# MEASURING MOISTURE CONTENT IN FOREST RESIDUES: A LITERATURE SYNTHESIS ON SAMPLING METHODS AND PROCEDURES

## Waste to Wisdom: Subtask 2.1.1

### Feedstock Development

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**Measuring moisture content in forest residues: A literature synthesis on sampling methods and procedures**

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***Abstract***

Taking moisture content samples from forest residue stack piles has been a challenge due to numerous factors such as varying shapes of piles, difference in material types, financial constraint of the research, etc. Additionally, there has been no standard sampling procedure set for the task encompassing the various constraints, especially in-woods conditions. For these reasons, samples taken from forest residue piles may not accurately represent the average moisture content of the population. This study attempts to classify the sampling methods commonly used for measuring moisture contents of forest residue piles for scientific research. We reviewed over 28 studies focusing on moisture content in forest residues to develop four general sampling methods, namely weighing stack piles, weight from scale ticket, fixed location sampling, and transect sampling. Advantages and limitations for each sampling method along with the type of data generated from each were described in detail. For example, weighing stack piles provided the most accurate form of continuous data, but could not be used for in-wood conditions and was usually limited to small pile structures. On the other hand, fixed location sampling, and transect sampling would be preferred in field experiments and could detect MC variation within layers of the pile. Attempts were also made to determine the situations in which each of these sampling methods could be adopted. The general procedures and models of a moisture content measurement for oven-drying wood samples were also discussed. This study could assist researchers set up their experimental designs and provide insight for handling potential challenges during data collection.

**Keywords**: bioenergy, data collection, renewable energy, slash piles, woody biomass.

## 1. Background

With recent trends to incorporate more renewable options into energy portfolios, forest residues generated from timber harvesting operations have been gaining increasing significance as a valuable feedstock source for bioenergy production. Around 11 million acres of timberland are harvested annually in the United States generating approximately 162 million dry ton of forest residues, which accounts to about 2.01 $x10^{15}$ btu of renewable energy (US Department of Energy 2016; EIA 2016). Woody biomass in the form of forest residues for energy production comes primarily from sources such as timber harvests, forest restorations, and fuel reduction thinning treatments.

Forest residues can be classified based on the forms of storage, material types and arrangement patterns. It is common for forest residues destined for bioenergy production to be temporarily stacked either in open or under roofed conditions. While left open, the storage could be either in-woods or in the yards of power plants. Stack piles are often covered with paper or plastic to protect from rain or snow. Forest residues can also be left at the harvest site, unstacked over long periods for drying, referred to as scattered (Nurmi 1999; Filbakk et al. 2011).

The next form of classification is based on the types of forest residue material. Whole trees of small-diameter and non-merchantable species are common forest residue generated during timber harvest and thinning treatments. Stem wood and tree tops are the next category of material types, which are typical to timber harvest operations (Nurmi 1999; Suadicani & Gamborg 1999; Golser et al. 2005; Filbakk et al. 2011; Erber et al. 2014). These two categories of materials can be chipped (instead of grinded) to produce feedstock with homogenous particle size distribution (Bisson & Han 2016). The last material type, namely slash, includes chunks (off-shoots), broken logs, roots, branches, and foliage, can be potentially bundled for feeding to grinders. However, slash materials are usually left at the harvesting sites for nutrient recycle considerations or burned on site for disposal.

Forest residues can also be classified based on shapes or arrangement patterns of the stack piles (Figure 1). This form of classification originated from fire ecology studies to predict the potential energy content and burning intensity of the pile. This technique may be used to estimate weight or volume of the piles for fire analysis purpose (Hardy 1996; Wright et al. 2010). Stack pile structures are constructed by different machines with specific intention. Some structures are built for production of energy or value added bio-based products such as briquettes and biochar, while others are meant for slash disposal as it would not be financially or technically viable to utilize them. Forest residues intended for high quality feedstock are processed and sorted into different material types to facilitate chipping process (Kizha & Han 2016).

