Modeling Air Drying of Sitka Spruce (*Picea sitchensis*) Biomass in Off-Forest Storage Yards in Ireland

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Abstract

Moisture management, through storage and drying in the supply chain between harvesting and use, is key to improving both transportation costs and market values of woody biomass. Storage can take place at sites within the forest or in off-forest storage yards. A model for predicting the moisture content of Sitka spruce roundwood and energy wood under an open, off-forest, environment was developed for Ireland. Experimental data for the model were gathered over a 16-month period beginning in April 2007. The major factors affecting biomass moisture content change are cumulative precipitation and evapotranspiration (ET_0), biomass type, and type of cover. ET_0 was computed using the FAO Penman-Monteith method, which requires temperature, solar radiation, wind, and relative humidity data. The model was easily used in a spreadsheet to estimate drying times for different locations in Ireland, different starting seasons for drying, different biomass types, and different types of cover. The model should not be used for estimating drying times for in-forest biomass storage because it will overestimate drying rates considerably.

With rising fossil fuel costs and enhanced environmental concerns, the use of renewable energy has been widely expounded as a solution to the challenges of global energy security and climate change. Ireland currently imports 90 percent of its energy needs and is very vulnerable to supply disruptions as well as price changes. To relieve Ireland's dependence on the import of energy, increase its energy security, and decrease the emission of carbon dioxide, the Irish government has established sustainable energy goals that will see a significant increase in the use of renewable energy by 2020. Biomass, along with wind and hydropower, has been identified as a renewable energy source with significant promise for reducing dependence on imported energy (Dennehy et al. 2010). Woody biomass, in particular, has the potential to play a major role in Ireland's national bioenergy strategy.

About 10 percent of Ireland is covered by forests. Sitka spruce (*Picea sitchensis* (Bong) Carr.), by area and by harvest volume, is currently Ireland's most important timber species, accounting for slightly less than 60 percent of the forested area but more than 80 percent of the harvest volume. Phillips (2011) has estimated that the potential availability of wood fiber for energy in Ireland is currently over 1 million cubic meters per y. Most of this, in the near future, could be expected to come from Sitka spruce stands. Small-diameter logs, as well as forest residue material, are considered to be a potential source of wood fiber for energy.

High collection and transportation costs, relative to market values, can be economic barriers to the widespread use of woody biomass for energy production, however (Rummer 2008). Moisture management, through storage and drying in the supply chain between harvesting and use, is key to improving both transportation costs and market values (Jirjis 1995). Wood is approximately 50 percent water by weight (Klass 1998). Reducing the amount of water, through air 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).

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A number of studies have compared storage and drying of various types of woody biomass at various locations (Jirjis 1995, Kent 2008). Results indicate that storage of uncomminuted logging residues showed many advantages compared with chip storage; risks of self-ignition were eliminated, and dry matter losses were minimized (Jirjis 1995). Storage of uncomminuted residues within a forest environment was less conducive to rapid drying than storage in exposed sites outside of a forest environment (Kent 2008).

The optimal storage method, location, and drying time are economic decisions, however. The benefits obtained from such factors as increased combustion efficiency and price and reduced transportation costs must be weighed against increased handling costs (e.g., harvesting machines having to return to the forest after drying to chip logs, or intermediate transport to an off-forest storage yard) and opportunity costs (i.e., capital is tied up in drying material).

