A Linear Programming Optimization Model of Woody Biomass Logistics Integrating Infield Drying as a Cost-Saving Preprocess in Michigan

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Abstract

Because of the greater demand in using woody biomass for bioenergy and bio-based products, feedstock supply chain optimization becomes more important to decrease supply chain logistics costs. As a primary component in the biomass feedstock supply chain, the storage of harvested woody biomass can directly affect transportation cost, biomass quality, and combustion efficiency. An improved operations system structured with linear programming was developed for minimizing the total cost of woody biomass preprocessing, storage, and transportation. The improved operations system was applied in a simulated case study for a power plant in Michigan. In addition, a simulated second feedstock end user was added to the operations system to further test the model. The results showed that the improved operations system could lower supply chain logistics costs, improve feedstock quality, and simultaneously meet the feedstock end user's demand. The sensitivity analysis indicated that the additional profit from selling higher-quality feedstock could offset the increased transportation cost for up to 171 miles. On average, every 1 percent decrease in biomass moisture content can result in a decrease of $760.68 in total cost and a reduction of 52.1 green tons of delivered biomass to satisfy the end user's demands. The operation details suggested by the improved operations system can be used as a guideline of real operations to achieve the lowest possible operations cost. The additional profit return from selling higher-quality feedstock needs to be quantified for various conversion and upgrading options besides direct combustion in the future.

As a renewable fuel source, forest-based biomass has gained popularity in recent years and has been widely used by independent power plants to generate energy in the United States (Biomass Energy Resource Center 2011). Results from a life-cycle inventory study in Wisconsin showed that wood pellet fuels produced 26.6 percent less carbon emission per megajoule of heat generation compared with natural gas (Katers et al. 2012). In 2010, 27 percent of the renewable energy consumed in United States was produced from woody biomass (White 2010). By 2015, there were 227 woody biomass–based power plants in the United States with a total capacity of 7,463.82 million MW (Biomass Magazine 2015). Owing to the ever-increasing demand for bioenergy, the number of biomass power plants will be steadily increasing (Berndes et al. 2003, Jager-Waldau and Ossenbrink 2004). The increasing number of power plants and their relatively scattered locations can greatly increase the transportation distances and production costs for woody biomass (Rauch and Gronalt 2010, Tahvanainen and Perttu 2011, Alam et al. 2012). To improve the efficiency of biomass procurement and to promote the utilization of woody biomass, supply chain optimization for woody biomass procurement is becoming an important research area (Tallaksen and Simo-Kush 2014).

With the development of computational tools, mathematical models for optimization have been widely used to implement cost-effective bioenergy production (Macmillan 2001, Mentzer 2001, Rönnqvist 2003, Gunnarsson et al. 2004, Bredström et al. 2004). As woody biomass transportation cost accounts for the largest part of the total cost and energy consumption (Eriksson and Björheden 1989, Allen et al. 1998,

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Forest Prod. J. 66(7/8):391–400.
doi:10.13073/FPJ-D-15-00077

Alam et al. 2012), the developed optimization tools focus primarily on two categories: location selection and woody biomass collection. The location selection models have emphasized mainly on finding the best location for single or multiple processing facilities over the large-scale biomass supply chain (Zhang et al. 2011). The optimization models for woody biomass collection have aimed generally to estimate the feedstock availability and reduce cost for biomass procurement (Ranta 2002, 2005; Panichelli and Gnansounou 2008). For instance, Lautala et al. (2012a) have published a cost minimization model to minimize the cost of woody biomass transportation using railroads in Michigan and Wisconsin. However, as a critical phase in woody biomass supply chain logistics, optimization of woody biomass storage has rarely been studied (Rentizelas et al. 2009).