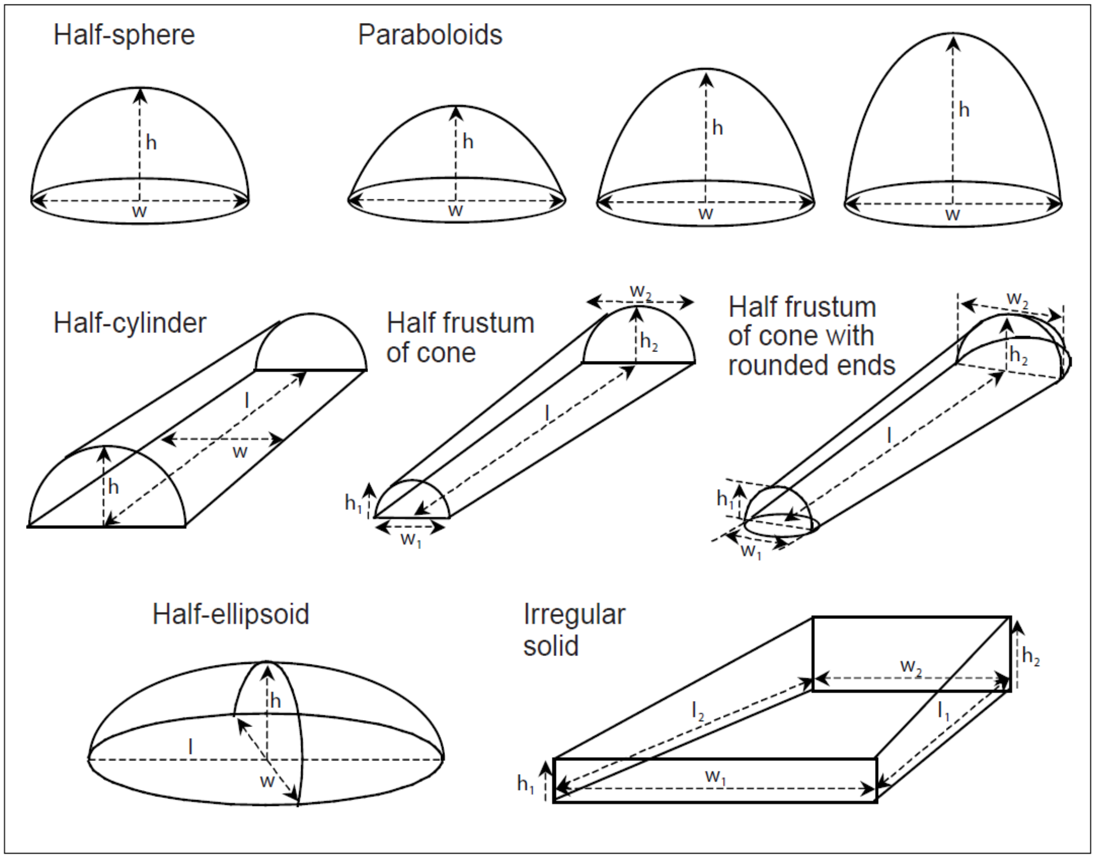


Figure 1. Classification of forest residue piles based on the geometric shape (Source: Hardy 1996).

Cost of piling and compactness of materials within are also dependent on the pile structure, which varies widely across different regions. The arrangement patterns of forest residues that are common to the western United States are:

1. Teepees: These piles are created by loader and compose all forest residues generated during timber harvest operations, such as tree-tops, chunks, branches, broken logs, small diameter, and non-merchantable whole-trees. The shape is usually asymmetrical with some resemblance to a cone. Even though the size of these piles vary, they tend to accumulate more materials per unit area and are less costly to construct compared to other pile structures. Teepees are generally intended for burning, but could be utilized for grinding if appropriate markets are available.
2. Windrowed: Processor-made piles located on the roadsides next to the log landing. They are common to steep grounds (cable yarded unit), where landing space is a major constraint. Similar to teepees, they comprise of all types of materials mixed within the same the pile and can be burned for slash disposal or grinded for utilization.

3. Stack / Processor piled: Uniformly arranged piles created by the processors with butt ends facing the same direction. These piles are usually intended for utilization, as they predominantly consist of tree-tops and stem wood materials that could be comminuted (processed) using a chipper (Spinelli & Hartsough 2001).
4. Criss-cross: Arrangement of tree tops, broken logs and stem wood piled to a 90-degree from each other to promote airflow between materials and thereby potentially increasing the rate of drying. This arrangement is not commonly practiced in timber harvesting operations and is currently restricted to research experiments (Golser et al. 2005; Elber 2007; Kizha. et al. 2015).
5. Scattered: Forest residues left in harvest unit (at stump) unstacked. Drying is promoted as a result of increased surface area being exposed to the surroundings. These materials are not brought to landing during skidding or yarding; thereby requires machine re-entry for collecting the materials later (Kizha. et al. 2015).

## 2. Controlling moisture content of forest residues for energy production

From an economic point of view, multiple factors affect the utilization of forest residues for energy production, among which high moisture content (MC) is regarded as one of the major issues (Jirjis 1995). The MC in feedstock affects everything from energy content to efficiency of transportation and conversion process. Dry feedstock increases heating value and improves boiler efficiency. Higher MC leads to lower heating value as a portion of the combustion energy is used to evaporate moisture (Röser et al. 2011; Roise et al. 2013). Energy efficiency of feedstocks increases by 1% for each 1% drop in MC above 50% and 0.5% for each 1% reduction in MC below 40% (Liang et al. 1996; Kim & Murphy 2013).