Being able to predict the number of days required to reach a specified moisture content is one of the essential prerequisites for selecting the optimal drying method and time. Yet there are many factors that can affect drying rate. A sevenfold change in the rate of moisture content loss at the beginning (3.5% per week) versus at the end (0.5% per week) of a 14-week period has been shown for air drying of sugar maple logs (*Acer saccharum* Marsh.) in Canada (Rojas et al. 2007) and indicates a nonlinear trend. Drying rate has also been shown to depend on species (Stokes et al. 1987, Brand et al. 2011, Nord-Larsen et al. 2011), bark loss (Defo and Brunette 2006), presence of a protective cover (Jirjis 1995, Nord-Larsen et al. 2011), and season in which drying began (Stokes et al. 1987, Brand et al. 2011, Nord-Larsen et al. 2011). Stokes et al. (1987) produced more than 40 drying rate models for groups of softwood and hardwood species and for individual species in the southeastern United States. Many of their models were nonlinear and depended on number of days since drying began, on rainfall, and on temperatures. Simpson and Wang (2003) produced two models for air drying of small ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) logs in the western United States. Their logs were debarked and covered with sheets of plywood to protect them from rainfall. Their models were based on log diameter, starting moisture content, relative humidity, and average temperature. Liang et al. (1996) developed a drying rate model for bundled Leucaena trees (*Leucaena leucocephala* (Lam.) de Wit) in Hawaii. Precipitation and reference evapotranspiration (ET_0) were the two predictive variables in their model. ET_0 was chosen because it was used internationally as a measure of moisture loss from crop lands and it rolls a number of climate variables into one parameter. Because their model was climate based, they were able to extend their model spatially to other parts of Hawaii and temporally to different seasons of the year.

Timing of drying initiation may affect the starting moisture content for wood as well as the drying rate. However, the literature is not clear on this. For example, studies in trembling aspen (*Populus tremuloides* Michx.) have shown a 9 percent difference in starting moisture content between summer and winter seasons (Jensen and Davis 1953)—summer being lower—while studies in eastern spruce (*Picea* spp.) and balsam fir (*Abies balsamea* (L.) Mill.) have shown no discernible difference between seasons (Shottafer and Brackley 1982). Clark and Gibbs (1957) comment that seasonal differences in moisture content of freshly felled trees in Canada are likely to be more evident for hardwoods than softwoods. A recent study of five species in Ireland, including Sitka spruce, showed a trend for moisture content of freshly felled trees to peak in the summer months of May to August, fall in September and October, remain low over winter, and rise again in the spring (Kent et al. 2009).

Long-term drying studies, extending over 1 to 2 years, have been carried out in Sitka spruce small log material in Ireland (Kent 2008) and Scotland (Webster 2006). The author of the Scottish trial noted that the sites for his trial were in very high rainfall areas and may not be applicable to other areas of Scotland. For both sets of trials, storage and drying began in a single season (summer). Data were not collected for either set of trials that would allow construction of a climate-based drying model that could be used to extend the results of the research spatially and temporally.

The review of the literature revealed, among other things, that air-drying rates for woody biomass depended on the species, season in which drying began, and the storage system. It showed that air-drying models, based on climatic factors, could be constructed, and that these models would allow prediction of drying rates at locations other than where the data for the models were collected. Finally, it revealed that an air-drying model for Sitka spruce woody biomass was not available for use in Ireland.

The objectives of this study were fourfold: (1) to assess optimum storage systems, which might be used to promote maximum seasoning at lowest costs, for a range of Sitka spruce woody biomass materials; (2) to investigate moisture content and climate relationships with the view to developing a moisture content reduction model based on simple climatic indicators; (3) to compare the Sitka spruce model with another readily available model; and (4) to demonstrate how the Sitka spruce climate-based model might be used to predict moisture content changes for different locations and timing of harvest in Ireland.

Methods

Objectives 1 and 2

A storage trial was constructed at Derrygreenagh, near Rochfortbridge (~100 km to the west of Dublin; 53.4°N, 7.3°W) on an open, exposed site to assess the drying potential of logs moved from the forest environment to a depot (Kofman and Kent 2009b). Eight large steel cradles were constructed and placed on load cells connected to a data-logger, which recorded weights at hourly intervals. The cradles were free-draining and were scaled to each hold at least one full truckload of roundwood, or approximately 30 m^3 solid volume. The load cells and data management system were supplied by Eilersen Electric Digital Systems A/S, Denmark. Approximately 25 tonnes of logs were placed in each cradle to assess the loss of weight over time. The assumption was made that any loss of weight would represent a loss of moisture.

