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Assessment of Moisture Effect in Simulating Forestry Biomass Supply Chain Strategy: Case Study of New Brunswick, Canada

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Abstract

In order to investigate the effect of variation of the moisture content of forest biomass residues on a supply chain strategy, a simulation was performed using integrated biomass supply analysis and logistics modeling. A simple supply chain strategy was chosen and applied for Miramichi and Plaster Rock, two different regions in New Brunswick, Canada. These regions are selected based on three criteria: annual potential harvest of forest biomass residues, annual production potential of electric and thermal energy and distribution of transportation zones. The moisture content of forest biomass residues was dependant on the weather conditions of the selected regions. The results show that the moisture content of the biomass in Plaster Rock was more stable but higher than the biomass in the Miramichi region. In simulating the supply chain strategy, particular attention is given to harvest, baling, storage and transportation of the biomass. The simulation results show that, during harvest and baling of the biomass, the moisture content affects the dry matter loss and, as a consequence, the customer and ownership costs of the operations. It also affects the energy input and the quantity of carbon dioxide released in the atmosphere. However, dry matter loss and accordingly the cost of the operations are the main parameters affecting the storage and transportation of forest biomass residues.

Keywords: supply chain, moisture content, forest biomass, transportation, storage, IBSAL model, dry matter losses

1. Introduction

In Canada, the forest sector is one of the most important industries that contribute significantly to the economy of the country. About 80% of the forestry sector's contribution to the Canadian economy is from solid wood product manufacturing for domestic consumption and export and pulp and paper product manufacturing (Government of Canada 2013). Logging is one the main activities of the forestry sector. It includes harvesting, storage and transportation of the wood to the mill. This sub-sector contributes about 20% of the forest sector's contribution to the Canadian economy. The forestry and logging operation engender a huge amount of residues estimated at about 20±0.6 million dry metric tonnes per year after the harvesting process (Cambero et al. 2015). Following the Bio-pathways Project developed by the Forest Products Association of Canada (2010) the interest in the use of the biomass forest residues for the production of bioenergy, such as pellets, briquettes or biofuel, is continuously increasing in Canada. Depending on the produced quantity and its cost, the bioenergy, in particular the biofuel, can be produced to meet the local energy need of the mills or sawmills existing in the region and the production surplus can be considered for export.

The biomass residues pass through several processes, mainly harvesting, storage in a pile or other forms, storage and transportation before delivery to destination (i.e. mills, sawmills or a biorefinery). Storage and transportation costs make the exploitation of biomass residues an expensive process that needs to be optimized in order to make it suitable, efficient and cost effective. To address this, different mathematical models have been developed, to support and optimize the planning and management of the biomass residues supply chain. Cambero and Sawlati (2014) and Hughes et al. (2014) presented different supply chain models designed for forest biomass with respect to the economic, social and environmental aspects. The mathematical models were classified in seven main categories according to the desired criteria (Cambero and Sawlati 2014) or to the type of modeling approach (Hughes et al. 2014). Cambero et al. (2015) used a multi-period mixed integer linear program (MILP) to optimize the design of the supply chain strategy for forest residues for bioenergy and biofuel. Their study was applied to a region of Williams Lake in British Columbia, Canada. They determined, in their developed model, different types of the collected biomass and their sourcing points, the needed amount of biomass to transport from source to facilities and from facilities to market, the location, type and size of the conversion technology to be installed and the amount of bioenergy and biofuel to be generated. Cambero et al. (2015) investigated the production of heat, electricity, pellets as well as the option of producing bio-oil using pyrolysis process. Frombo et al. 2009a and 2009b focused in their study on the introduction of the geographical position and distances between the biomass sources and facilities by using GIS (Geographic Information System) based EDSS (Environmental Decision Support System). The optimized supply chain strategy considered different types of biomass (untreated woody and agro-forest biomass) with the particular objective of optimizing the transportation cost, considered as the one of the most expensive elements in the supply chain strategy. Freppaz et al. (2004) and Zhang et al. (2016), using the same GIS system, developed a more complete model by introducing the economic, regulatory and social criteria. This approach allowed to make a more appropriate and suitable supply chain strategy for the exploitation of forest biomass for energy supply. However, the application of the developed model was limited to a small mountain region in Italy that has its specific characteristics. The environmental criterion is crucial for the development of an appropriate supply chain strategy (Rafael et al. 2015a, 2015b, Jäppinen et al. 2014, Palak et al. 2014). Accordingly, including this criterion, the developed mathematical models will play an important role for its credibility. The multi-criteria supply chain optimal strategy developed by Vasković et al. (2015) was based on three criteria: energy efficiency of the production, economy of the production and the environmental issues represented mainly by the greenhouse gaseous (GHG) emissions. The authors (Vasković et al. 2015) investigated the production of solid biofuel including different options, such as production of briquettes and pellets using wood residues from mills or sawmills. In addition to the different criteria cited above, variation of the moisture content of the biomass and all the parameters depending on the moisture content, such as the density and the heating value of materials and the influence of this change on different stages of the supply chain, have been introduced in the studies published recently (Jäppinen et al. 2014, Windisch et al. 2015, Daystar et al. 2014). Sokhansanj et al. (2006) developed and implemented a supply chain model called integrated biomass supply analysis and logistics model (IBSAL). The authors (Sokhansanj et al. 2006) studied the outdoor storage of agricultural biomass and subsequently simulated the effect of weather conditions on the variation of the moisture content of agricultural biomass and all moisture content related parameters (i.e. mass, density, equilibrium moisture content and heating value). The results of the study were presented in terms of energy input, carbon emissions, but did not specify which element of the supply chain model was affected by the variation of the moisture content. Ebadian et al. (2013) focused on the effect of different storage methods using (IBSAL) model. The authors (Ebadian et al. 2013) compared three different storage systems. It was possible, using IBSAL model, to determine the most suitable storage method by determining the cost of storage and transportation and by calculating the amount of the dry matter loss. This parameter is considered as an important element for analyzing the suitability of the supply chain strategy.