MC also plays a significant role in determining transportation costs and subsequent market price of the delivered commodity. It has been proven that feedstock with lower MC has higher market value, therefore, letting feedstock dry up to one year is a profitable investment for suppliers as long as purchasers pay based on MC of the feedstock (Casal et al. 2010; Roise et al. 2013; Erber et al. 2014). Additionally, current state-of-the-art biomass conversion technologies like torrefaction, palletization, and briquetting, have very narrow MC specification range for their feedstock (Uslu et al. 2008). On a broader perspective, proper management of MC can lead to economic gains (Gigler et al. 2000).

Accurate measurement of MC also plays a critical role for many other applications within the forest products industry. For example, in chemical pulping, dosing of digestion chemicals can be more precisely determined if MC of feedstock is known. In mechanical pulping, MC critically influences the feedstock processing properties related to fiber quality (Järvinen 2013). All of these suggest that an accurate MC measurement using efficient sampling methods is pivotal to the forest products and wood bioenergy industries.

There have been several studies related to the MC in forest residues. While results and implications of these studies are well documented, often times the sampling method (SM) is not described in explicit detail. Furthermore, most of these studies have employed different types of SM which shows a lack of standardized methods, making it difficult for other researchers to adopt them. One major reason is due to the varying nature of the residues itself, such as, species composition, material types, size and shape of piles. Adopting the appropriate SM often governs the applicability of any results furnished. On the other hand, difference in the SM and measurement techniques can yield a range of results with varying degrees of accuracies (Ochoa 2012). Researchers have also been developing unique SMs to measure MC primarily based on their objective and other factors, such as type of data required, financial budget of the study, structural arrangement and shape of piles, etc. One of the major reasons for these differences is due to the lack of a concrete procedural standard to sample MC in varying stack pile, especially in-woods.

## 3. Study scope

This study attempts to examine and document some commonly adopted MC measurement techniques and SMs to monitor MC for various forest residues in different pile structures in the research world. Sampling method (SM) is defined as the scientific procedure of selecting samples which would provide the required estimates with associated margins of uncertainty, arising from examining only a portion of the whole population (Fairfax County 2012). For this study, we reviewed over 28 research articles and found four major sampling methods, namely weighing stack piles, weight from scale ticket, fixed location sampling, and transect sampling, that were most commonly used for MC measurement (Table 1). Attempts were made to identify the purpose behind using each SM and to classify the conditions in which they could be adopted. Some of these SMs were either interchangeable or could be used in combination; this article closely examined the limitations and advantages of each method in different scenarios. Sampling methods for comminuted forest residues such as hog fuels and wood chips were not the focus for this study; however, common issues related to them were briefly discussed.

Table 1: A summary of different sampling methods adopted for determining moisture content in the past studies

| Study | Geographical location | Objective | Sampling method | Material type | Pile type/ dimension |
|---|---|---|---|---|---|
| Gigler et al. 2000 | Netherlands | Investigate the mechanism of natural wind drying and develop a drying model | Weighing stack piles | stems | Stack piles; 7m × 7m × 3.6m |

| | | | | | |
|---|---|---|---|---|---|
| Pettersson & Nordfjell 2007 | Sweden | Examining fuel quality of compacted small diameter trees and both Stacked and scattered logging residues | Comminution (chipping) | logging residues | baled, windrowed, scattered |
| Casal et al. 2010 | Spain | Develop a methodology for forest residues to be used as fuel in a co-combustion plant | Chipped followed by fixed location sampling | Wood chips | pyramidal configuration; 3m x 10.5m |
| Flibakk et al, 2011 | Norway | Models moisture content changes related to species, climate, tree size, harvesting time and storage time | Fixed location sampling followed by chipping | tree tops | stack piles 2.5m × 10m |
| Brand et al. 2011 | Brazil | Evaluate the influence of species, harvest season, storage season and storage span in the physical and chemical properties of the wood biomass | Fixed location sampling followed by chipping | logs (length 2.5m) | stack piles 6m x 2.5m x 2.5m |
| Röser et al. 2011 | Finland, Scotland, and Italy | Investigate the natural drying in different regions | Weighing stack piles and fixed sample location | smalldiameter trees | covered pile; ~ $5m^3$ |
| Gautam et al. 2012 | Canada | Determine a storage regime to enhance the fuel quality | Transect sampling | logging residues | teepees and windrow |
| Kim & Murphy 2013 | USA | Forecasting air-drying rates of stacked logs | Weighing stack piles | small logs | stack piles (2261kg) |
| Erber et al. 2014 | Austria, Finland and Sweden | Develop prototypes for estimating the optimal storage time and sorting of fuel wood | Weighing stack piles and chipping | fuel wood | stack piles (2.5m × 2.5m × 2.7m) |
| Kizha & Han 2015 | USA | Estimating amount of logging residues | Scale ticket | small-diameter trees and logging residues | teepees and scattered |
| Kizha. et al. 2015 | USA | Estimating moisture content changes in different arrangement patterns | Transect sampling | small-diameter trees and logging residues | teepees, stack piles, scattered, and criss-cross |