Two types of Sitka spruce material were used in the trial: cleanly delimbed roundwood with an approximate top diameter of 70 mm and smaller, and crudely delimbed energy wood with no minimum top diameter. The length of the roundwood material was 3 m, and the length of the energy-wood material was random lengths up to 4.5 m. All wood was put into the storage trial within weeks of being harvested. Some of the cradles were covered with agricultural plastic to keep out the rain. Most cradles had their cover replaced once during the storage period to ensure continuity of cover because the original cover degraded. Wood stored in the cradles was raised 50 cm above ground level, with no contact between wood and soil. Three types of cover were used: none (on roundwood only), top only, and top and sides. The combination of material type and cover provided five treatments. Only one of the treatments, roundwood with cover, was replicated.

Cradles were filled at different times of the year during 2007 with freshly felled material to assess the variation in drying seasonally. Cradles 1 to 7 were filled in the week of April 27, 2007. Cradle 8 was filled on June 15, 2007. Cradle 1 was emptied on August 31, 2007, and then refilled with fresh material on September 5, 2007. Cradle 2 was emptied on December 12, 2007, and then refilled with fresh material on December 14, 2007. The refilled Cradles 1 and 2 are hereafter referred to as Cradles 9 and 10, respectively. Cradles 3 to 10 were emptied in the week of August 11, 2008.

Moisture content (green weight basis) and other material parameters were sampled at the beginning of the trial. Twenty random sample logs were measured to establish the degree of delimbing, bark loss, diameter (top, middle, and butt), length, and weight. Each log was then chipped, the chips were mixed carefully, and three replicate moisture content samples were taken, weighed, oven dried, and then reweighed to establish the starting moisture content. The ending moisture content was established in a similar manner from 20 random samples of woodchips gathered periodically because the logs contained in each cradle were completely chipped at the trial end. Each 50-liter sample was subdivided into three moisture content samples that were assessed using the ovendry method.

Moisture content change over the storage trial was calculated from the recorded weight data and the end dry matter weight derived from the end weight and end moisture content, as follows:

$$M_{\mathrm{de}} = W_e \times (100 - M_e)/100 \quad (1)$$

$$M_n = [(W_n - M_{\mathrm{de}})/W_n] \times 100 \quad (2)$$

where

M_{de} = dry matter at trial end (kg),
M_e = moisture content at trial end (%, total weight),
M_n = moisture content at n time (%, total weight),
W_e = total log weight, at trial end (kg), and
W_n = total log weight, at n time (kg).

Although calculated moisture content data were available for hourly intervals from when the cradles were loaded, only a subset of these data was used in this study because first, useful climate data were only available on a daily basis and, second, biomass supply managers would be unlikely to need moisture content predictions at hourly, or even daily, time frames. Moisture content at the end of each 10-day period was, therefore, used. We created a minimum of 13 and a maximum of 48 records per cradle. We used a total of 370 records.

Daily climate information was obtained primarily from a portable Watchdog 2700 weather station (Spectrum Technologies Inc., USA) placed at the storage site. In addition, an Irish Meteorological Service climatological station at Derrygreenagh, less than 500 m from the trial site, provided some data. Data included rainfall (millimeters), mean wind speed (meters per second), relative humidity (percent), minimum and maximum temperature (degrees Celsius), and sunshine hours. Daily wind speed, humidity, temperatures, and sunshine hours were used to calculate ET_0 (millimeters) in Microsoft Excel, based on the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith method (FAO 1998). Daily rainfall and ET_0 data were summed to provide 10-day rainfall and 10-day ET_0 data for the same periods that moisture content records were created.

Moisture content, rainfall, ET_0, cradle number, and treatment data were entered in the SAS 9.2 statistical package (SAS Institute Inc., Cary, North Carolina). Because the data consisted of repeated measures of moisture content on the same cradles, it was deemed necessary to fit a mixed effect model to the data. This was done using the Proc Mixed procedure within SAS with a range of covariance structures. Model selection was based on the overall Akaike information criterion and on the significance of individual variables. Moisture content at the end of a 10-day period was predicted as a function of moisture content at the beginning of the period, rainfall, ET_0, and treatment. Days to dry from a starting moisture content to a specified ending moisture content could then be predicted by stepping from one 10-day period to the next and finally interpolating between the last and second-last predictions once the specified moisture content had been exceeded.