The aim of this study is to answer the question: does the variation of the moisture content of forest biomass residues have an effect on supply chain strategy? A simple supply chain strategy is chosen and simulated, using IBSAL model, in two different regions in New Brunswick, Canada. A particular attention is given to the effect of the variation of the moisture content during storage and the consequences during transportation.

2. Methodology

2.1 Selection of the potential regions in New Brunswick

As reported by Bouchard et al. (2012, 2013) and Wilson et al. (2010), around 80 to 85% of the area of the province is covered with forests. It represents approximately 60,000 km^2 of productive forests and from 3.3 to 2.8 million ha of forest is managed by the New

Table 1 Total annual potential harvest of forest biomass residues, in green metric tonnes (Bouchard et al. 2012)

Region	Total annual harvest, GMT
Dalhousie	143,634
Bathurst	249,335
Tracadie-Sheila	68,017
Miramichi	**337,942**
Richibucto	138,368
Doaktown	260,541
Moncton	**322,973**
Chipman	177,056
Sussex	261,992
St-John	172,239
St Stephen	189,989
Fredericton	260,816
Nackawic	241,868
Juniper	257,893
Plaster Rock	**482,217**
Edmundston	**321,596**
Kedgwick	**365,451**

Table 2 Total annual production potential of electric and thermal energy presented by regions in New Brunswick (Bouchard et al. 2013)

Region	Energy, PJ	Power, MW	Heat, MW
Dalhousie	1.42	11.3	27.0
Bathurst	2.55	20.2	48.5
Tracadie-Sheila	0.61	4.9	11.6
Miramichi	**3.47**	**27.5**	**66.0**
Richibucto	1.43	11.3	27.1
Doaktown	2.65	21.0	50.4
Moncton	3.26	25.8	62.0
Chipman	1.84	14.6	34.9
Sussex	2.65	21.0	50.4
St-John	1.73	13.7	33.0
St Stephen	1.93	15.3	36.8
Fredericton	2.64	21.0	50.3
Nackawic	2.44	19.3	46.4
Juniper	2.54	20.2	48.4
Plaster Rock	**4.98**	**39.5**	**94.8**
Edmundston	3.25	25.8	61.8
Kedgwick	**3.76**	**29.8**	**71.4**

Brunswick Department of Natural Resources (NBDNR) (Wilson et al. 2010, Martin 2003). The focus of this part of the work is to determine the most suitable regions of the New Brunswick that have a potential of production and exploitation of forest biomass residues. The selection was made based on the potential harvest of forest biomass, generation of electric and thermal power and finally transportation distances from the source to the plant. Five potential regions in New Brunswick were selected in terms of production of forest biomass residues, based on the study by Bouchard et al. (2012, 2013). These regions are: Plaster Rock, Miramichi, Kedgwick, Edmundston and Moncton. Table 1 summarizes the total annual potential harvest of forest biomass residues expressed in green metric tonnes (GMT) calculated on wet basis and assuming an average value of the moisture content of forest biomass residues to be about 50% (Bouchard et al. 2012). The production of this main group varies from 480,000 to 320,000 GMT. Fredericton, Doaktown and Sussex can also be selected in a secondary group. These regions produce around 260,000 GMT. Table 2 represents the total annual potential of producing electric and thermal energy using forest biomass residuals. It shows that the selected regions are now restricted to three regions; Plaster Rock with a total potential of energy equal to 4.98 PJ, then Kedgwick and Miramichi with 3.76 and 3.47 PJ, respectively. The transportation zones were divided into 5 ranges, 1–25 km, 26–50 km, 51–75 km, 76–100 km and 101–125 km. It was assumed that going above 50 km as transportation zone is not efficient and, therefore, this study is limited to the first two laps. Table 3 shows the percentage of distribution of forest biomass across the transportation zone. Table 3 confirms the selection of the three above said regions, with a total of 63% of forest biomass being within the transportation zone not exceeding 50 km. However, the regions of Miramichi and Plaster Rock show a higher percentage in the distribution of forest biomass in the transportation zone from 1 to 25 km. The selection of potential regions for this study is limited to Miramichi and Plaster Rock.

Table 3 Distribution of forest biomass (in percentage %) across the transportation zones in New Brunswick (Bouchard et al. 2013)

Region	Transportation zone	
	1–25 km	26–50 km
Dalhousie	25	47
Bathurst	19	48
Tracadie-Sheila	23	77
Miramichi	20	43
Richibucto	29	65
Doaktown	26	43
Moncton	21	58
Chipman	26	53
Sussex	27	65
St-John	26	46
St Stephen	22	46
Fredericton	26	54
Nackawic	22	51
Juniper	19	59
Plaster Rock	24	39
Edmundston	21	52
Kedgwick	15	48

2.2 Presentation of the simulation supply chain model and scenario

The main objective of this study is to investigate the effect of the moisture content of biomass on the supply chain strategy. Accordingly, the Integrated Biomass Supply Analysis and Logistics (IBSAL) model was selected. As described by Sokhansanj et al. (2006), IBSAL model is a simulation of a biomass supply chain using different linked modules, and each module represents an element (process or event) of the supply chain (Sokhansanj and Ebadian 2007, Sokhansanj et al. 2008). As input data, logistic features, such as the number of agricultural farms, the average yield and the progress of the harvest schedule, are primarily introduced into the model. The variation of the moisture content of biomass is an important part of the model. Accordingly, this variation is defined by the introduction of the daily weather conditions (i.e. temperature, relative humidity, wind speed, rainfall and snow fall). The model will then deliver as output data, the cost and energy needed to complete different processes of the supply chain, carbon emission, final quantity of biomass delivered and dry matter loss of biomass. The simulation is performed using the simulation language EXTEND. The input and output data are inserted and obtained in Excel sheets. Both IBSAL and EXTEND are available in public domain.