Storage is complicated because of the changing seasonal availability of woody biomass and the varied demand of energy plants throughout the year (Sokhansanj et al. 2006, Lin and Pan 2013). Meanwhile, different storage methods will produce biomass at various quality levels, which can significantly affect the transportation and energy conversion efficiency (Jirjis 2005, Casal et al. 2010). The most common way in the northern United States to store green biomass is to directly process wood into chips and store these in piles before being used (Lin and Pan 2013). This storage method poses several problems, such as dry matter loss, moisture content (MC) increase, and energy content reduction (Fredholm and Jirjis 1988, Thörnqvist and Jirjis 1999, Jirjis 2001, Garstang et al. 2002, Afzal et al. 2010). Storing forest harvesting residues in bundles, as the second option, can produce high-quality biomass feedstock with low biomass MC, higher energy content, and low ash content (Lehtikangas and Jiris 1998, Pettersson and Nordfjell 2007, Afzal et al. 2010). Yet the bundling technology is associated with several problems, such as high capital investment and low productivity caused by saw binding, materials handling, twine spool collapse, and slow movement at the harvesting site (Leinonen 2004, Rummer et al. 2004, Harrill 2010). Compared with piling wood chips and bundling residues, leaving unchipped or unbundled harvesting residues on-site in piles can avoid high processing costs and effectively reduce biomass MC, thus increasing transportation and conversion efficiency (Amos 1998, Lin and Pan 2015).

Michigan is a state with 84 percent forest cover; forest resources have been viewed as a widely available and promising resource for renewable energy production (Dickmann and Leefers 2003, Zhang et al. 2011). In Michigan, there are 11 biomass-based power plants with a total of 210 MW of energy generated annually, which is about 2.8 percent of the total production in the United States (Biomass Power Association 2014, Biomass Magazine 2015). During the winter in Michigan, from October to March, the average high temperature is about 41°F, and the average low temperature is about 26°F. With more than 51 inches of annual snowfall, forest harvesting operations are not always possible in the winter months. To ensure a cost-effective and reliable supply of high-quality biomass feedstock to the power plants, a computer-aided improved operations system was developed. The objectives of this research were (1) to develop an improved operations system that can increase biomass feedstock quality and minimize the total cost, including processing, storage, and transportation, and (2) to test the effects of transportation distance and biomass MC on the total cost of processing, storage, and transportation. In this article, the objective function is set to be the total cost (in dollars). The unit cost of the biomass feedstock (dollars per green ton; short ton) is also reported.

Problem Description

Feedstock storage and transportation operations

Because the quantitative relationships between local weather factors and biomass MC during storage are developed based on two previous studies conducted in Michigan from August to November, the woody biomass is assumed to be harvested at the beginning of August and stored in the field from August to November (Lin and Pan 2013, 2015). The selected harvest site is a natural forest stand with mixed hardwood and softwood species 40 miles away from the feedstock end user, Cadillac Renewable Energy LLC. A part of the logging residues are in-woods chipped and then transported to and stored in the end user's facility to meet its first-month demand. The remaining unprocessed residues are allowed to be piled at the harvest site for a certain time. The unprocessed residues are chipped and hauled to the end user based on its continued monthly demand.

Feedstock end user and demand

The feedstock end user, Cadillac Renewable Energy LLC, is located in Cadillac, Michigan. It is one of the largest biomass-based power plants in Michigan and is exclusively designed to use recycled wood waste as its primary fuel source. This power plant has a 38-MW energy production capability, and the average monthly use of woody material (~45% MC) is about 35,000 green tons in the wintertime and about 25,000 green tons in other months. These feedstocks are constantly supplied by 40 logging companies delivering around 1,000 green tons (equivalent to 550 dry tons if assuming 45% MC) per month. Although the hauling distance varies for each logging company, the average feedstock supply radius is around 20 to 40 miles.

Traditional operations system and improved operations system

In this case simulation, a traditional operations system refers to the traditional way of handling harvested biomass, where logging residues are directly processed into wood chips and immediately delivered to the feedstock end user and then stored in the facility as a wood chip pile. In an improved operations system (Fig. 1), a linear programming model is used to determine the weight of the logging residue that will be chipped right away and delivered to the feedstock end user to meet its immediate demand; the remaining unprocessed portion will be stored as a large logging residues pile at the roadside. After several months of air-drying, unprocessed logging residues will be chipped by a mobile chipper and delivered to the feedstock end user monthly.