Objective 3

Woody biomass with a maximum moisture content of 30 percent is preferred for use in small commercial boilers. Drying times to reach 30 percent predicted by the Sitka spruce model were compared with times from another climate-based drying model used for predictions of small conifer wood (Simpson and Wang 2003). The latter model, which was developed in the western United States for predicting drying times for debarked Douglas-fir logs, used relative humidity and temperature as its climate variables. Rainfall was not included in the model. The logs stacks were stored outside but had a sheet of plywood on top of the stack. Logs within the stacks were separated by wooden stickers.

Objective 4

The Sitka spruce model was also used to predict drying times, based on historical climate data, for storage initiated in four seasons (summer, autumn, winter, and spring) at four additional locations around Ireland: Knock, Ballyhaise, Oakpark, and Valentia (Fig. 1). These sites were selected because they represent a range of climatic conditions in Ireland. Historical data were obtained from the Irish Meteorological Service. Table 1 shows the rainfall and ET_0 for these sites for a similar period to that of the drying storage trial at Derrygreenagh.

Two sets of drying times were predicted for these sites: one set where the assumed starting moisture content was the same for all seasons (57.5%) and one set where the starting moisture

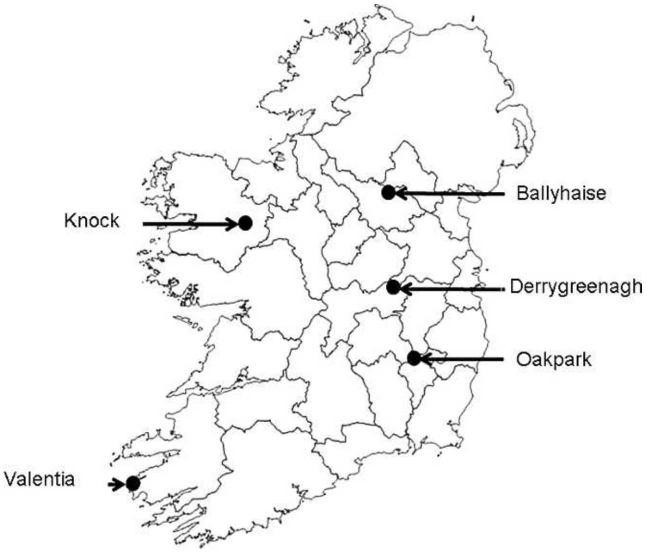

Figure 1.—The drying storage trial site (Derrygreenagh) and prediction sites were located near Irish Meteorological Service climate stations.

content varied with season (summer, 61%; autumn and spring, 58%; and winter, 55%). The first set was representative of the average starting moisture contents from all cradles for the storage trial. The second set was representative of results reported by Kent et al. (2009), who noted a trend in seasonal moisture content of felled Sitka spruce.

Results and Discussion

Objectives 1 and 2

Table 2 provides an overview of the treatments and the woody biomass characteristics at the beginning and end of the trial. At the start of the trial, each cradle contained a minimum of 345 and a maximum of 832 logs. Initial green weights per cradle ranged from 20 to 28 tonnes. Starting moisture contents ranged from 51.6 to 61.2 percent and averaged 57.5 percent. Ending moisture contents ranged from 18.4 to 24.4 percent and averaged 21.1 percent. These ending moisture contents were not the lowest (16.8%) achieved during the trial, however, because cradles would absorb moisture during periods of high rainfall as well as lose moisture during periods of high ET_0. This can be seen in Figure 2, which shows drying curves for one of the treatments (roundwood with top cover) initiated at four different times of the year.