## 4. Determining moisture content in piled forest residues

There are two approaches adopted to measure MC in forest residues in the scientific world: 1) Indirect measurement, and 2) Direct measurement. The indirect approach is defined by two interpretations. First, indirect measurements have been defined as the measurement techniques that do not involve the removal of water present in the wood sample during MC quantification (Owens & Soderlund 2006). Taking this definition into account, all techniques, other than oven drying, could be potentially classified as indirect measurement. According to the second interpretation (which was used to interpret indirect measurements in this article), indirect measurements are based on models built using results from direct measurements and weather parameters such as equilibrium moisture content, temperature, humidity, and precipitation, to predict the drying rates (Ochoa 2012; Roise et al. 2013). Here, MC readings need to be recorded initially.

In direct approach, MC data is collected directly from the population (i.e. forest residue piles). While implementing direct measurement, it is critical to ensure that samples truly represent the target population. Every material type within a pile must have an equal probability of being sampled. In reality, this is not often feasible for non-comminuted forest residue piles due to the restricted accessibility to the interior of the pile. Therefore researchers have developed several techniques to obtain samples that are representative of the population. It has been proven that both indirect and direct measurement approaches complement each other (Fauchon et al. 2000). However, for this study we focused on the different direct sampling methods commonly used.

#### 4.1.1. Weighing stack piles

Weighing stack piles is a SM employed to obtain MC of the entire pile over a period of time. With this SM, fluctuations in total weight of piles can be captured over time, without samples being drawn from the pile every time (Gigler et al. 2000; Röser et al. 2011; Erber et al. 2014). Samples are initially drawn from various parts of the pile to estimate MC, and are later used to relate difference in total weight to the whole pile. This SM offers the best opportunity to acquire data on a continuous scale. It can be used to compare variation in MC between various attributes such as material types, species composition, etc., if stacked in respective piles (Gigler et al. 2000). This SM has been used to sample both comminuted and non-comminuted forest residues and is highly recommended for its accuracy (Erber et al. 2014).

Forest residues are erected on frames (pallets or metal), which hold the piles together and facilitate weighing process (Figure 2). It is important to erect the frames free from distortive stresses to ensure precision during load measurement. Additionally, metal frames are preferred over wooden frames, as the latter can be affected comparatively more by air temperature and humidity (Erber et al. 2014). This SM can be carried out by multiple approaches based on the availability of equipment. The stack piles can be weighed using external lifting mechanism (like fork-lift/ front end loaders) or supported by load sensors attached to the frame (Röser et al. 2011). While using load sensors, the ground pressure is to be evenly distributed by putting metal plates or square edged logs as a platform (Figure 2).

