <sup>a</sup> (2.35) <sup>b</sup> a 36 <sup>c</sup>	61.77 (9.39) b 15	65.25 (5.06) b 15	52.40 (13.87) a 15
Bulk Density (od·kg/m <sup>3</sup> )	112.78 (26.94) bc 36	89.78 (9.10) ab 9	124.49 (17.53) c 9	73.25 (6.72) a 9
Large Particle Fraction (% od mass)	60.65 (8.81) a 3	56.58 (8.26) a 9	42.94 (7.88) b 9	57.42 (7.32) a 9
Small Particle Fraction (% od mass)	39.35 (8.81) a 3	43.42 (8.26) a 9	57.06 (7.88) b 9	42.58 (7.32) a 9
Proximate Analysis				
Volatiles %	71.1 (4.85) b	73.03 (2.40) b	59.54 (4.98) a	76.38 (3.04) b
Oven Dried	12	6	4	4
Fixed carbon %	16.47 (2.13) a	21.78 (2.64) b	21.92 (0.56) b	20.14 (3.57) ab
Oven Dried	12	6	4	4
Ash %	8.94 (5.08) a	5.18 (1.08) a	18.54 (5.52) b	3.48 (0.53) a
Oven Dried	12	6	4	4
Higher Heating Value (MJ/kg-od)	19.51 (1.08) ab 12	20.35 (0.39) b 6	18.37 (1.05) a 6	20.43 (0.21) b 6
Net Heating Value (MJ/kg)	8.58 (0.75) c 12	4.31 (0.54) a 6	4.06 (0.53) a 6	5.81 (0.45) b 6
Energy Density (MJ/m <sup>3</sup> )	967.6	386.9	505.4	425.6
Carbon (%)	49.92 (2.23) a 9	51.6 (0.6) a 3	48.6 (0.9) b 3	51.3 (0.7) a 3
Hydrogen (%)	5.70 (0.26) a 9	5.6 (0.1) ab 3	4.86 (0.1) c 3	5.46 (0.06) b 3
Oxygen (%)	43.74 (2.25) a 9	42.2 (0.6) a 3	46.0 (0.6) b 3	43.3 (0.8) a 3
Nitrogen (%)	0.64 (0.09) a 9	0.6 (0.04) a 3	0.61 (0.03) a 3	0.57 (0.06) a 3

<sup>a</sup> Numbers in table are mean values; <sup>b</sup> Values in parentheses are the standard deviations; <sup>c</sup> Values below means and standard deviations denote sample size; Different letters across rows denote a significant difference according to Tukey's HSD at the 95% confidence interval.

### 3.3. Physical Characteristics

#### 3.3.1. Moisture Content

After one year of storage, both the untarped control pile and the plastic-based tarp pile experienced a significant increase in moisture content ( $p < 0.01$ ) as compared to the original material. While the paper-based samples also underwent an increase in moisture content, this change was not significant, as shown in Table 1 and Figure 7. Tarping of piles ensures protection against rain and snow ingress to the pile, which should reduce the moisture content over the storage period. However, reduced air circulation and moisture evaporation brought about by an impermeable tarp actually traps moist warm air in the pile environment, increasing biological degradation and moisture content [23]. In general, it is a well established fact that moisture permeable tarps or sheets help to lower the pile moisture content. On the other hand, impermeable covers resulted in higher moisture content in the pile because surface evaporation of moisture is difficult and the majority of moisture is trapped under the covering.

The effectiveness of the paper tarp cannot be properly surmised from the trial because of its degradation and loss of function in a six-month period. This may have contributed to the high variability in moisture contents in this pile because some areas remained covered and other areas were completely exposed to the environment. The paper-based tarps were thoroughly degraded on the top-middle section of the pile where heat would have concentrated, however they were relatively intact after six months around the edges of the pile. This may have helped stave off excess moisture later in the storage period. The pile's configuration may have also opened up a vent for the moisture to leave. A study by Jirjis [24] cited a ventilation tunnel as the reason for a woodchip pile losing both substantial heat and moisture content while in storage. Potentially, using the paper-based cover with an exposed area at the top centre of the pile to permit moisture and heat transfer away from the biomass to the atmosphere may be worth exploring.