The number of weeks required to dry Sitka spruce woody biomass below 30 percent ranged from 14 to 26 weeks for an off-forest storage yard. The season that storage began had some effect on this duration; shorter durations tended to be associated with spring and summer seasons, and longer durations tended to be associated with autumn and winter seasons. However, the longest drying time was associated with a cradle where drying was initiated in summer.

It should be noted that these drying rates are much faster than were found by Kofman and Kent (2009a) for Sitka spruce woody biomass stored in forest environments in Ireland; similar procedures for assessing starting and ending moisture contents were used in both studies. Even after more than 450 days of drying in the forest, no material had dried below 30 percent moisture content, and few wood stacks had dried below 45 percent. Material in this off-forest storage trial dried to 45 percent moisture content in 9 to 10 weeks, whereas it took 80 weeks for similar material to reach this moisture content in Kent and Kofman's in-forest storage trial.

Table 1.—Total rainfall and reference evapotranspiration (ET_0) at five sites around Ireland for the period June 6, 2007 to May 30, 2008.

Site	Rainfall (mm)	ET_0 (mm)[a]
Derrygreenagh	1,248	542
Knock	1,352	624
Ballyhaise	967	700
Oakpark	779	657
Valentia	1,455	755

[a] Based on the Food and Agriculture Organization (FAO) Penman-Monteith method (1998).

A mixed model, with a heterogeneous compound symmetry covariance structure, was found to fit the data best:

$$
\begin{aligned}
MC_{10} = {} & B_0 + B_1 \times mc_0 + B_2 \times mc_0^2 + B_3 \times Rain_{10day} \\
& + B_4 \times ET_{10day} + B_5 \times i_2 + B_6 \times i_3 + B_7 \times i_4 \\
& + B_8 \times i_5 + B_9 \times i_2 \times mc_0 + B_{10} \times i_3 \times mc_0 \\
& + B_{11} \times i_4 \times mc_0 + B_{12} \times i_5 \times mc_0 \\
& + B_{13} \times i_2 \times mc_0^2 + B_{14} \times i_3 \times mc_0^2 \\
& + B_{15} \times i_4 \times mc_0^2 + B_{16} \times i_5 \times mc_0^2
\end{aligned}
$$

where MC_{10} is the moisture at end of a 10-day period; mc_0 is the moisture at beginning of a 10-day period; mc_0^2 is $mc_0 \times mc_0$; $Rain_{10day}$ is the cumulative rainfall for a 10-day period; ET_{10day} is the calculated cumulative ET_0 for a 10-day period; i_2, i_3, i_4, and i_5 are binary variables (0/1) for treatments 2 through 5, respectively; and B_0 to B_{16} are model coefficients ($B_0 = 6.6367$, $B_1 = 0.6222$, $B_2 = 0.004008$, $B_3 = 0.01221$, B_4 –0.04933, $B_5 = -5.9390$, $B_6 = -5.9994$, $B_7 = -6.9249$, $B_8 = -5.9828$, $B_9 = 0.3214$, $B_{10} = 0.3345$, $B_{11} = 0.3920$, $B_{12} = 0.3375$, $B_{13} = -0.00368$, $B_{14} = -0.00417$, $B_{15} = -0.00472$, and $B_{16} = -0.00427$).

Treatments 1 through 5 were roundwood with top cover, energy wood with top and side cover, roundwood with top and side cover, energy wood with top cover, and roundwood with no cover, respectively. Treatment 1 was the base treatment and had the most data points associated with it.

All variables were significant at the $P = 0.001$ level or better. A null model likelihood ratio test indicated that the model was significant at the $P < 0.0001$ level ($\chi^2 = 186.8$, df = 47).

The model indicates, as one would expect, that rainfall increases the biomass moisture content and ET_0 decreases it. The model also indicates that the moisture content at the beginning of a 10-day drying period positively influences the moisture content at the end of the 10-day period and that the influence is nonlinear. Finally, the model indicates that all treatments were significantly different from each other and that there were interactions between treatments and moisture content at the beginning of a 10-day drying period. Because of the nonlinear interactions between treatments and starting moisture content, it is not obvious, without reference to the model, how treatments compare with each other for the same conditions.

