FORECASTING AND MONITORING MOISTURE CONTENT OF WOODY BIOMASS IN IRELAND AND OREGON TO IMPROVE SUPPLY CHAIN ECONOMICS

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ABSTRACT

Wood is approximately 50 percent water by weight. Reducing the amount of water, through drying, reduces transportation costs (more wood and less water can be delivered per load) and increases combustion efficiency (less energy is required during combustion to evaporate water).

Researchers in Ireland and Oregon are collaborating on storage and drying research on a number of fronts:

(1) they have completed, air-drying trials for three softwood and two hardwood species at seven locations. The trials will allow the development of climate based drying models for forecasting drying rates for different species, for different seasons of the year in different locations within their regions.

(2) a number of moisture monitoring tools, using a variety of technologies, are being evaluated for their efficiency and effectiveness in measuring moisture in a range of materials such as roundwood, chips, hogfuel, and bundled biomass in twelve species. Some of the same tools are being evaluated in both Oregon and Ireland.

(3) an economic model, that spans the supply chain from standing tree through to delivery to the customer and includes the effects of moisture management on costs and revenues, has been developed.

An overview of the research and preliminary results are included in this paper.

INTRODUCTION

Biomass dependency has been increasing gradually and is currently over 4 percent of U.S. total energy consumption (Energy Information Administration 2010). Half of this biomass energy consumption comes from wood sources; wood residue, wood waste, and woody plants.

High production and transportation costs, relative to market values, can be economic barriers to the widespread utilization of woody biomass for energy production. Moisture management, through storage and drying in the supply chain between harvesting and utilization, is key to improving both transportation costs and market values (Jirjis 1995).

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Wood is approximately 50 percent water by weight. Reducing the amount of water, through drying, reduces transportation costs (more wood and less water can be delivered per load) and increases combustion efficiency (less energy is required during combustion to evaporate water). Moisture can be actively reduced through input of energy at an off-forest facility, or it can be passively reduced through air-drying on- or off-forest. Air-drying is generally the more common and lower cost alternative.

Managing woody biomass moisture requires tools for forecasting and monitoring drying rates and determining, in economic terms, when is the best time to cease drying and deliver the biomass to the customer (Fauchon et al. 2004). Quick, accurate and simple methods of determining moisture content along the supply chain will facilitate trade by reducing risk.

Researchers in Ireland and Oregon are collaborating on storage and drying research on a number of fronts. An overview of the research being undertaken and preliminary results on climate based drying models, moisture monitoring tools, recommended sampling protocols, and economic analyses of woody biomass supply chains is presented below.

**METHODS**

**Supply Chain Economic Models**

Supply and utilization of biomass as an energy source must be economically competitive for both buyers and sellers if its contribution to meeting energy needs is to be viable in the long term. Evaluating economic competitiveness can be complex. Harvesting biomass crops, collecting biomass residues, and storing and transporting biomass resources are critical elements in the biomass resource supply chain.

In 2010 the Irish Council on Forestry Research and Development group (COFORD) commissioned two of the authors of this paper (Kofman and Murphy) to develop two tools to help small wood energy businesses evaluate supply chain economics: a Fuel Cost Comparison Tool, which as the name suggests allows comparison of the costs of fuel alternatives by fuel users, and a Wood Fuel Value Calculator, which allows wood energy sellers to compare the net value alternative wood supply systems.

Both models were developed as stand alone programs in Visual Basic. User’s manuals were also prepared. Training in use of the models has been provided to wood energy providers in Ireland and Europe.

Use of the models affirmed the importance of having good measures of the moisture content of the energy material to be supplied.

**Drying Trials**

Six air-drying trials were established at six sites; two of the sites were in Ireland and four in Oregon. Three softwood species (Sitka Spruce, Lodgepole pine and Douglas-fir) and two hardwood species (Eucalyptus nitens and hybrid poplar) were included in the trials.
Daily or hourly climate data was collected at each site. Moisture content related data was collected on a regular basis.

The first Irish trial was begun in April 2007 and was ended over 450 days later. Bins of small diameter Sitka Spruce logs (approx. 25 tons), resting on load cells were monitored hourly for changes in weight that were assumed to be related to changes in moisture content. Samples of the logs were taken at the beginning of the trial to establish initial moisture content. The trial included five treatments that related to wood size (two classes) and cover (three classes). Some bins were followed for the full 450 days, others were terminated early then reloaded with new logs to assess the effects of changes in the season in which trees were felled and drying began. The data from the first trial was used to develop climate related air-drying models.