As the main focus of this work is to study the effect of the moisture content on different steps of supply chain, a simple scenario is adopted. The scenario is shown in Fig. 1. It starts with harvesting forest biomass residues (after wood harvesting). Usually, the

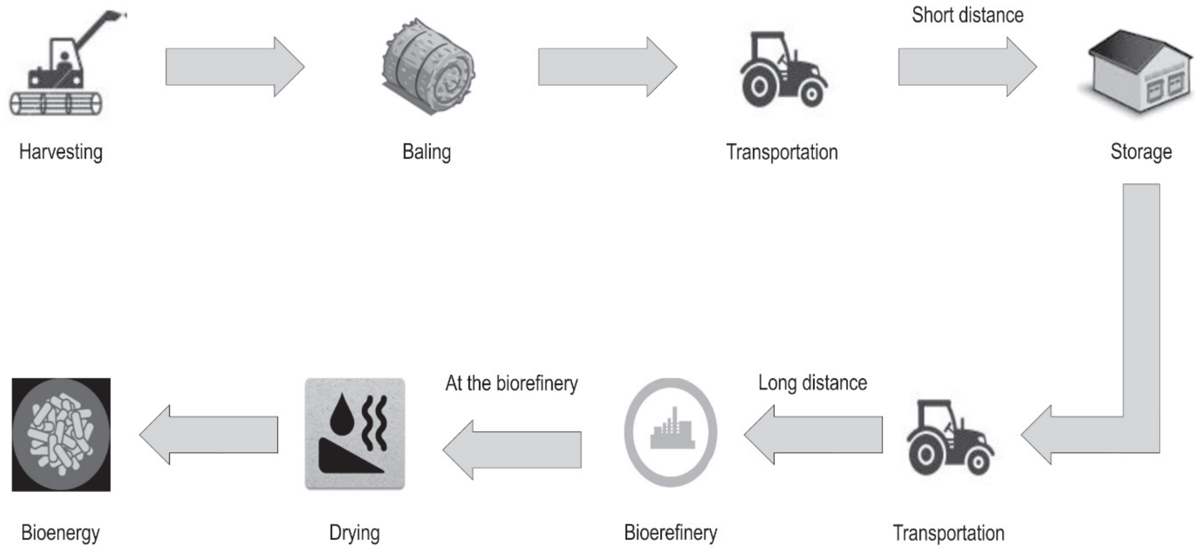

Fig. 1 Adopted supply chain scenario

harvested biomass comes in the form of rectangular or round bales. In our case, the bale of the biomass is supposed to have a rectangular shape with the following dimensions 1.22×1.22×2.44 m^3. The next procedure of the supply chain scenario is transportation of the biomass bales for a short distance to the storage points. In order to obtain variation in the moisture content of biomass, we simulated outdoor storage. The weather condition changes will then have a direct impact on the variation of the moisture content of the biomass bales. Afterward, the biomass bales are transported to the biorefinery for utilization as a source of bioenergy. As, in general, the biomass bales come in a wet form with moisture content around 50%, performing drying process is inevitable to make the biomass bales exploitable.

2.2.1 Modeling forest biomass residue moisture content

The moisture content of forest biomass residues was supposed to be the sum of the internal and external moisture (Sokhansanj et al. 2006). This approach was successfully used for different types of forest and agriculture biomass (Sokhansanj et al. 2006, He et al. 2015, Nilsson and Karlsson 2005). The internal moisture content was represented using Lewis equation, written in the following form:

$$\frac{dM_\mathrm{i}}{dt} = -aE_\mathrm{p}(M_\mathrm{i} - M_\mathrm{eq}) \qquad (1)$$

Where:

M_i internal moisture content of forest biomass residues expressed in dry basis (kg of water/kg of dry matter)

E_p pan evaporation (mm/day). This coefficient depends on weather conditions (Appendix A)

a a coefficient that depends on the studied material

M_eq equilibrium moisture content of biomass. It is represented using the following equation:

$$M_\mathrm{eq} = D + \frac{E.T}{\left(\frac{1}{rh} - 1\right)^{\frac{1}{F}}} \qquad (2)$$

Where:

D, E and F coefficients that can be determined from the sorption isotherms of the studied material.

He et al. 2015 find that D, E and F have the values of: 0.1211, –0.00074 and 2.41 for the adsorption process of aspen biomass and equal to 0.1248, –0.000011 and 2.059 for desorption process of the same material.

T and rh temperature and relative humidity of the air.

The external part of the moisture content of forest biomass residues varies with the weather conditions. It was proposed as a function of the pan evaporation E_p and the precipitation rate noted P_e, as defined below (Sokhansanj et al. 2006):

$$\frac{dM_\mathrm{ex}}{dt} = bP_\mathrm{e} - cE_\mathrm{p} \qquad (3)$$

b, c coefficients depending on the studied material.