Table 2.—Overview of the storage trial with assortments, covering, start and end months, and biomass characteristics.[a]

	Cradle no.									
	1	2	3	4	5	6	7	8	9	10
Log assortment	RW	RW	EW	RW	RW	EW	RW	RW	RW	RW
Covering	Top	Top	T&S	T&S	Top	Top	None	Top	Top	Top
Start (mo-y)	4-07	4-07	4-07	4-07	4-07	4-07	4-07	6-07	9-07	12-07
Stop (mo-y)	8-07	12-07	8-08	8-08	8-08	8-08	8-08	8-08	8-08	8-08
Storage duration (wk)	20	35	70	70	70	70	70	63	51	37
Start green wt (kg)	25,584	28,450	23,122	26,365	27,112	20,338	24,869	28,405	21,455	25,853
No. of logs	767	832	457	735	789	345	781	596	489	504
Avg. log length (m)	2.94	2.93	4.11	2.95	2.96	4.49	2.96	3.29	2.96	2.94
Avg. midpoint diam. (mm)	104	103	87	112	101	116	112	123	134	134
Bark cover (%)	69	64	76	63	62	83	62	39	40	57
Green density (kg/m^3)	993	1,051	1,101	1,046	1,061	998	1,029	1,081	925	1,078
Basic density (kg/m^3)	433	446	519	451	433	406	432	419	448	409
Start MC (%)	56.4 (±2.0)	57.6 (±1.1)	52.8 (±4.5)	56.8 (±1.4)	59.2 (±2.4)	59.4 (±2.4)	58.0 (±1.0)	61.2 (±1.3)	51.6 (±1.9)	62.1 (±1.1)
End MC (%)	24.4 (±0.7)	22.6 (±0.2)	18.4 (±0.3)	18.6 (±0.2)	20.7 (±0.4)	20.5 (±0.6)	21.6 (±1.8)	20.2 (±0.5)	20.4 (±0.6)	23.6 (±1.2)
Wk to get below 30% MC	14	14	18	16	17	21	17	26	15	25

[a] Cradles 1 and 2, when refilled, were relabeled as Cradles 9 and 10. Figures in parentheses are the 95 percent confidence limits for moisture content (MC). RW = roundwood; EW = energy wood; T&S = top and side.

Figure 3 demonstrates how well the model fit the drying curves for 2 of the 10 cradles. The two chosen are those with the best and worst fit, based on predicted versus actual number of days to achieve 30 percent moisture content. Predicted drying times for 9 of the 10 cradles were within 10 percent of the actual number of days and no worse than 15 days. Predicted drying time for one of the cradles was underestimated by 25 percent (44 d); however, the predicted time for this cradle would have been within 10 percent of the actual number of days but for an extended period of rain beginning on the day the actual moisture content was at 30.1 percent.

The effect of treatments, that is, biomass type and type of cover, was determined by setting the initial moisture content for all treatments to 57.5 percent (the average for all cradles) and running the model using the same climatic conditions (drying beginning at the beginning of June 2007). Figure 4 shows the drying curves for the five treatments. There was about a 160-day difference between the minimum time and the maximum time required to dry biomass to 30 percent moisture content.

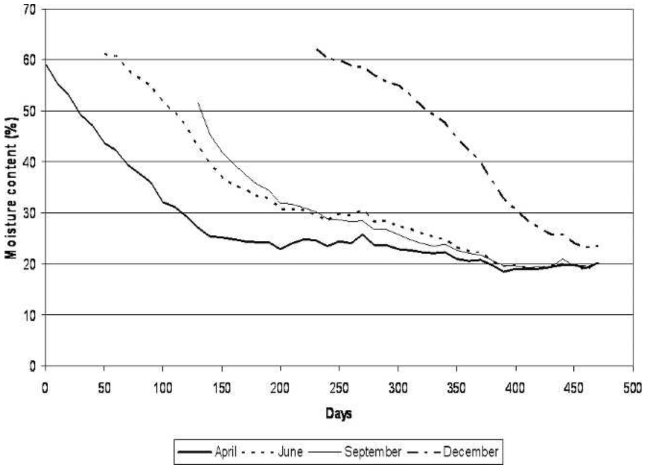

Figure 2.—Drying curves for Sitka spruce roundwood with top cover after trees were felled at different times of the year.