The second Irish trial was begun in March 2011 and was continued for 12 months. Bins of small diameter Sitka Spruce, Lodgepole pine and Eucalyptus nitens logs (approx. 25 tons) were monitored for changes in weight. The trial included two treatments; covered and uncovered logs. The trial was used to determine differences in drying rates between species and to confirm the impact of cover on drying rates.

Two Douglas-fir drying trials were begun in northern (wet site) and southern (dry site) Oregon in December 2010. The trial continued for 12 months. Drying trials were initiated four times at each study site. At each trial, three bundles were built (about 3 m long and with an average log diameter of about 156 mm) and each bundle was air dried under different canopy conditions: open, intermediate, and closed. A total of 24 Douglas-fir biomass bundles were built over the study period and the average initial weight of the bundles was about 2,261 kg. Bundles were weighed using crane scales on regular intervals (approx. 10 days). The data from these trials was used to develop climate related air-drying models for Douglas-fir.

Two hybrid poplar drying trials were begun in western (wet) and eastern (dry) Oregon in April 2011. The trial continued for 9 months. At each trial, two different types of bundles were built: denoted as small and large. The small hybrid poplar bundles consisted of logs with average diameter of 82 mm. The average initial weight of the small bundles was about 3,444 kg. The large hybrid poplar bundles consisted of logs with an average diameter of about 150 mm. Their average initial weight was about 5,413 kg. A total of 8 hybrid poplar bundles were built over the study period; 4 small poplar bundles and 4 large poplar bundles. Bundles were weighed using crane or truck scales on regular intervals (approx. 10 days). The data from these trials was used to develop climate related air-drying models for hybrid poplar.

Evaluation of Monitoring Tools
Evaluations were undertaken in Ireland and Oregon of three classes of tools for monitoring moisture content in woody material; capacitance, conductance (or resistance) and acoustic tools. A total of nine species (five softwood and four hardwood) and four material types (small logs, chips, hogfuel and slash bundles) were included in the trials. Not all tools were evaluated in all species or material types.
Capacitance tools evaluated in Ireland were Wile Bio Meter, Humimeter BM1, Humimeter BLL, and GE Balemaster. All four capacitance tools were evaluated in chips but only the Wile Bio Meter and Balemaster were evaluated in slash bundles. Conductance tools evaluated in Ireland were the Humimeter BLW and the GE Timbermaster. Conductance tools were used for measuring the moisture content of small logs. No acoustic tools were evaluated in Ireland. Tools were evaluated in Sitka Spruce, Lodgepole pine and Eucalyptus nitens.

Capacitance tools evaluated in Oregon were Wile Bio Meter and Humimeter BM1. Both capacitance tools were evaluated in. Conductance tools evaluated in Oregon were the Humimeter BLW and the GE Timbermaster. Acoustic tools were the Fiber-Gen HM200 and the IML Hammer. Both conductance tools and acoustic tools were used for measuring the moisture content of small logs. Tools were evaluated in Douglas-fir, Western hemlock, Ponderosa pine, hybrid poplar, Garryana oak, and madrone. Samples were repeatedly measured from freshly felled material to dry material over a four month period at regular intervals – four day intervals for chips and hogfue and 10 day intervals for small logs.

Tools were evaluated in terms of accuracy, precision, mechanical reliability and efficiency (total time required to obtain a mean measurement within a stated accuracy range).

RESULTS AND DISCUSSION

Supply Chain Economic Models
The Wood Fuel Value Calculator that was developed requires data related to purchase type (standing tree, roundwood or chips); wood data (basic density, volume conversion factors, ash content); moisture content at various points in the supply chain; harvesting costs, chipping costs and storage information; transport (hourly costs, trucking distances, load volumes, unloading method); and price, profit and interest. Conversion between different units of measurement at various points in the supply chain can be easily accommodated.