The pan evaporation is presented as a function of the weather conditions and the saturation vapor pressure. The formulas used for determination of the pan evaporation (from Holman 2002 and Eluripati 2007) and the saturation vapor pressure (from ASABE 1994) are presented in Appendix A. The total moisture content is simply the sum of the internal and external moisture content:

$$M_\mathrm{tot} = M_\mathrm{i} + M_\mathrm{ex} \qquad (4)$$

Furthermore and as proposed by Sokhansanj et al. (2006), the initial moisture content of the internal and external parts are proposed to be equal:

$$M_\mathrm{i} = 0.8\, M_0 \qquad (5)$$

and

$$M_\mathrm{ex} = 0.2\, M_0 \qquad (6)$$

Where:

M_0 initial moisture content of biomass, usually determined by introducing samples of the biomass in an oven at 105 °C until no variation in the moisture content of the biomass can be recorded (Bennamoun et al. 2015). It is assumed for the simulation performed in this study that the initial moisture content of forest biomass residues, before storage process, is equal to 50% on wet basis.

He et al. (2015) determined experimentally the value of (a) and (b) defined in equations (1) and (3) for aspen biomass. They find (a) equal to (0.203±0.023 mm^{-1}), with a mean value of 0.206 mm^{-1} and the range of (b) was between 0.11 and 0.15 mm^{-1} with a mean value of 0.129 mm^{-1}.

3. Results and discussion

The focus is, as discussed previously, on the two selected regions in New Brunswick; Miramichi and Plaster Rock. The weather conditions of the selected regions, represented by air temperature, air humidity, wind speed, precipitation and snow on the ground, with daily frequency are first elements to be introduced to simulate the supply chain scenario using

IBSAL model. Fig. 2a and 2b represent the weather conditions for the region of Miramichi and Fig. 3a and 3b are data for Plaster Rock region. The presented data are for the year 2014 and are obtained from the government of Canada (http://climate.weather.gc.ca/). The observation and the comparison of the figures (2a, 2b and 3a,3b) show that the variation of the weather temperature, for both regions, is quite similar with low temperatures in winter. The lowest temperature was registered in January and was around –26.5 °C in Miramichi and –31.5 °C in Plaster Rock. In this study, the focus will be on the after-snow period, which means from April to October. In this period of the year, in two regions the weather temperature changed from around 5 °C to 25 °C. The highest temperatures were registered in the months of June and July. The observa-

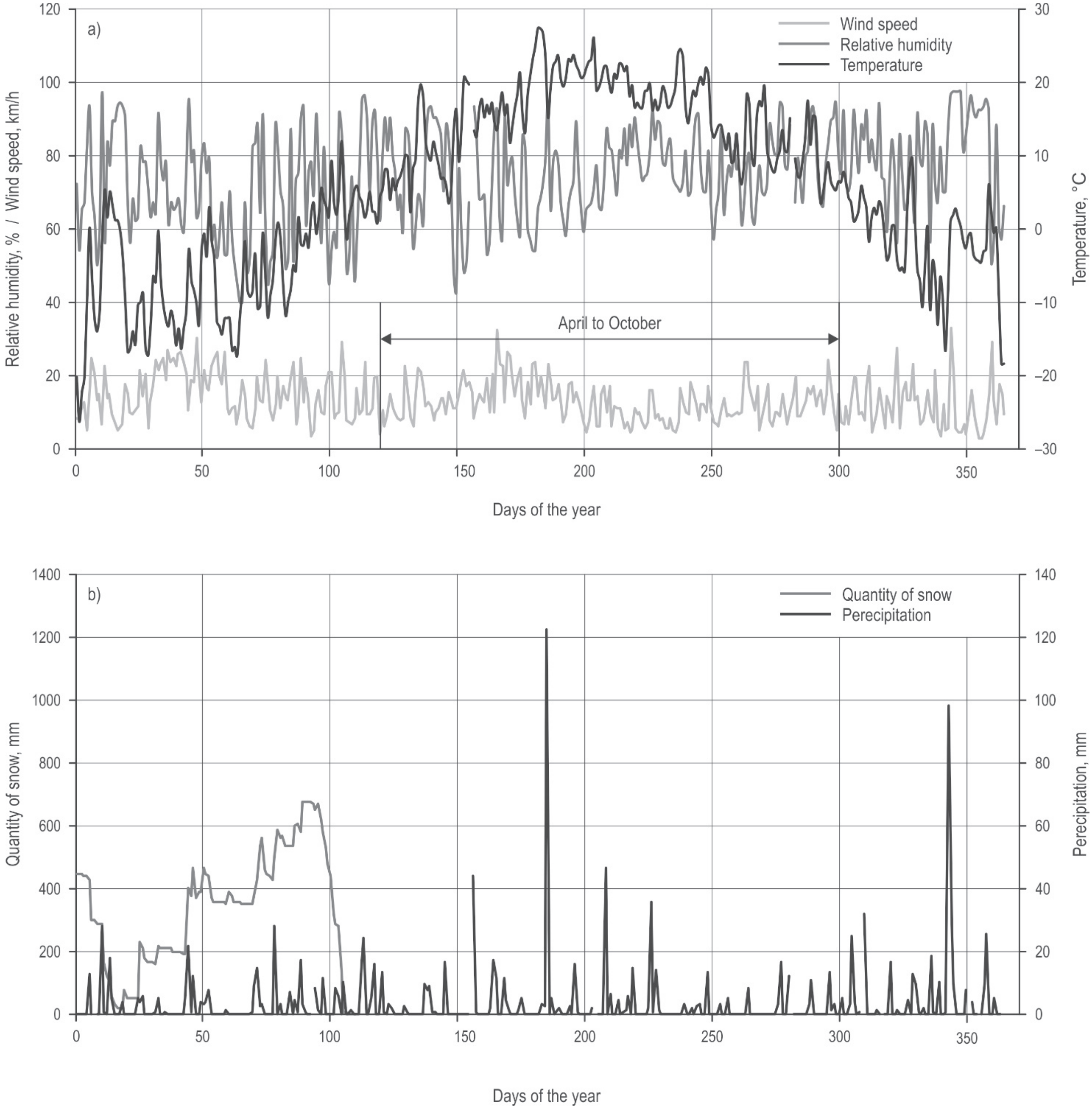

Fig. 2 Weather conditions in Miramichi in 2014: a) Temperature and relative humidity of the air and wind speed; b) Precipitation and snow in the ground