Unexpectedly, energy wood took longer (~110 d) than roundwood for the same types of cover. Lumber drying research would indicate the opposite, that is, small-diameter woody material would be expected to dry at a faster rate than thicker material (Simpson et al. 1999). The reverse trend may have been due to the presence of bark; bark cover was 40 percent greater on average on the energy wood than on the roundwood. Defo and Brunette (2006) have shown that drying rate is negatively affected by the amount of bark present.

Energy wood with top and side cover dried faster (~70 d) than energy wood with a top cover but no side cover. Roundwood with a top cover dried faster (~20 d) than roundwood with no cover. Unexpectedly, roundwood with top and side cover dried at almost the same rate as roundwood with no cover. We have no explanation for this, although the model output reflected the observed similar drying rates of the two trial cradles.

Objective 3

An evaluation of an alternative and readily available climate-based drying model showed that it was inappropriate for predicting drying times for Sitka spruce in Ireland. Simpson and Wang's Douglas-fir drying model (2003) predicted times that ranged from 7 to 12 days for the cradles containing the roundwood with top cover treatments to dry to 30 percent moisture content for the same humidity and temperature conditions recorded at the Derrygreenagh site

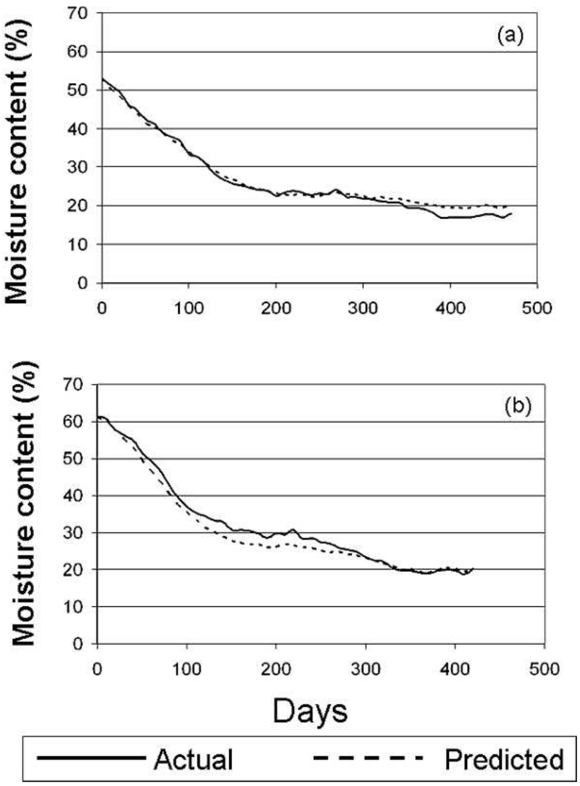

Figure 3.—Actual and predicted drying curves for Sitka spruce biomass for two cradles chosen to represent the (a) best and (b) worst fits based on number of days to reach 30 percent moisture content.

in Ireland. These predictions underestimate drying times of Sitka spruce biomass material in Ireland by a factor of about 10. These results highlight (1) the importance of including rainfall in Irish drying models and (2) how debarking and filleting of logs can speed up the drying process.

Objective 4

Table 3.—Predicted number of days required to dry roundwood biomass with a top cover to 30 percent moisture content (MC) at five sites around Ireland representing different climatic conditions.[a]

	Season in which drying began			
Location	Summer	Autumn	Winter	Spring
Starting MC (%)	57.5	57.5	57.5	57.5
Derrygreenagh (d)	104	154	141	103
Knock (d)	98	148	140	98
Ballyhaise (d)	92	125	127	90
Oakpark (d)	91	121	126	93
Valentia (d)	92	140	131	95
Starting MC (%)	61.0	58.0	55.0	58.0
Derrygreenagh (d)	123	157	132	105
Knock (d)	116	150	132	100
Ballyhaise (d)	106	127	119	91
Oakpark (d)	105	125	116	94
Valentia (d)	108	143	122	97

[a] Two starting moisture content scenarios are presented: one where starting moisture does not change with season and one where it does change with season.