One of the primary quality aspects of biomass when used as feedstock to industrial boilers is the consistency of the moisture content. It can be seen in this trial that the original material has a much lower variability ( $sd = 2.35$ ) as compared to the material stored in piles for 1 year, as shown in Figure 7. It has been noted in previous works that moisture will migrate in a pile and produce areas of relatively drier and wetter biomass; in other words, there was found to be a significant interaction effect of storage time and location within a pile on biomass moisture [25]. Our finding suggests that prolonged storage of biomass, under any of the three storage regimes, reduces the quality of the biomass as a feedstock for industrial boilers because of the increase in variability of the moisture in the fuel.

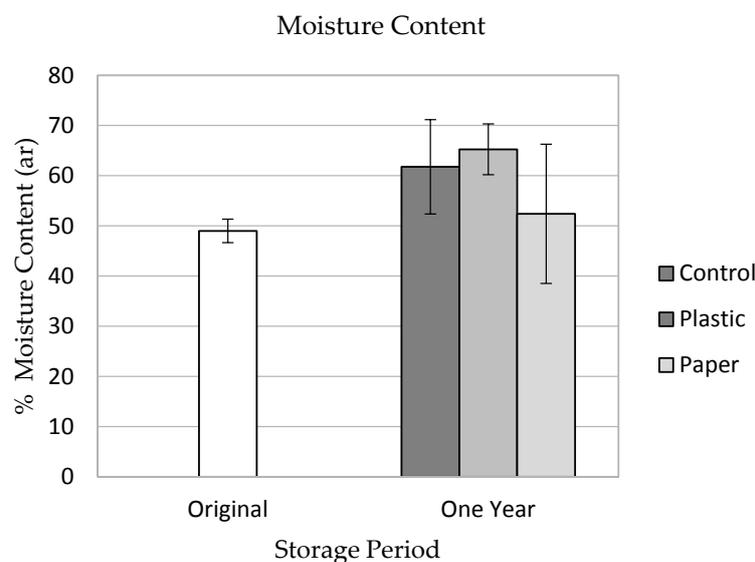
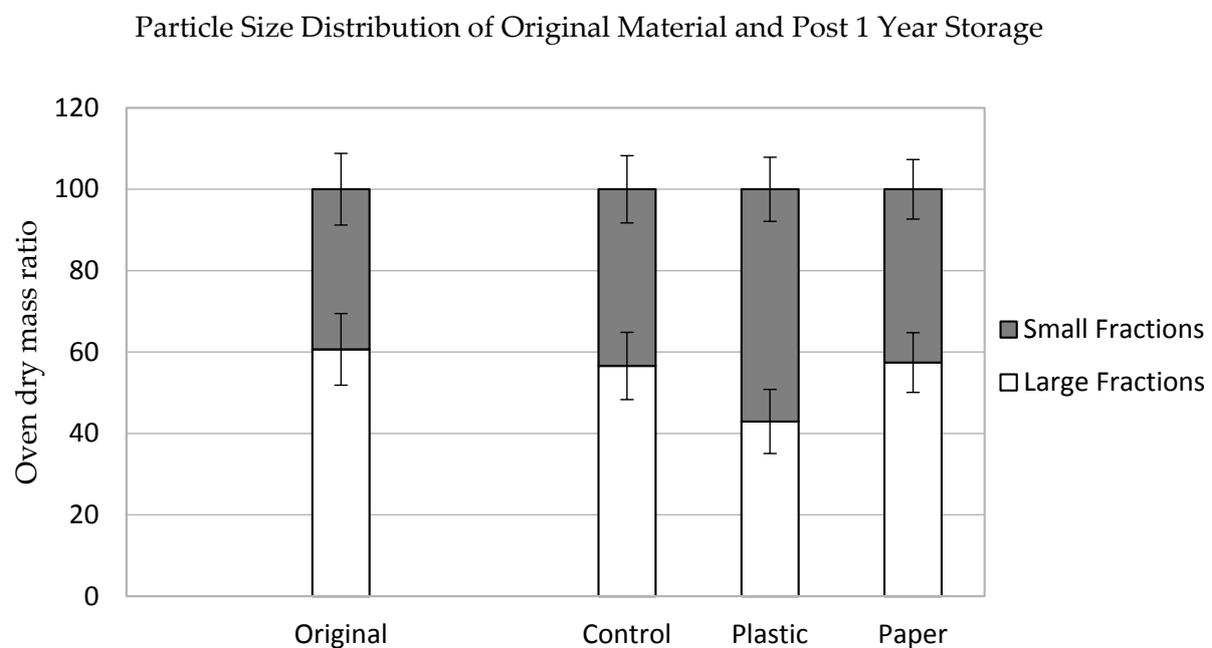