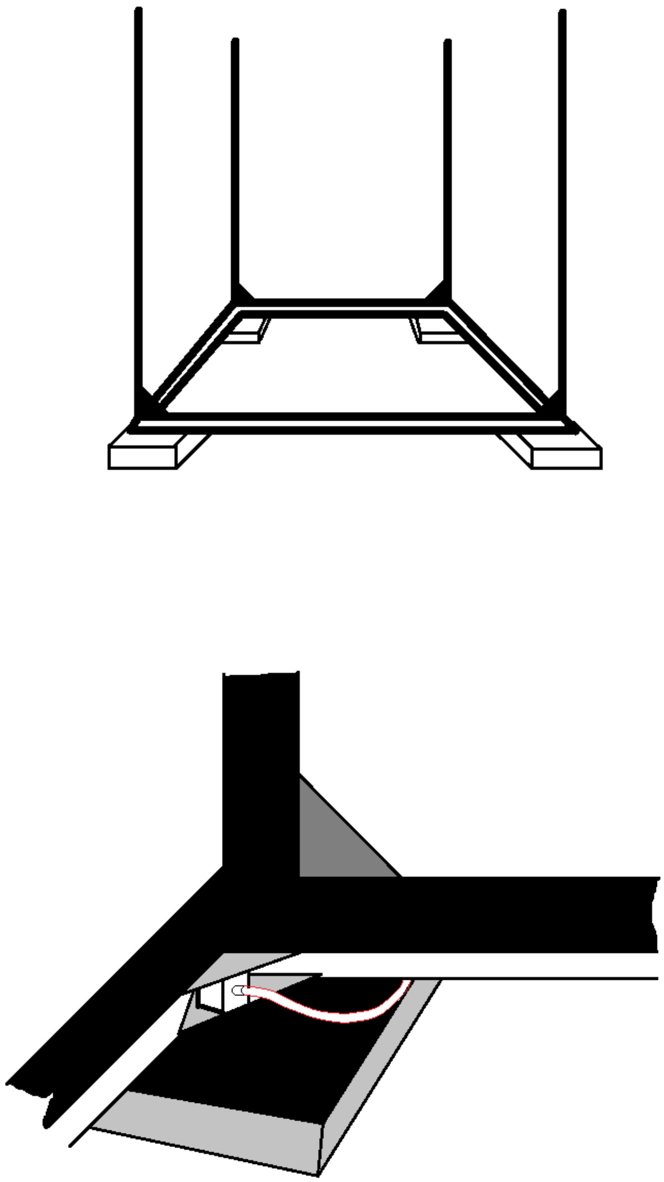

Figure 2. Metal frame (above) and load cells (below) used for weighing piles (Source: Erber et al. 2014).

Utilizing external lifting mechanism to weigh the residue piles provides data in longer fixed time intervals compared to the load sensor data logger which generate data on a more continuous level depending on the time interval set. Other limitations while using fork-lifts are the possibility of disrupting pile structure during the weighing process, and weight being limited to measurable load of the scale. Therefore, this SM is usually restricted to small stack piles up to 20 metric tons (Erber et al. 2014). In field-based experiments, using external lifting mechanisms leads to multiple-entry equipment costs. Hence, this method is often restricted to controlled experiments. Additionally, weighing stack pile SM cannot be used for determining variation within and across the pile.

### 4.1.2. Weight from scale ticket

Scale ticket is a different version of weight sampling where MC of forest residues is provided via scale tickets at the end-use facility. This SM is widely used in forest operations research (Kizha. et al. 2014). In most cases, measurement are obtained by weighing loaded trucks on a weighbridge followed by taking random samples. MC estimation using radio frequency waves have also been adopted at certain power plants (Nyström 2006). The main reasons for measuring MC at the facilities are to determine price and fuel combustion efficiency. MC provided by scale tickets are generally very accurate because suppliers are often paid based on these values. However, as various industries have adopted different standards for drawing samples, and measurement methods, the procedure adopted by each facility have to be carefully comprehended and to properly interpret the results. In some cases, the values from scale tickets are further modified by accounting specific gravity of the species delivered (Kizha & Han 2015).

### 4.1.3. Fixed location sampling

Storage of forest residues in piles results in uneven moisture loss throughout the pile structure. During winter, the best drying conditions occur inside the pile where there is less exposure to the elements (rain and snow) and no direct contact with the ground. In summer, this effect is reversed due to lack of air flow within the pile (Filbakk et al. 2011). Sampling at fixed locations provides an opportunity to evaluate variations in MC across the various strata or layers of the pile (Casal et al. 2010; Filbakk et al. 2011; Brand et al. 2011). This SM, regarded as a stratified random sampling technique, identifies sampling locations prior to sample collection. For example, sampling points are designated as top, middle and bottom of the stack pile (Figure 3) (Filbakk et al. 2011; Brand et al. 2011; Gautam et al. 2012). Samples are taken from a particular point or fixed location using either moisture meters from freshly cut wood or by extracting wood discs using chainsaws. The spots are usually marked/ flagged on the pile to help identify sampling locations during re-entry. Another approach to this SM is to comminute the selected sample materials prior to MC analysis (Brand et al. 2011).

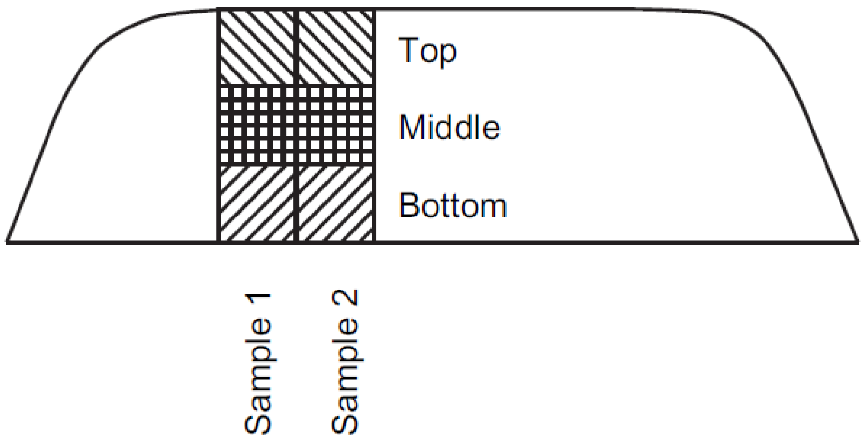


Figure 3. Schematic diagram of drawing samples for fixed point sampling method (Source: Filbakk et al. 2011).