tion of the variation of the relative humidity (*rh*) of the air, from Figures 2a and 3a, shows that *rh* in Miramichi changed from 40 to 95% against 50 to 90% for Plaster Rock. Regarding the studied period (April to October), the *rh* in Plaster Rock was more stable and more humid with variation between 70 to 90%, in particular during the month of June and July, comparing to Miramichi. In this latter region (Miramichi), in June and July the *rh* changed from 50 to 90%. This means that in the period of April to October, the weather was more humid in Plaster Rock than in Miramichi, which could have an influence on the moisture content of forest biomass residues. The registered wind speed in Miramichi was higher than in Plaster Rock; the wind speed for Miramichi region was not less than 10 km/h with a mean value of about 15 km/h. The values of the

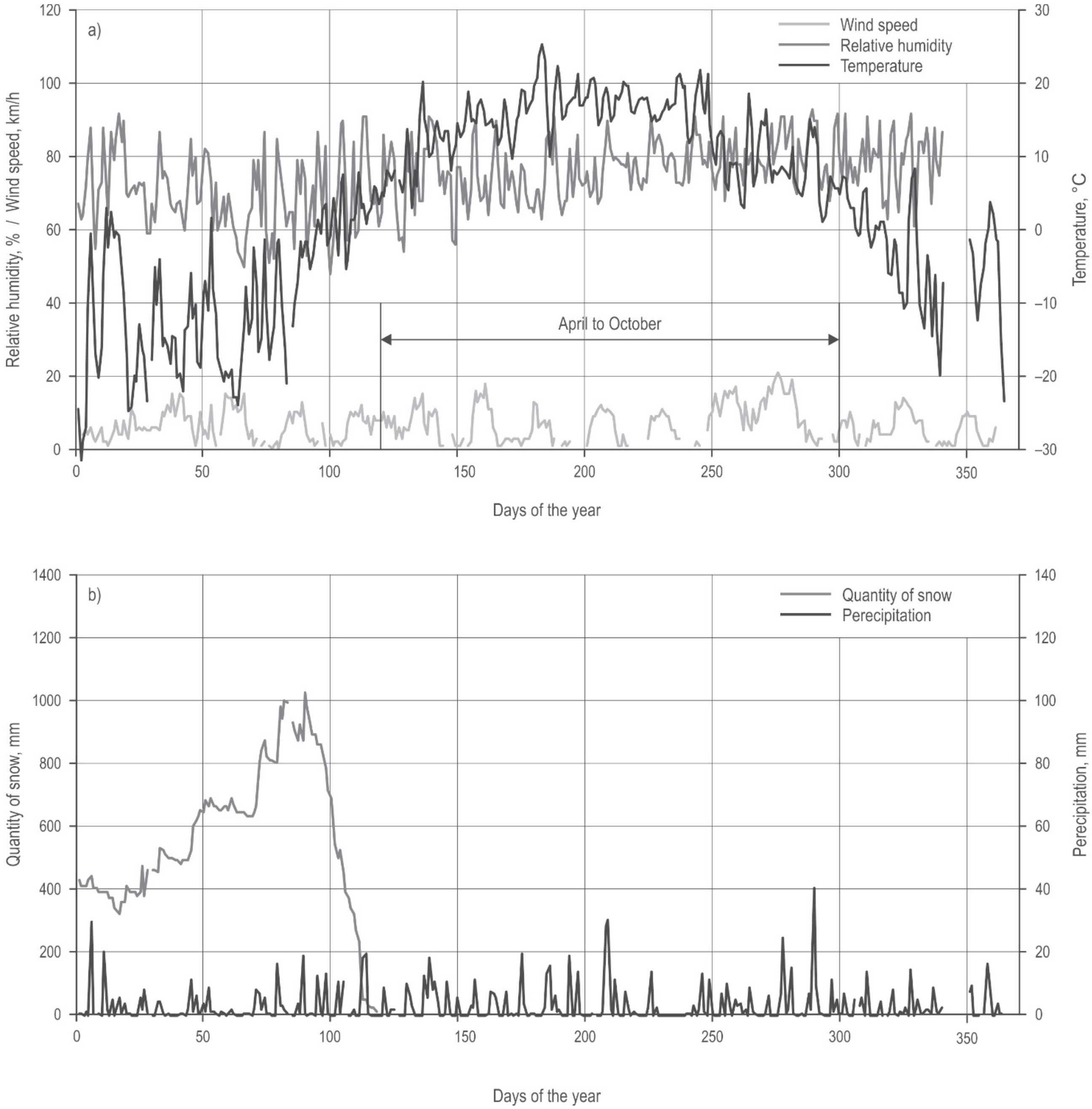

Fig. 3 Weather conditions in Plaster Rock in 2014: a) Temperature and relative humidity of the air and wind speed; b) Precipitation and snow in the ground