Figure 7. Change in moisture content of comminuted biomass after a storage period of one year.

### 3.3.2. Particle Size Distribution

The average particle size distribution of the biomass did not change after the 1-year storage, with the exception of the material in the plastic tarped pile, as shown in Figure 8. In this pile, there was a small reduction in the proportion of larger particles as compared to the small particles ( $p < 0.05$ ). At the end of the storage period, plastic-based samples had a significantly lower percentage of large fractions and significantly higher percentage of small fractions than the original material and the uncovered control samples ( $p < 0.05$ ) as well as the paper-based samples ( $p < 0.01$ ). These results provide evidence that the impermeable plastic-based tarp facilitated a greater degradation of the biomass material. These findings are supported by the higher bulk density of the material in the plastic-tarp pile. The bulk density of this material is significantly higher than material in either the control pile or the paper-tarped pile (Table 1). Higher bulk density suggests a reduced internal airflow which will result in higher internal temperature [25], increasing degradation (both microbial and chemical), increasing moisture generation and ultimately greater decomposition and material loss. Relating observations from our analysis, the plastic-tarped pile had higher moisture content, higher bulk density and the highest proportion of small particles as compared to the other storage regimes, thus suggesting that the plastic-based tarp is not ideal for maintaining the original biomass quality.



**Figure 8.** Change in particle size distribution (% o.d. mass ratio) of comminuted biomass after a storage period of one year.

### 3.4. Thermochemical Characteristics

#### 3.4.1. Heating Values

The higher heating value of biomass stored for 1 year under the various tarp regimes, were not significantly different to the original biomass material (Table 1). However, the net heating values of the 1-year old stored biomass were significantly lower than the original material. This can be explained by the higher moisture in all of the post storage samples as compared to the original material. Moisture is generated within the stored biomass from the biological breakdown of the lignocellulosic material. Aerobic and anaerobic metabolic processes generate carbon dioxide, water and energy on consumption of organic matter. Previous research has shown a link between increased moisture content in stored woodchip piles and decreased net heating value [25,26], which aligns with our findings.

From an energy density ( $\text{MJ}/\text{m}^3$ ) perspective, the original material is at least twice as high as any of the post storage materials, as shown in Table 1. The higher energy density of the fresh material signifies that one load of fresh material will be equivalent to at least two loads of any of the post storage materials. This finding suggests that the cost of transportation to the energy generating facility, per unit of energy of the post storage material, will be double that of the original material.