The piles selected for fixed location sampling should preferably have uniform geometric shapes to facilitate extrapolation of data to intended layers. The samples are usually collected from designated parts of the pile throughout study. This method is suited for taking measurements from covered stack piles, along with large piles (which cannot be weighed). Forest residue piles are generally arranged with butt ends aligned together, as it is the easiest way to pile and handle (Gigler et al. 2000). In this case, special access to an interior sampling point should be considered during the construction of the pile. Thermocouples or other weather data loggers can be set inside the pile to monitor internal micro-weather conditions. This data are often compared with external weather conditions and MC of the interior is estimated using regression models (indirect measurement).

Fixed location sampling is often employed to estimate variation in MC within piles that differ in height, length, and azimuth. This method is best suited for in-woods measurements which lack access to weighing mechanisms. This SM can also deal with heterogeneous forest residue variables (such as species, diameter, residue type, etc.). Fixed location sampling allows for frequent readings without multiple machine entry costs that are incurred when weighing stack piles using external lifting mechanism. This SM provides less accurate data compared to weighing stack piles or scale tickets, due to the low probability of equally sampling every materials in the population. Even though frequent data can be collected, these data are not as continuous compared to weighing stack piles with sensors, in other words, “snap-shots” of the drying behavior are the results from this SM (Erber et al. 2014).

#### 4.1.4. Transect sampling

Similar to fixed location sampling, transect sampling is also employed to account for MC measurement within the pile. However, here no fixed sampling points are plotted prior to sampling; instead transects are drawn across the piles. Transects are created by markings or laying ribbons in a specific orientation at required intervals /depths. Materials that fall on the transect are then systematically selected based on the required number of samples for each class (e.g. diameter class, tree species, etc.) (Filbakk et al. 2011). Selected sample materials are cut with chainsaws at the point of the intersection with the transect, to expose the complete diameter for MC estimation (Gautam et al. 2012). Appropriate actions are taken to prevent edge effects. The remaining un-sampled materials are left undisturbed for future sampling. The sampled wood materials (branches) are discarded after the diameter is exposed. This approach is most suitable for teepee, windrowed piles or scattered trees (Figure 4), where the shape and size of the material vary considerably. In such conditions, fixed location sampling would not provide a true representation of the stack pile.


Figure 4. Wood disc being extracted for moisture content measurement from teepees piles using transect sampling method. New transects are marked every time prior to the data collection with flags or ribbon.

Advantage of this SM is in its ability to capture variation across different depths and lengths and increases the probability of all materials being sampled compare to fixed location. Similar to fixed location sampling, transect sampling method can also be utilized for comparing various piles structure and arrangement patterns. Some of the advantages transect sampling has over fixed location sampling are: 1) can capture piles with irregular shapes and structure; 2) the possibility of including different materials into the sampling population is comparatively higher as transects are not predetermined; 3) interior entry to the piles is relatively easier by adjusting alignment of the transects, allowing to capture variation in MC within pile in more detail; and 4) more applicable in regions with limited woody biomass market where all forest residues generated are usually piled as teepees. However, this method is more labor intensive and demands a high attention to safety when compared to fixed location sampling during sample collections from interiors of pile (Figure 4).

#### 4.1.5. Sampling methods for comminuted forest residues (wood chips/hog fuel)

Evaluating MC in comminuted forest residues such as wood chips and hog fuel necessitates adoption of one of the previously described SM. When comminuted materials are measured with weighing stack piles, it can provide continuous and accurate estimates of the average MC, but cannot be used to show the variation in MC within the pile. Fixed location SM can be used to determine the variation between different strata of the comminuted pile. In such cases, probes have to be used for sampling the interiors. Here, the geometric shape of pile has to be adjusted to allow access. Sample collection from the interior of piles has also been done by making vertical cuts at the sides of pile (Casal et al. 2010). A drawback to this approach is that subsequent sampling results could be impacted due to exposure of sampling point to atmosphere. MC through Scale tickets are also used commonly when the processed forest residues are sent to end use facilities.

### 4.2. Factors affecting selection of sampling methods

Each SM has their own unique advantages and shortcomings; and are designed for specific situations. Some of the factors effecting the selection of SM are:

1. Utilization of data derived: Objective of the study and nature of data required is a crucial factor that dictates the choice of SM. For example, SM will vary based on whether the study objective focuses on MC variation within the pile or variation between the piles. Again, data collection techniques employed for one-time data would be different from that for a continuous scale. Experimental design (e.g. simple random, stratified random or purposive sampling) would also effect the choice of the SM.
2. Field study or controlled experiment: In-woods studies often have limited access to equipment compared to controlled experiments which are usually near research facilities and have more equipment accessible.