Figure 1 provides an example of a completed form. In this example, hardwood trees with a basic density of 490 kg per m$^3$ were purchased standing in the forest for €10.50 per m$^3$, then felled, extracted to roadside and chipped in the forest for a total of €23 per m$^3$. Chipped material had a moisture content of 50% (wet basis). Chipped material was then transported in 90 m$^3$ (loose volume) vans to a customer 80 km away from the forest. The customer was prepared to pay €6.45 per GJ for the delivered material. A net value of -€3.23 per ton of delivered material would be incurred. The supplier would either to reduce his profit goal substantially (from 9.00% to 2.75%) or look at other approaches, such as drying the material in the forest.
If the felled and extracted timber had been left at roadside in the forest to dry for five months, reaching a moisture content of 30% before it was chipped, net value would have gone from negative to positive (€0.38 per ton) despite the system incurring additional chipping costs (allowing for additional wear on chipping knives) and storage costs. The supplier would also achieve his 9% profit goal.

**Drying Trials**
The first drying trial in Ireland allowed the development of an air-drying model based on climatic conditions (precipitation and reference evapotranspiration) and treatment (material type and cover type). Figure 2 shows that the forecast number of days to dry depends on where drying takes place in Ireland when drying begins in summer. If drying is delayed three months, to the beginning of autumn, drying could be expected to take an additional 66 to 101 days depending on drying location.
Figure 2. Predicted number of days for Sitka spruce energywood to dry from 55% to 30% moisture content at various locations within Ireland when initial drying began at the beginning of summer. Differences are due to precipitation and evapotranspiration.

The second drying trial confirmed that uncovered material dried at slower rates (-8 to -33%) than covered material. It also showed that there were differences between species; covered lodgepole pine dried slightly faster than Sitka spruce (+8%) and considerably faster than Eucalyptus nitens (+87%).

The data collected on Douglas-fir and hybrid poplar moisture contents in Oregon allowed the development of drying curves (e.g. Figure 3.) and climate based air-drying models. Oregon can be divided into nine climate zones. Similar to the work completed in Ireland, the models allowed extension of the results to other climate zones than those in which the data was gathered.

Figure 3. Drying curves for Douglas-fir smallwood log bundles in northern and southern Oregon.

Considerable differences were noted in drying rates between:
- climate zones (not unexpectedly, in dryer zones wood dries faster than in wetter zones)
- season in which drying began (spring or summer are better seasons to begin drying than fall or winter)
• material size (smaller poplar logs dry faster than larger poplar logs), and
• species (poplar logs dry faster than Douglas-fir logs of the same size).

As an indication of the variability in forecast drying rates, there was a range of 507 days between the lowest and highest number of days required to dry woody material down to 30% moisture content.

Evaluation of Monitoring Tools

Virtually all of the tools evaluated required some form of calibration to improve the accuracy of moisture content measurements. The Humimeter BLW used on Sitka Spruce roundwood in Ireland was the exception. This same tool, however, required calibration for all of the species evaluated in Oregon. Calibration models between actual and measured moisture content (or acoustic velocity in the case of the acoustic tools) generally explained less than 80% of the variability in measurements.

In both Ireland and Oregon, the Humimeter BLW tool proved to be the better of the two conductance tools evaluated for roundwood moisture content measurement from accuracy and precision perspectives. However, when an attempt was made in Oregon to validate the calibration model with a data set gathered four months later the Humimeter BLW gave unacceptable correlations between calibration adjusted measurements and actual moisture content measurements ($R^2 = 0.09$). On the other hand, this tool did give acceptable moisture content measurements in Ireland, particularly at lower moisture content levels (Figure 4).

![Figure 4. Actual versus measured moisture content using the Humimeter BLW on Sitka spruce roundwood logs in Ireland.](image)

The Fiber-Gen HM200 proved to be the best of the two acoustic tools evaluated for measuring moisture content of roundwood logs ($R^2 = 0.82$ for the calibration model and 0.78 for the validation model when tested with Douglas-fir). The calibration model indicated that a number of species (western hemlock, Douglas-fir, ponderosa pine, and
Neither of the capacitance tools performed well when measuring moisture content of slash bundles in Ireland. Both tools required calibration, but the best calibration model still accounted for less than 36% of the variability in measurements. The Wile Bio Meter performed slightly better than the GE Balemaster in slash bundles.

Tests in Ireland of the four capacitance tools for measuring lodgepole pine wood chip moisture contents showed that all of the tools required calibration and different tools performed better within given moisture content ranges than others (Figure 5). At moisture contents above 40% all tools would significantly underestimate moisture content without calibration. Accuracy of the tools was slightly better at moisture contents below 40%. Variability in measurements was greatest for the Wile Bio Meter and GE Timbermaster tools and least for the Humimeter BM and Humimeter BLL tools over all moisture contents.