Proximate analysis shows that the post-storage material under the plastic-tarp was significantly different to the original biomass. It possessed a lower volatile content, a higher fixed carbon content and a much greater inorganic (ash) content. These changes support the hypothesis that the plastic tarp storage regime caused degradation of the material over the extended storage period. This is contrary to findings reported by Feist et al. 1971, that plastic covers could deter decomposition by limiting the availability of [27] oxygen to the aerobic micro-organisms. The plastic tarp piles bore the greatest temperature change, increasing a maximum of  $11\text{ }^\circ\text{C}$  compared to a  $4\text{ }^\circ\text{C}$  increase in the uncovered control piles. Internal pile temperature readings of the plastic tarped piles were in excess of  $60\text{ }^\circ\text{C}$ , with the highest at  $76\text{ }^\circ\text{C}$ . Ernston et al. [28] note that degradation happens in successive stages in which low molecular weight sugars and other easily degradable compounds are first metabolized followed by cellulose and finally lignin, if more specialized fungal species are present. The mould fungi typically found in forest residue chips may consume cellulose and hemicellulose whereas white-rot fungi, which consume lignin, are rare in forest residue chips [29]. The higher fixed carbon proportion in the proximate analysis of the stored woods is a good indicator of the selective loss of the carbohydrate versus lignin through microbial activity.

The ash content of all of the biomass tested in this study was higher than has generally been reported for other forest residue biomass. Acquah et al. [26] found ash contents of less than 5% for biomass collected from an industrial biomass harvesting site. The biomass in that study was comprised of a substantial amount of white wood from undersized and undesirable species in addition to tops/branches and bark. The material collected in this study is far “dirtier” in that it consists entirely of bark, branches and foliage. It is apparent from our results that the bark is contaminated with soil and grit from the skidding and handling operations, creating the unusually high ash content. Examination of ash content of forest harvest residues by other researchers has found that ash percentage increased over storage time due to degradation and loss of organic fraction [26].

The material in the plastic-tarped pile had a very high proportion of ash as compared to any of the other biomass materials. In fact, 18% is abnormally high and suggests that the samples were likely highly contaminated with inorganics such as soil and grit. The standard deviation for this sample is also relatively high, suggesting that the grit and soil were more predominate in certain parts of the pile than others. Our findings show that the plastic-tarp covered material is the only material that had significantly higher ash than the original material, indicating an apparent loss of organic matter. The fixed carbon content of the plastic-tarped material was higher as compared to the original material, suggesting that it may be a preferred feedstock for torrefied pellets, where pyrolyzed organic matter (char) is the desired outcome.

### 3.4.2. Ultimate Analysis

The carbon–hydrogen–oxygen content of the biomass materials is quite consistent across all samples. The plastic-tarp biomass is the only material that deviates significantly from the original biomass. The molecular formula (derived from the percent composition) for the original biomass is  $\text{C}_{4.2}\text{H}_{5.7}\text{O}_{2.7}$  or  $(\text{C}_{4.2}\text{H}_{0.3}(\text{H}_2\text{O})_{2.7})$ , while the molecular formula of the plastic-tarp is  $\text{C}_{4.1}\text{H}_{4.9}\text{O}_{2.9}$  or  $(\text{C}_{4.1}\text{O}_{0.45}(\text{H}_2\text{O})_{2.45})$ , clearly showing that the stored material has become more oxygenated and has a lower water of constitution. So, while the plastic tarped biomass has been degraded from its original composition, it may lend itself better to biorefining options such as pyrolysis or torrefaction. The lower water of constitution and higher fixed carbon content offer an interesting alternative to the original biomass for this application.

#### 4. Conclusions

The quality characteristics of “fresh” forest biomass are commonly accepted as the standard measure of biomass when biomass is being considered for industrial applications. This study illustrates that long-term storage of forest biomass can significantly alter its chemical, physical and thermal properties and lead to higher costs over the entire bioenergy supply chain. Although the loss of dry matter was not accounted for in this study, increased costs to deliver stored biomass can be a consequence of degradation, resulting in lower net energy density and ensuing higher transport costs and GHG emissions. In addition, the tarping operation added extra cost and GHG emissions to the supply chain through materials, labour and extra machinery time.