3. Financial budgets and time needed: Cost of initial experimental set-up and measurement varies with each SM. SMs like weighing stack piles using sensors would incur higher cost for initial set up followed by lesser price to collect data periodically. On contrast, the initial set up cost is often not expensive for transect sampling and fixed location sampling methods, however these come with a high cost for sample collection (due to the involvement of professional sawyers). Other SMs like weighing using forklifts may require multiple machine entry cost, for in-wood data monitoring.
4. Equipment and drying site availability: Availability of equipment such as forklift trucks, weight data loggers, frame works for placing the forest residues, moisture meter, professional sawyers, etc., also plays a major role in the selection of the SM.
5. Material type: SM employed for evaluating MC of comminuted forest residues (woodchips and hog fuel) will be different from that of non-comminuted forms such as tops, chunks, branches, small-diameter trees, etc.
6. Material size: Pieces greater than 15 cm in diameter have to be dealt differently from those with small diameter materials (<15 cm). The 15 cm diameter range was adopted considering the general market conditions for pulpwood in western US.  Twigs less than 5cm can be collected in plastic bags, weighed, and later sent to lab for drying to get the moisture content. However for larger size material, chain saws are used for both extracting wood discs and ensuring fresh-cut for accurate moisture meter readings.
7. Shape and structure of forest residue piles: An important factor to be considered is the structure of piles along with its shape. Shapes of forest residues piles have been generalized by forest fire ecologists for estimating the volume (Hardy 1996). Recently, LiDAR technology are utilized to accurately model the shape of the pile to predict the quantity of forest residues (Long & Boston 2013). In comminuted forest residues, piles usually have a pyramidal structure or similar.
8. Compactness of material: It can be challenging to acquire samples from the middle of the pile when the materials are tightly packed. As a solution, special access are created to sampling points while constructing the pile (Casal et al. 2010).

## 5. Techniques for moisture content measurement

After acquiring samples, the next step is the actual estimation of MC:

### 5.1. Oven drying

Oven drying is regarded as the most common method. Here, samples are taken in the form of disc (cookies) or sawdust by cutting with a chainsaw. Wood discs are generally preferred, as sawdust samples can become contaminated with chainsaw lubricants and lose higher percentage of water due to heat generated during sawing (Erber et al. 2014). Wood discs are cut from branches of the required samples with a thickness ranging from 2–3 cm. Once a branch is selected, the sample should be cut at least 0.5 m away from the end of branch because wood gains and loses moisture very rapidly through the end grain; a phenomenon referred to as edge effect (Reeb & Milota 1999). MC within the branch varies along the length, with lower MC towards the ends. Freshly cut disc are weighed in field or immediately placed in sealed plastic bags to be weighed later in a laboratory setting (Röser et al. 2011). Samples are then oven dried for one to four days (ASTM standard D 2016) depending on the procedure adopted (Kim & Murphy 2013; Kizha. et al. 2015). Dried weight of the disc is later measured and MC is calculated in green basis for woody biomass [Equation 1].

$$Mositure\ content\ \%\ (Green\ basis) = \left(\frac{Weight\ of\ water}{Weight\ of\ water + dry\ weight\ of\ wood}\right) * 100 \qquad [1]$$

Where, weight of water is the difference between fresh weight and oven dry weight of the wood sample.

Even though, oven drying techniques provide very accurate MC measurement, there are certain inherent limitations, such as being a destructive sampling method, and requiring a minimum timeframe of 24 hours (depending on the standards used) to attain results. Additionally, oven drying can drive volatile compounds out of the wood (ASTM D4442). Here the wood weighs lesser than only water being removed, resulting in an overestimation of MC.

## 5.2.Moisture meters

Moisture meters predominantly come in the form of dielectric and resistance meters. They are considered a quick, reliable, and non-destructive way to assess moisture content and are widely used in both research and commercial practices. Measurements are taken along the rays and cross section of the branch. While collecting samples, similar to disc collection (for oven drying techniques), fresh cuts are made from the middle of the stem rather than measuring from the exposed outer portion, to avoid the edge effect. Studies have shown that it is important to evaluate reliability of the readings obtained from the moisture meter by comparing readings to MC estimated from oven dry measurements (Garrahan & Lavoie 2005; Gautam et al. 2012). Prior to data collection, a paired t-test analysis is done to understand the variation between the two measurement techniques. The equality test would involve collecting a number of samples from various species and diameter classes used in the study. The difference in the value should also be gauged.