wind speed in this region ranged between 5 km/h and 35 km/h. However, in Plaster Rock region (Fig. 3a), the range of the wind speed was between 0 km/h and 20 km/h with several days without wind, which is not the case for Miramichi (Fig. 2a). As, for this study, outdoor storage of biomass residues is simulated, having a windy region can be an advantage, as moisture transfer exchange with the air can be increased with the wind speed increase. On the other hand, the data presented in Fig. 2b and 3b shows that Miramichi region is more exposed to rain and that it had received more precipitation with a total of around 1266 mm in 2014 compared to Plaster Rock region with 935 mm. The maximum amount of precipitation received per day in Miramichi was 120 mm, which is two times more than the maximum quantity in Plaster Rock. However, precipitation in Plaster Rock was more frequent than in Miramichi with a range between 10 to 20 mm per day. In Miramichi, several days without precipitation can be observed, in particular during the study period (April to October). As shown in the moisture content modeling (section 2.2.1.), the precipitation has a direct influence on the external part of the moisture content of biomass residues, which will increase with the increase of the received quantities of rain. Furthermore, Fig. 2b and 3b show that the quantity of snow registered in the ground increases continuously until the month of March. Afterwards, within a month, the quantity of snow dramatically decreases. The registered quantity of snow was much higher in Plaster Rock than in Miramichi with around 1000 mm for the first region (Plaster Rock) and 700 mm for the second region (Miramichi).

3.1 Effect of weather conditions on moisture content of forest biomass residues during outdoor storage

During outdoor storage, the physical properties of biomass residues, in particular its moisture content, are directly linked to and influenced by the weather conditions (i.e. temperature, wind speed and relative humidity), as confirmed by the studies published by Mohanraj (2014), Visser et al. (2014) and He et al. (2015). Accordingly, the proposed model for simulating the variation of the moisture content represented by equations 1 to 6 clearly shows the effect of the weather conditions, introduced in equations 1 to 3. Fig. 4 shows the variation of the moisture content of forest biomass residues, during outdoor storage from April to October. In fact, Fig. 4 confirms the direct effect of the weather conditions on the variation of the moisture content of biomass residues. A particular attention is given to the temperature of the weather and the rain precipitation. It is shown that the moisture content decreases during periods with high or moderate temperature (above 15°C) and low precipitation, as shown in the first 20 days. In other terms, there is a significant evaporation of the moisture content of the biomass. Moreover, Fig. 4 shows clearly that during periods with high precipitation, such as around day 190 with 120 mm for Miramichi and about 20 mm for Plaster Rock, the moisture content of the biomass in Miramichi increased from around 0.35 to 0.5 (wet basis) and from 0.3 to around 0.35 for the region of Plater Rock. Similarly, at the end of the studied period, the precipitation in Plaster Rock was much higher (40 mm) than in Miramichi (less than 20 mm), which was replicated by a higher moisture content of Plaster Rock's biomass. Due to the large and frequent variation of the wind speed and relative humidity, it was not convenient to follow the effect of each parameter. Nevertheless, it is common to see in drying, wetting and heat and mass transfer field that increasing the velocity of the air or the wind speed increase the heat transfer exchanges with the surrounding air, which leads to a faster drying or evaporation of the moisture content of the studied material (Bennamoun and Belhamri 2006). Similarly, it was found that the *rh* of the air has a negative effect on the evaporation of the moisture content and accordingly on the drying time; the increase of *rh* results in an increase of the moisture content, which is reflected in a longer drying time (Bennamoun and Belhamri 2008a, Bennamoun and Belhamri 2008b). Mostly due to the frequent precipitation of rain in the region of Plaster Rock comparing to Miramichi, the moisture content of biomass residues in Plaster Rock had no low values as in Miramichi. Hence, it can be speculated that the moisture content of biomass in Plaster Rock was higher than the one in Miramichi.

3.2 Effect of moisture content on simulated supply chain strategy

Dry matter loss (DML) and cost of the operations are the most important elements that give a picture of the effectiveness of the studied supply chain strategy. Accordingly, the effect of the moisture content on the supply chain strategy is then represented in terms of variation of the dry matter loss and the cost of different operations. A particular attention is given to storage and transportation of biomass residues. Furthermore, the environmental aspect defined by means of studying the energy input consumed by different equipment and the gaseous emissions are presented in this study.

Fig. 5 shows the simulation results of harvest and storage operations of biomass residues for Miramichi (Fig. 5a) and Plater Rock (Fig. 5b) regions. The com-