![Figure 5. Performance of four capacitance tools for measuring moisture contents in lodgepole pine wood chips.](image)

Tests in Oregon of the two capacitance tools for measuring wood chip moisture contents showed that both tools required calibration. Neither tool performed well at moisture contents below 30%. Above 30% the Wile Bio Meter performed slightly better ($R^2 = 0.82$) than the Humimeter BM1 ($R^2 = 0.79$). The calibration model for the Wile Bio Meter indicated that a number of species (western hemlock, Douglas-fir, and madrone) had similar calibration coefficients, while other species (ponderosa pine, oak and poplar) required individual species calibration coefficients. Similarly, the calibration model for the Humimeter BM1 indicated that a number of species (western hemlock, madrone, oak and poplar) had similar calibration coefficients, while other species (ponderosa pine and Douglas-fir) required individual species calibration coefficients.

The two capacitance tools tested in wood chips in Oregon were also tested in hogfuel (chipped limbs and tops). Results were similar to those for wood chips, except that...
performance tended to be worse for both tools ($R^2$ between 0.62 and 0.76) and species groupings for calibration purposes were slightly different.

There are some similarities and differences between these results and those obtained by Jensen et al. (2006). Jensen et al. (2006) evaluated one NIR reflectance, five capacitance, zero acoustic, and zero conductance moisture meters to test their capability of measuring moisture content on solid biofuels. Results obtained showed that the most promising calibrations were acquired with an NIR reflector (Mesa MM710, $R^2 = 0.84$-0.99) and two of the capacitance moisture meters (Pandis FMG 3000, $R^2 = 0.89$-0.99 and Schaller FS 2002-H, $R^2 = 0.86$-0.96). The Wile Bio Meter did not rate in the top three meters evaluated by Jensen et al. (2006). In our study the Wile Bio Meter capacitance tool ($R^2 = 0.92$) and the Fiber-Gen Hm200 acoustic tool ($R^2 = 0.78$) were the most effective tools. The calibration equations developed by Jensen et al. (2006) indicate that both laboratory and fuel type affect measured moisture content. Differences between our results and their results could be due to the effect of the operator (i.e., level of experience with a given tool), number of samples used, methods used, data analysis methods, and the species and fuel types evaluated.

Of the eight tools evaluated, three exhibited mechanical reliability problems within the test periods; problems occurred with the Humimeter BM after about 100 readings, with the Humimeter BLW after about 400 readings, and with the Humimeter BLL after about 1000 readings. No mechanical reliability problems were found with the other tools evaluated.

The best two in each tool category was determined on the basis of tool efficiency (Figure 6). Tool efficiency was determined from the time per sample measurement multiplied by the sample size needed to be within 3% of the true mean value. Variance in the sample size calculations was based on the combined data from all six species measured. The Wile Bio Meter was the most efficient capacitance tool in chips or hogfuel. The Humimeter BLW was the most efficient conductance tool in roundwood logs. The Fiber-Gen HM200 was the most efficient acoustic tool in roundwood logs. Follow on tests indicated that sample size could be reduced and tool efficiency improved when working with a single species.

![Figure 6. Tool efficiency (time required to obtain mean sample measurements within +/- 3% of the true mean moisture content.)](image-url)
PRELIMINARY CONCLUSIONS

Software tools have been developed which allow quantification of the economic effects of moisture content in forest to buyer supply chains. These show the importance of managing moisture and can be used to evaluate different moisture management approaches.

Drying trials and the climate based air-drying models that have been developed based on these, allow forecasting of time to dry in various locations around Ireland and Oregon. They also allow determination of the effects of different harvesting seasons, different storage methods (covered or uncovered), and different species on drying time.

Although there are a range of different tools and technologies available for in-situ measurement of moisture content most tools require calibration for species and material type. Even then, these tools are not particularly precise. For some tools mechanical reliability has been identified as an issue. Considerable range in measurement efficiency was identified between tools. Further work is required on tool selection and development of sampling protocols is needed.

LITERATURE CITED


Fauchon T., Deleuze C., and Chantre G. 2006. How to control the variation of the wood moisture content of logs from the stand to the woodyard? The contribution of both direct techniques of assessment and modeling. AFOCEL. Laboratorie Bois Process (Wood Processing Lab). France.