At present, different types of moisture content measuring instruments are available. Ochoa (2012) tested six different tools and utilized three different measurement technologies (acoustic, conductance, and capacitance) on different species in various forms such as sawlogs and comminuted forest residues.

Results showed even the best model/tool combination was only explaining about 80% of the variability in measurements. Other types of measurement techniques such as electro-magnetic rays including ultra-violet, near infrared, resonance acoustic velocity and dynamic modulus of elasticity have also been used to monitor MC with varying degrees of accuracy (Carter et al. 2006; Jensen et al. 2006; Chan et al. 2011). Currently, these methods are still under development and are mostly restricted to laboratories.

**6. Accessory data: weather parameters**

Changes in MC are directly associated with weather and climatic conditions under which forest residues are placed. The ambient temperature (ºC), relative air humidity (%), wind speed ($km \cdot h^{-1}$), wind direction (degree), insolation ($W \cdot m^{-2}$) and precipitation (mm) are usually measrured (Filbakk, Høibø, et al. 2011; Kim & Murphy 2013). The data can also be taken from nearby meteorological stations (Casal et al. 2010). Thermocouples or atmospheric data loggers have also been placed in the stack pile at strategic positions to monitor internal weather condition. These procedures have been adopted for fixed location sampling, and transect sampling. However, due to smaller size of stack pile used in the weighing stack pile method, internal weather monitoring would not provide any substantial data.

**7. Comparison of the sampling method techniques**

Each SM comes with its own advantage and limitations; therefore, meant for achieving the targeted objectives. Apart from monitoring MC, these SM have been also be used for sampling materials for collecting data on other attributes, including energy content, ash content, etc. The scale ticket method is accurate and comparatively inexpensive, yet only provides one-time data. Weighing the stack pile can provide greater accuracy and is useful in estimating the variation of a pile's MC over a given time period. The sampling frequency can range from monthly to seasonal sampling (Casal et al. 2010; Brand et al. 2011). However, the weighing method is not appropriate to estimate the variation in MC within the pile and involves greater costs associated with equipment requirements (Table 2). Weighing stack pile would provide best results for the following situations:

- Developing drying models based on weather condition
- MC variation in piles differing in material types, species, etc.
- Evaluate drying patterns over time

Table 2. Advantages and limitations of sampling methods that are commonly used for sampling moisture content in forest residues for energy production. The factors for each sampling methods were ranked based on comparison.

| | Weighing stack pile | Transect sampling | Weight from scale tickets |
|---|---|---|---|

| Factors | Sensors on platform | External lifting mechanism | Fixed location sampling | | |
|---|---|---|---|---|---|
| 1. Periodic interval of data collection | continuous | snap shots | snap shots | snap shots | one time data |
| 2. Multiple entry cost | least | high | minimal | minimal | not applicable |
| 3. Accuracy in data | highest | high | limited | limited | high |
| 4. In-woods data collection | possible | limited | preferred | preferred | not applicable |
| 5. MC variation within forest residue pile | not suited | not suited | preferred | most preferred | no |
| 6. Comminuted forest residues | preferred | limited (chances in disrupting pile shape) | preferred | not applicable | preferred |
| 7. Cost of periodic sampling | less | high | medium | medium | minimum |
| 8. Initial cost of experimental set up | high | high | Low | low | low |
| 9. Controlled experiments | preferred | preferred | not suited due to high variation | not suited due to high variation | no |

[1]Refering to the continuity of data. Snap shots represents one-time measurement during the data collection period.
[2]Cost associated with bring in the machines or equipment required for data collection
[4]Data collected from piles built during forest harvesting operation
[6]Processed (grinded or chipped) forest residues
[9]Studies exclusively designed for estimating moisture content and not typically the piles built during forest operation activities

For evaluating the variation of MC across the depth of a wood stack pile and across various diameter classes, the transect method and fixed point sampling method are very effective. In cases, where it becomes physically not feasible to extract samples from the interiors of the pile (especially while estimating the variation between layers of the pile), regression models are developed to predict MC variation within the pile. Here, selected wood pieces from the pile are initially pulled out and several samples are taken along the length of the piece. These measurements are used to model the MC variation within the pile. Additionally, once a sample is taken from a branch, the remainder of that material is generally excluded from the study unless the sampling population is small.

## 8. Conclusion

Selection of the appropriate SM is pivotal for addressing the objectives for any research. The scope of this article was to comprehend the different sampling method adopted for measuring the MC in forest residue feedstock. As MC in forest residue after felling is dependent on several factors including, weather, post-harvest handling and storage conditions, it is important to consider the advantage and limitation of the different SMs (Kim & Murphy 2013). This article reviewed four SMs to sample MC from a forest residue pile.

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