Biomass storage

In the improved operations system, chipping, storage, and transportation costs are closely related to the woody biomass MC, which is significantly affected by storage form. Two previous studies (Lin and Pan 2013, 2015) showed that piling unprocessed logging residues can effectively reduce biomass MC but that piling wood chips cannot. Several predictive equations were developed in

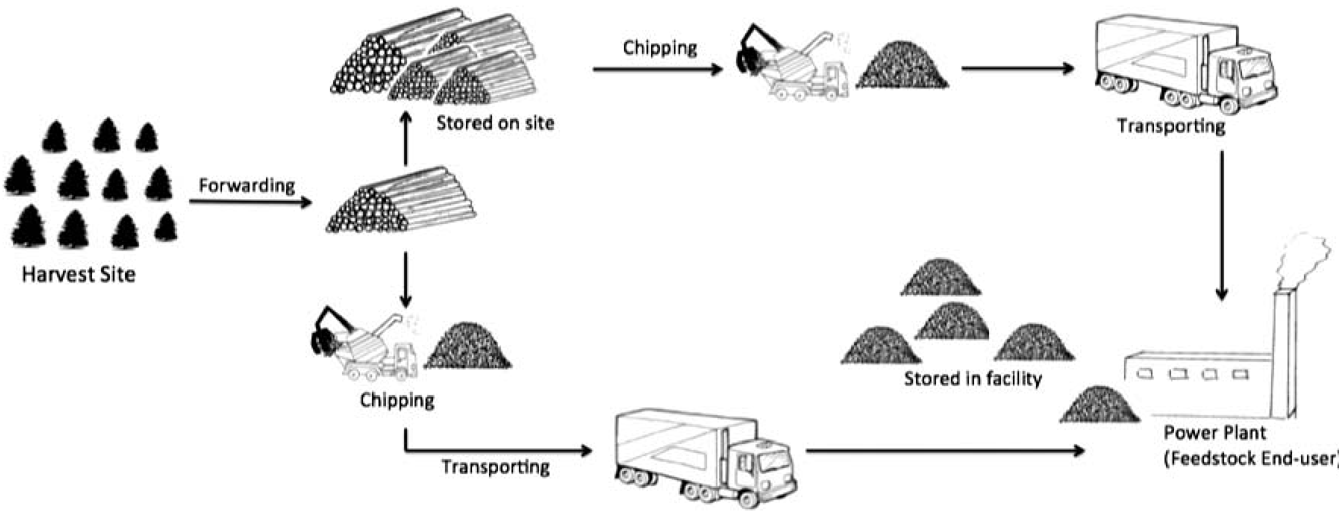

Figure 1.—An illustration of the improved operations system includes biomass chipping, storage, and transportation.

these two previous studies to reveal the quantitative relationship between certain weather conditions and the MC of the logging residues pile (Table 1). Because biomass MC is critical for deciding the selling price of woody biomass in this model, we use the previously developed predictive model and the local weather conditions from August to November 2013 to predict the monthly MC of piled logging residues. The biomass MCs of the wood chip pile are cited values from the study published by Lin and Pan (2015).

Transportation costs

The one-way transportation distance is set to be 40 miles in this case simulation. The transportation cost in dollars per green ton is estimated based on the equation developed for the Lower Peninsula of Michigan (Lautala et al. 2012b; Table 2).

Holding cost and additional profit

In the improved operations system, part of the fresh biomass will be stored as residue piles at the harvest site for air-drying. This will delay the feedstock suppliers' cash flow and lead to future operation costs, such as those for machine mobilization. The delay in cash flow in this model is defined as the holding cost, which accounts for the interest lost from the revenue of all the piled logging residues. The equation used to calculate the holding cost (HC) is

$$HC = R_R \cdot \left[1 + r \cdot t + (1 + r \cdot t)^2 + \cdots + (1 + r \cdot t)^j\right] \quad (1)$$

$$R_R = WR_n \cdot PR_0 \quad (2)$$

Table 1.—August through November woody biomass moisture content (MC) in Michigan.[a]

Biomass MC (%)	Wood chip pile (%)	Logging residues pile (%)
Aug.	40.3	23.8
Sep.	39.3	18.1
Oct.	40.7	26.1
Nov.	45.5	25.9

[a] Sources: Lin and Pan (2013, 2015).

where j is the total time of biomass storage ($j = 3$ mo); R_R is the total revenue for selling all the biomass stored in logging residue pile form; WR_n is the green weight of biomass harvested in August, stored as piled logging residue for n months; PR_0 is the purchasing price ($/green ton) of logging residues that were harvested in August; r is the yearly interest rate (0.03); and $t = 1$ month (0.08 yr).