The results of this study did not support the efficiency of using covers to preserve the quality of comminuted biomass piles stored at the roadside. Biomass covered with plastic-based tarps experienced accelerated degradation and increased moisture content over uncovered control piles due to an apparent lack of ventilation. Biomass covered with paper-based tarps was not much better off than uncovered biomass after six months in storage, at which point the tarps had lost their protective properties. The paper-based tarp did not retain its structural integrity past six months. As this rapid degradation made a proper comparison between tarps impossible, it would be worthwhile to investigate the efficiency of this tarp over a shorter storage period or to conduct a similar study using a different type of ventilated cover that may better withstand harsh weather conditions.

This study underscores the importance of continuing to evaluate residues in order to help handling practices reduce decomposition and preserve quality. Although they did not prove effective tools for the purpose of this study, in the greater context of the supply chain, covers have great potential to promote desirable biomass qualities. For instance, if a supplier wishes to change pile characteristics before end-use, a cover could be employed as an incubator for pre-treatment. If the end-use requires a biochar or torrefied pellet, then higher degradation may be the favourable condition. In addition, accelerating degradation can result in a material that is more amenable to enzymatic treatment as it is already partially broken down. At present, the supply chain is largely uncontrolled; it is based on the availability of residues rather than the demand for their specific applications. This highlights the need to develop standards that will help optimize biomass supply based on specific user-demand to ultimately improve bioenergy applications in Canada.

**Acknowledgments:** This work would not have been possible without the significant contributions of Gifty Ewurama Acquah and Gireesh Gupta. The authors also gratefully acknowledge the ongoing support of Natural Resources Canada’s Program of Energy and Research Development (PERD) to this work.

**Author Contributions:** Suzanne Wetzel, Sally Krigstin and Sylvain Volpe conceived and designed the experiments; Sylvain Volpe and colleagues from FPInnovations contributed materials; Sally Krigstin and students from the University of Toronto as well as Sylvain Volpe and colleagues from FPInnovations performed the experiments; Sally Krigstin and Janet Damianopoulos ran the statistical software; Sally Krigstin wrote the paper.

**Conflicts of Interest:** The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results

#### References

1. Ontario Ministry of Natural Resources. Available online: <https://www.ontario.ca/document/forest-biofibre-allocation-and-use> (accessed on 28 September 2016).
2. Hall, J.P. Sustainable production of forest biomass for energy. *For. Chron.* **2002**, *78*, 391–396. [CrossRef]
3. Ministry of Forests, Lands and Natural Resource Operations, British Columbia. Available online: <https://www.for.gov.bc.ca/hfd/pubs/docs/tr/tr081.htm> (accessed on 29 September 2016).
4. Forest Products Association of Canada. Available online: <http://www.fpac.ca/forest-industry-innovation/construction/> (accessed on 22 November 2016).
5. Duchesne, L.C.; Wetzel, S. The bioeconomy and the forestry sector: Changing markets and new opportunities. *For. Chron.* **2003**, *79*, 860–864. [CrossRef]