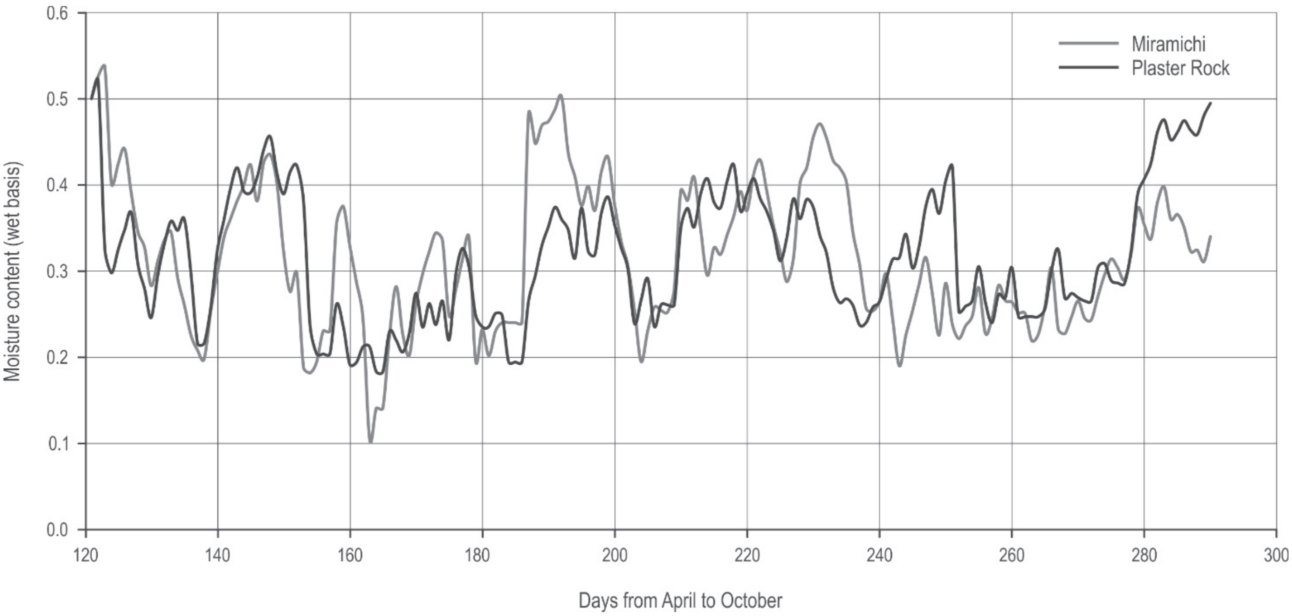

Fig. 4 Effect of weather conditions on moisture content of forest biomass residues during outdoor storage

parison between Fig. 5a and Fig. 5b shows that the dry matter loss (DML), after shredding, forming the collected biomass residues in rectangular bales, transporting to the storage and then storing the bales in outdoor gravel pad storage spaces, attained a maximum of 31.88% of the initial total amount of the biomass in the region of Plaster Rock. This amount increased to 31.93% for the region of Miramichi. This difference is probably due to the variation of the weather conditions, which has a direct effect on the moisture content of the collected biomass, as discussed previously (Fig. 4). Accordingly, increasing the moisture content of the biomass leads to a decrease of the dry matter loss. A similar result was obtained by Sokhansanj et al. (2008). As an example, they showed that increasing the moisture content of biomass from 30% to 40% (wet basis), decreased the dry matter loss from 25% to around 15%. The simulation using IBSAL

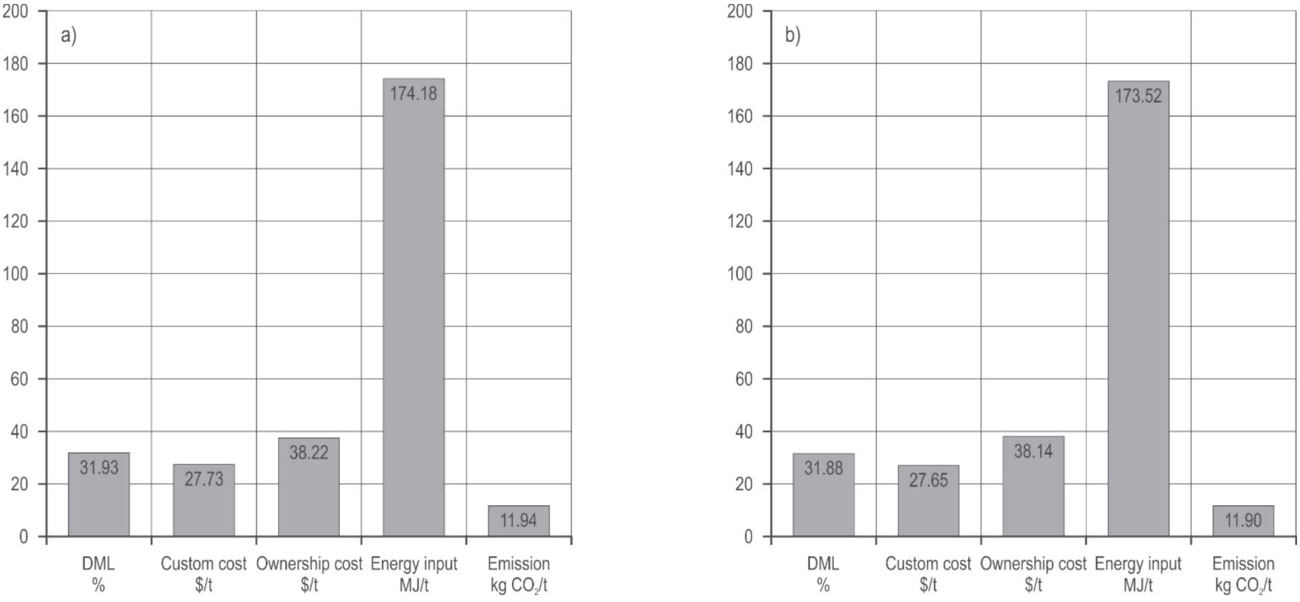

Fig. 5 Simulation results of harvest and storage operations using IBSAL model; a) Miramichi, b) Plaster Rock

model showed almost similar total custom and ownership costs for both studied regions. However, the costs were higher by 0.3% per ton for Miramichi than in Plaster Rock, probably as a direct consequence of the dry matter loss. Besides, the total energy input consumed by the equipment and the total quantity of carbon dioxide released in the atmosphere were quite similar for both regions. The quantities in Miramichi were higher by 0.4% per ton for the total consumed energy and 0.3% per ton for the carbon dioxide released.