It is beneficial for feedstock end users to use feedstock with higher energy content and lower MC to increase energy conversion efficiency. To offer an incentive and profit for feedstock suppliers to store biomass in residue piles, it is assumed that the feedstock purchase price is based on their lower heating value (LHV), which will increase with the decrease of biomass MC. Therefore, drier biomass has higher purchasing prices (Roise et al. 2013). The Michigan-based prevailing purchase price for wood chips is assumed to be $23.00 per green ton for biomass with 45 percent MC (L. Heibel, personal communication, June 11, 2014; N. Verhanovitz, personal communication, June 25, 2014). The LHV of the 45 percent MC wood chips can be estimated using the following equation (Maker 2004):

$$LHV = HHV \times (1 - MC/100) \quad (3)$$

where HHV is the higher heating value of the oven dried biomass and MC is the wet-basis MC of the received biomass.

For instance, if the HHV of the woody biomass is assumed to be 8,400 BTUs/lb (Maker 2004), the LHV of 45 percent MC woody biomass is calculated to be 4,620.00 BTUs/lb. When the Michigan-based prevailing purchase

Table 2.—Transportation costs at different transportation distances in Michigan.

One-way transportation distance (mi)	Transportation cost ($/green ton)
20	5.88
30	6.42
40	6.97
50	7.52
60	8.07

Table 3.—Calculated feedstock purchase prices based on the LHV and the energy cost of $2.49/MM BTUs.[a]

Biomass MC (%)	HHV (BTUs/lb)	LHV (BTUs/lb)	Calculated purchase price ($/green ton)
60	8,400	3,360.00	16.73
55	8,400	3,780.00	18.82
50	8,400	4,200.00	20.91
45	8,400	4,620.00	23.00
40	8,400	5,040.00	25.09
35	8,400	5,460.00	27.18
30	8,400	5,880.00	29.27
25	8,400	6,300.00	31.36
20	8,400	6,720.00	33.45

[a] LHV = lower heating value; MC = moisture content; HHV = higher heating value.

price is $23.00/green ton, then the energy cost is determined to be $2.49 per million BTUs ($2.49/MM BTUs). The calculated feedstock purchase prices for woody biomass at various MC levels are summarized in Table 3.

Mathematical model

Indices.—n: biomass storage time ($n = 0, 1, 2, 3$ months).

Variables.—WC_n: green weight of biomass harvested in August, stored as piled wood chips for n months (Fig. 2); WR_n: green weight of biomass harvested in August, stored as piled logging residue for n months (Fig. 2).

Parameters.—db: monthly feedstock demand of 1,000 green tons (45% MC in wet basis; equivalent to 550 dry tons) for the energy plant; Z: total cost of preprocessing, storing, and delivering feedstock; KC: total chipping cost ($) for processing all the biomass; KP: total piling cost ($) for shaping the logging residues into biomass piles; KMG: machine mobilization cost ($) of moving a mobile grinder to the harvest site; KML: machine mobilization cost ($) of moving a loader to the harvest site; KT: transportation cost ($) of delivering chipped biomass to the end user; AP: additional profit ($) earned by selling higher-quality biomass; mc_{Cn}: MC of biomass harvested in August and stored as wood chips for n month(s); mc_{Rn}: MC of biomass harvested in August and stored as logging residue for n month(s); hhv: higher heating value (BTUs/lb); LHV_{Cn}: net energy content of wood chips (BTUs/lb); LHV_{Rn}: net energy content of logging residue (BTUs/lb); PC_n: purchasing price ($/green ton) of wood chips that were harvested in August and stored for n month(s); PR_n: purchasing price ($/green ton) of logging residues that were harvested in August and stored for n month(s); p_s: standard purchasing price ($23/green ton) for energy plant to purchase biomass (45% wet basis); ec_s: energy cost ($/BTU); HC: costs ($) incurred while holding the biomass stored as logging residues piles; r: yearly interest rate.