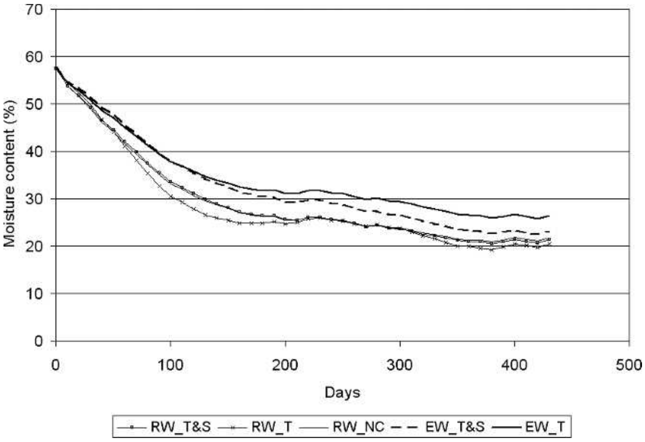

Figure 4.—Effect of biomass type and cover on predicted moisture content of Sitka spruce when air drying was initiated at the beginning of May 2007. Initial moisture content was set at 57.5 percent.

The results shown in Table 3 demonstrate how an appropriate Sitka spruce climate-based model could be used to predict drying times for different seasons in which drying was initiated and for different locations. If there is no difference between starting moisture conditions, as indicated in some reports for softwoods (Clark and Gibbs 1957, Shottafer and Brackley 1982), the year can be split into two periods from the perspective of drying rates: spring/summer harvesting requiring 30 to 50 fewer drying days than autumn/winter for the five locations. If there is a difference in starting moisture conditions for Sitka spruce, as reported by Kent et al. (2009), initiating drying in spring would lead to the fastest drying rates for all five locations. Summer, winter, and then autumn is the order of the drying rates for the remaining seasons in which drying is initiated.

There was about 16 days' difference in predicted drying rates between the fastest (Oakpark) and slowest (Derrygreenagh) locations for the summer, winter, and spring harvesting seasons, and 27 days' difference for the autumn harvesting season. Looked at in a different way, the difference between the shortest (spring harvesting) and longest (autumn) drying time for a given site was 45 to 50 days for the Knock, Valentia, and Derrygreenagh sites and 30 to 35 days for the Oakpark and Ballyhaise sites. The Knock and Valentia sites had the highest rainfalls. The Derrygreenagh site was characterized by high rainfall and the lowest ET_0. The Oakpark and Ballyhaise sites had comparatively low rainfall and high ET_0.

Concluding Remarks

The application of mixed effects regression modeling to air-drying data for Sitka spruce logs has resulted in a method for estimating drying times of covered and uncovered roundwood and energy-wood logs stacked any day of the year at any off-forest location in Ireland where historic weather data are available. The regression model constructed relates moisture content loss over a 10-day interval to moisture content at the start of the interval, cumulative precipitation and ET_0 for the period, woody biomass type, and type of cover. The model was easily used in a spreadsheet to estimate drying times for different locations in Ireland, different starting seasons for drying, different biomass types, and different types of cover. The predicted number of days was determined via a chained procedure in increments of 10 days. The calculated final moisture content at the end of each 10-day interval became the initial moisture content at the beginning of the next 10-day interval. This calculation was repeated for the period of interest or until the target moisture content had been reached. The model provided more accurate estimates of drying rates than an alternative model developed for off-forest drying of small conifer logs in the western United States. The model should not be used for estimating drying times for in-forest biomass storage because it will overestimate drying rates considerably.

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