Transportation is considered as one of the most expensive operations, amounting to approximately 50% of the total cost of the supply chain (Hamedani 2015). Fig. 6 shows the quantity of dry matter loss during different transportation steps. The simulation gives two types of transportation: »bale«, which can be defined as transportation for short distance, such as to the storage. The second type is defined by »bulk«, which represents transportation for a long distance from storage to the biorefinery. The simulation results, using IBSAL model, show that the DML during transportation of the bales in Plaster Rock was higher than in Miramichi with 28.59% and 22.65%, respectively. This means that, during transportation, increasing the moisture content of the biomass increases the quantity of the DML. Accordingly and as discussed previously, the bales created after harvesting forest biomass residues in the region of Miramichi had a lower moisture content, which implies that the bales were more compact in Miramichi than in Plaster Rock. In other words, more DML is obtained with the bales in Plaster Rock. A consequence of compact bales can also be seen in the bulk transportation, where the DML in Miramichi was much lower than in the region of Plaster Rock. The effect of the moisture content on the custom cost of the »bale« transportation was not significant, as the total amount was \$27.27 for both regions. However, the total ownership cost (calculated per ton) was 0.9% higher in Plaster Rock probably because the DML was higher in this region. Likewise, no effect of the moisture content of the biomass was observed on the results related to the energy input and the total amount of carbon dioxide released in the atmosphere with 556.98 MJ per ton and 103.16 kg of CO_2 per ton of biomass for both regions.

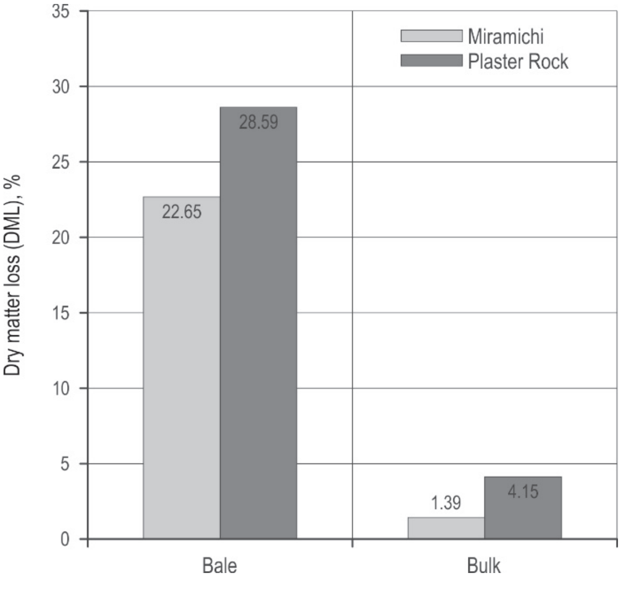

Fig. 6 Dry matter loss (DML) simulation results during transportation of biomass bales using IBSAL model

4. Conclusions and recommendation

This study presents the variation of the moisture content of forest biomass residues defined by studying the weather conditions of the regions of Miramichi and Plaster Rock in New Brunswick, Canada and its effects on a simple supply chain scenario. The study shows that the dry matter loss DML is directly linked to the moisture content of biomass residues. From harvest to storage of the biomass, the increase of the moisture content leads to the decrease in the DML, and consequently also to the decrease of the cost of operations, energy input and gaseous emissions of the harvest and storage operations. However, during transportation, the decrease of the moisture content helps to have biomass bales more compact, which reduces the DML. Accordingly, the study shows that the moisture content can have a direct or an indirect effect on a supply chain strategy. Consequently, introducing the variation of the moisture content of the studied material can be an important element for the development of a realistic model and simulation of a supply chain strategy.

During the harvesting period, from April to October, the solar radiation in Canada and in New Brunswick in particular, is significant. Taking advantage of this source of energy to reduce the moisture content of the biomass during outdoor storage and before long distance transportation can be a real advantage that can additionally reduce the total transportation cost of forest biomass residues to the biorefinery by reducing the moisture content of forest biomass residues.

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Appendix A

The pan evaporation is determined using Holman's evaporation formula (Holman 2002, Eluripati 2007):

$$E_\mathrm{p} = A\ (0.37 + 0.0041\ u)\ (P_\mathrm{s} - P_\mathrm{w})^{0} \cdot 88 \qquad (A–1)$$

Where:

A a coefficient that takes the value of 0.8 for the floating pan and 0.7 for a land pan

E_p, u, P_s and P_w expressed in in/day, mi/day and in of Hg respectively

Using the International system of units, equation (A–1) takes the following form:

$$E_\mathrm{p} = A\frac{\left(0.37 + \frac{0.0041V}{0}\cdot 0186\right)\left(2.953\cdot 10^{-4} P_s(1-rh)\right)^{0}\cdot 88}{3401575} \qquad (A–2)$$

Where:

E_p the pan evaporation expressed in mm/day

V the speed of the wind, m/s

P_s the saturation vapor pressure, given in Pa

rh the relative humidity of the air, in decimal

The saturation vapor pressure is determined using the following equations (ASABE 1994):

For 255.38≤T≤273.16 (in K)

$$ln(P_\mathrm{s}) = 31.9602 - 6270\cdot\frac{3605}{T} - 0.46057\ln(T) \qquad (A–3)$$

And: 273.16≤T≤533.16 (in K)

$$\ln\left(\frac{P_\mathrm{s}}{R}\right) = \frac{A + BT + CT^2 + DT^3 + ET^4}{FT - GT^2} \qquad (A–4)$$

Where:

$R = 2210564925$

$A = –27405.526$

$B = 97.5413$

$C = –0.146244$

$D = 0.12558 \times 10^{-3}$

$E = –0.48502 \times 10^{-7}$

$F = 4.34903$

$G = 0.39381 \times 10^{-2}$

The temperature T of the air is expressed in K.

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