Constraint.—Satisfy the monthly demand (dry weight) of the energy plant

$$[(1 - mc_{Cn}) \cdot WC_n + (1 - mc_{Rn}) \cdot WR_n] - (1 - 45\%)\, db \geq 0$$

where $n = 0, 1, 2, 3$ months; mc_{Cn} = MC of biomass harvested

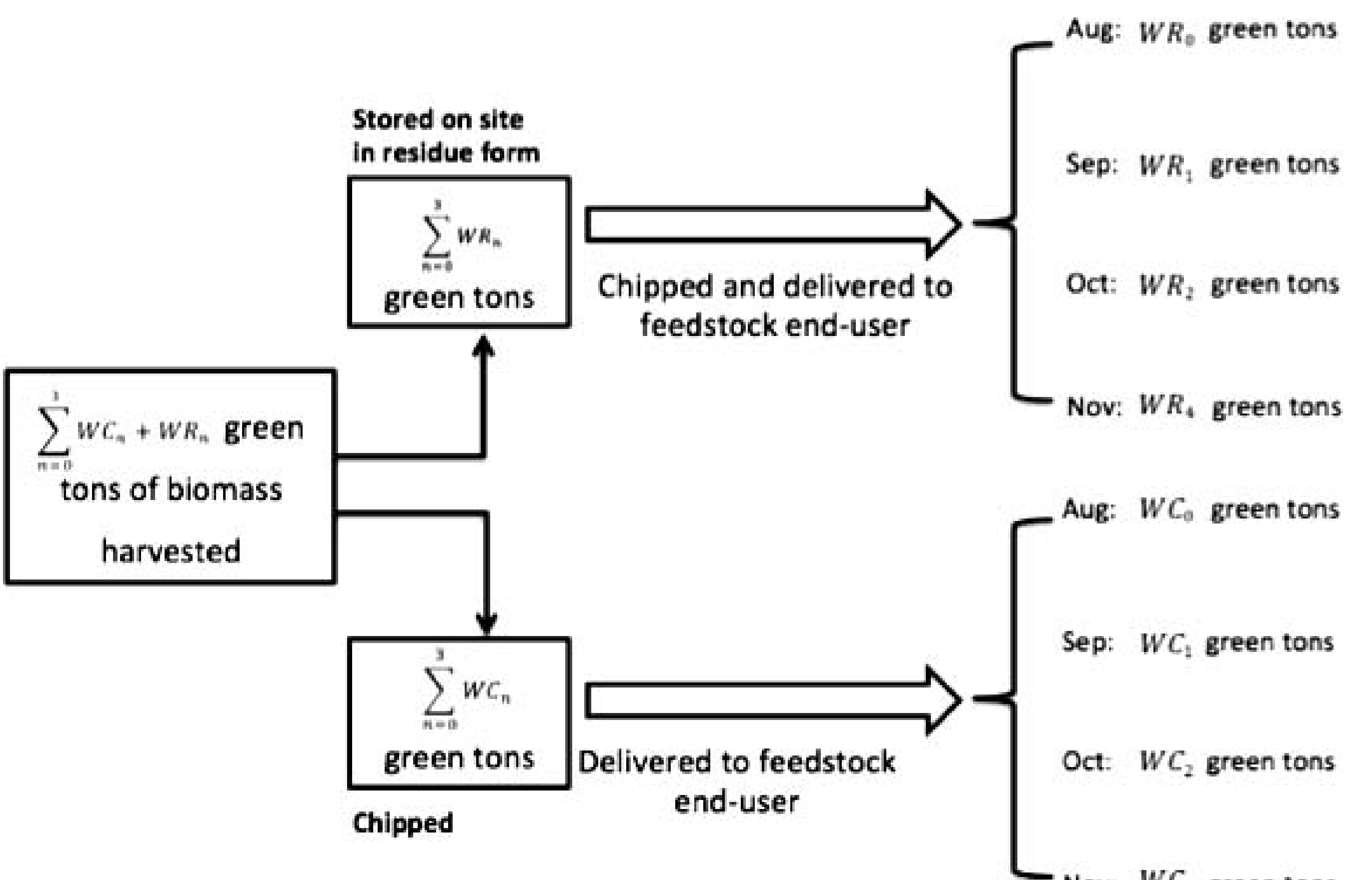

Figure 2.—The weight of woody biomass feedstock delivered to the end user.