6. Natural Resources Canada. Available online: <http://www.nrcan.gc.ca/forests/industry/products-applications/13359> (accessed on 28 September 2016).
7. Krigstin, S.; Wetzel, S. A review of mechanisms responsible for changes to stored woody biomass fuels. *Fuel* **2016**, *175*, 75–86. [CrossRef]
8. Afzal, M.T.; Bedane, A.H.; Sokhansanj, S.; Mahmood, W. Storage of comminuted and uncomminuted forest biomass and its effect on fuel quality. *BioResources* **2009**, *5*, 55–69.
9. Sebastian, A.; Madsen, A.M.; Martensson, L.; Pomorska, D.; Larsson, L. Assessment of microbial exposure risks from handling of biofuel wood chips and straw-effect of outdoor storage. *Ann. Agric. Environ. Med.* **2006**, *13*, 139–145. [PubMed]
10. Nurmi, J.; Hillebrand, K. The characteristics of whole-tree fuel stocks from silvicultural cleanings and thinnings. *Biomass Bioenergy* **2007**, *31*, 381–392. [CrossRef]
11. Roser, D.; Mola-Yudego, B.; Sikanen, L.; Prinz, R.; Gritten, D.; Emer, B.; Väätäinen, K.; Erkkilä, A. Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. *Biomass Bioenergy* **2011**, *35*, 4238–4247. [CrossRef]
12. Suadicani, K.; Heding, N. Wood preparation, storage, and drying. *Biomass Bioenergy* **1992**, *2*, 149–156. [CrossRef]
13. WeatherPro® Lumber Wrap & Protective Packaging. Available online: <http://www.interwrap.com/Protective-Packaging/WeatherPro.html> (accessed on 21 August 2017).
14. Walki, 2010. Walki® Biomass Cover. Available online: [http://www.walki.com/material/attachments/walki.com/brochures/53sD8gFOD/Walki-BiomassCover\\_gb.pdf](http://www.walki.com/material/attachments/walki.com/brochures/53sD8gFOD/Walki-BiomassCover_gb.pdf) (accessed on 21 August 2017).
15. American Society for Testing and Materials (ASTM). *Standard Test Method for Moisture Analysis of Particulate Wood Fuels*; ASTM E871–82; ASTM: West Conshohocken, PA, USA, 2006.
16. European Committee for Standardization (CEN). *Solid Biofuels, Methods for the Determination of Bulk Density*; CEN/TS 15103; CEN: Brussels, Belgium, 2005.
17. Parr Instrument Company. *Operating Instructions No. 205M for the Parr 1108 Adiabatic Oxygen Combustion Bomb Calorimeter*; Parr Instrument Company: Moline, IL, USA, 2008.
18. American Society for Testing and Materials (ASTM). *Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter*; ASTM D2015–77; ASTM: West Conshohocken, PA, USA, 1983.
19. American Society for Testing and Materials (ASTM). *Standard Test Method for Ash in Wood*; ASTM D1102–84; ASTM: West Conshohocken, PA, USA, 2007.
20. European Committee for Standardization (CEN). *Solid Biofuels, Method for the Determination of Ash Content*; CEN/TS 14775; CEN: Brussels, Belgium, 2004.
21. Buggelen, R. Outside storage of wood chips. *Biocycle* **1999**, *40*, 32–34.
22. Maechler, M.; Rousseeuw, P.; Struyf, A.; Hubert, M.; Hornik, K. Cluster Analysis Basics and Extensions. R package. R package version 1.14.4. 2013.
23. Nurmi, J.; Hillebrand, K. Storage alternative affect fuelwood properties of Norway spruce logging residue. *N. Z. For. Sci. J.* **2002**, *31*, 289–297.
24. Jirjis, R. Storage and drying of wood fuel. *Biomass Bioenergy* **1995**, *9*, 181–190. [CrossRef]
25. Casal, M.D.; Gil, M.V.; Pevida, C.; Rubiera, F.; Pis, J.J. Influence of storage time on the quality and combustion behaviour of pine woodchips. *Energy* **2010**, *35*, 3066–3071. [CrossRef]
26. Acquah, G.E.; Krigstin, S.G.; Wetzel, S.; Cooper, P.; Cormier, D. Heterogeneity of forest harvest residue from Eastern Ontario Biomass Harvests. *For. Prod. J.* **2016**, *66*, 164–175. [CrossRef]
27. Feist, W.C.; Springer, E.L.; Hajny, G.J. Encasing wood chip piles in plastic membranes to control chip deterioration. *Tappi J.* **1971**, *54*, 1140–1142.
28. Ernston, M.-L.; Jirjis, R.; Rasmuson, A. Experimental determination of the degradation rate for some forest residue fuel components at different temperatures and oxygen concentrations. *Scand. J. For. Res.* **1991**, *6*, 271–287. [CrossRef]
29. Jirjis, R. Enumeration and distribution of fungi in stored fuel chip piles. *Mater. Org.* **1989**, *24*, 27–38.