in August and stored as wood chips for n month(s); mc_{Rn} = MC of biomass harvested in August and stored as logging residue for n month(s); WC_n = the green weight of biomass harvested in August and stored as wood chip pile for n month(s); WR_n = the green weight of biomass harvested in August and stored as piled logging residue for n month(s); db = 1,000 green tons (MC = 45%, or 550 dry tons).

Objective function.—The total cost can be expressed as

$$Z = KC + KP + KMG + KML + KT - AP + HC \quad (4)$$

where

$$KC = 5.00 \sum_{n=0}^{3} (WC_n + WR_n) \quad (5)$$

$$KP = 4.59 \sum_{n=0}^{3} WR_n \quad (6)$$

$$KMG = 2.52 \sum_{n=0}^{3} (WC_n + WR_n) \quad (7)$$

$$KML = 2.52 \sum_{n=0}^{3} WR_n \quad (8)$$

$$KT = 6.97 \sum_{n=0}^{3} (WC_n + WR_n) \quad (9)$$

$$AP = \sum_{n=0}^{3} (PC_n \cdot WC_n + PR_n \cdot WR_n) - PC_0 \cdot \sum_{n=0}^{3} (WC_n + WR_n) \quad (10)$$

$$PC_n = LHV_{Cn} \cdot \frac{2{,}000\text{lb}}{\text{green ton}} \cdot ec_s \quad (11)$$

$$LHV_{Cn} = \sum_{n=0}^{3} hhv(1 - mc_{Cn}) \quad (12)$$

$$PR_n = LHV_{Rn} \cdot \frac{2{,}000\text{ lb}}{\text{green ton}} \cdot ec_s \quad (13)$$

$$LHV_{Rn} = \sum_{n=0}^{3} hhv(1 - mc_{Rn}) \quad (14)$$

$$HC = WR_n \cdot PR_0 \cdot r \cdot t \cdot \left[1 + (1 + r \cdot t) + (1 + r \cdot t)^2 + (1 + r \cdot t)^3\right] \quad (15)$$

Table 4.— Parameter values used in the case simulation.

Parameter	Value	
Site conditions		
Feedstock user	Cadillac Renewable Energy	
Transportation distance (mi)	40	
Costs ($/green ton)	Wood chip pile	Logging residues pile
Chipping	5.00[a]	5.00[a]
Piling[b]	0	4.59[c]
Machine mobilization[d]	2.52[e]	2.52[e]
Total processing	7.52	12.11
Transportation[f]	6.97[a]	6.97[a]

[a] Lautala et al. (2012b).
[b] Assume the chipper has an attached loader; the wood chips are blown to a chip van and hauled away immediately after the chipping operations.
[c] Harrill (2010).
[d] The mobilization cost includes cost for moving chipper and loader.
[e] Zamora (2013).
[f] The transportation cost is $9.75/green ton with additional $0.15/green ton per mile after 20 miles (Barnes 2010).

where n = 0, 1, 2, 3 months; r = 0.03 (yearly interest rate); t = 1 month (0.08 yr); WC_n = green weight of biomass harvested in August and stored as wood chips for n month(s); WR_n = green weight of biomass harvested in August and stored as piled logging residue for n month(s); PC_n = purchasing price ($/green ton) of wood chips that were harvested in August and stored for n month(s); PR_n = purchasing price ($/green ton) of logging residues that were harvested in August and stored for n month(s); hhv = higher heating value (BTUs/lb); LHV_{Cn} = net energy content of wood chips (BTUs/lb); LHV_{Rn} = net energy content of logging residue (BTUs/lb); ec_s = energy cost ($/BTU); mc_{Cn} = MC of biomass harvested in August and stored as wood chips for n month(s); and mc_{Rn} = MC of biomass harvested in August and stored in logging residue for for n month(s). Other parameter values are listed in Table 4.

This linear programming optimization model is analyzed by Solver (Frontline Systems, Inc. 1990–2009) and can also be solved by other software, such as the General Algebraic Modeling System (GAMS Development Corporation 2013), LINDO API 9.0 (LINDO Systems, Inc. 2015a), or LINGO 15.0 (LINDO Systems, Inc. 2015b).

Results and Discussion

The improved operations System A

The details of using the improved operations system to continuously supply the end user with high-quality biomass feedstock for 4 months is summarized in Table 5. The improved operations system favors a shift from piling wood chips toward piling logging residues for achieving lower MC.

At the beginning of August, a total of 3,079.68 green tons of biomass will be harvested to meet the end user's demand until November. An amount of 921.69 green tons of biomass will be immediately processed into wood chips and delivered to the end user to meet its August demand. The remaining 2,157.99 green tons of biomass will be stored as piled logging residues at the harvest site. At the end of August, a mobile grinder needs to be moved to the harvest site to process 671.51 green tons of 1-month air-dried logging residue into wood chips. The wood chips will then

Table 5.—The costs of using an improved operations system to sell biomass feedstock to the end user in improved System A.[a]

	Storage form		Split cost ($)					
Month	Wood chip pile	Logging residues pile	Chipping	Piling	Machine mobilization	Transportation	Holding cost ($)	Total cost ($)
Aug.	$\sum_{n=0}^{3} WC_n = 921.69$[b]	$\sum_{n=0}^{3} WR_n = 2{,}157.99$[c]	4,608.45	9,905.16	7,760.78	6,424.18	164.96	28,863.54
Sep.	$WC_1 = 0.00$	$WR_1 = 671.51$	3,357.53	0.00	1,692.19	4,680.39	165.36	9,895.48
Oct.	$WC_2 = 0.00$	$WR_2 = 744.49$	3,722.45	0.00	1,876.12	5,189.10	165.76	10,953.44
Nov.	$WC_3 = 0.00$	$WR_3 = 741.99$	3,709.95	0.00	1,869.81	5,171.67	166.15	10,917.60
Total	921.69	2,157.99	15,398.38	9,905.16	13,198.91	21,465.34	662.24	60,630.06
Total biomass harvested (green tons)								3,079.68
Additional profit ($)								22,204.90
Total cost after additional profit ($)								38,425.16
Production cost ($/green ton)								12.48

[a] Definitions of the abbreviations used in the equations are provided in the text.
[b] Total weight of green biomass stored as wood chip pile.
[c] Total weight of green biomass stored as logging residues pile.

be delivered to the end user to meet its September demand. During October and November, a similar process will take place. The chipper will produce 744.49 green tons of 2-month field-stored biomass and 741.99 green tons of 3-month field-stored biomass to meet the end user's October and November demands, respectively.

The highest total operations cost of $28,863.54 occurs in August. The chipping cost, piling cost, machine mobilization cost, and transportation cost account for 15.96, 34.31, 26.89, and 22.26 percent of the total cost, respectively. The lowest total cost of $9,895.48 is in September. This includes the chipping cost, machine mobilization cost, and transportation cost for selling 671.51 green tons of biomass stored as logging residue pile. The monthly total costs for October and November are $10,953.44 and $10,917.60, which depend mainly on the weight of biomass processed and delivered in each month. The total cost for the 4 months of operations sums up to $60,630.19, and the unit production cost is $19.68/green ton. The largest component of the total cost is the transportation cost, which represents 35.40 percent of the total cost. The holding cost of $662.24 accounts for only 1.09 percent of the total cost owing to the relatively small amount of held biomass.

Comparison between improved operations System A and the traditional operations system

The total cost of the improved operations System A is $60,630.19, which costs the feedstock supplier $6,089.70 more compared with the traditional operations system because of the extra machine mobilization cost and the piling cost associated with establishing logging residue piles (Table 6). However, the higher cost of the improved operations system can be offset by the additional profit of $22,204.90 from selling higher-quality feedstock (Table 5). As a result, the feedstock suppliers can expect a net cost (total cost minus the additional profit) of $38,425.29 by adopting the improved operations system.

In improved operations System A, the total amount of biomass required to meet the end user's 4-month demand is 3,079.68 green tons, while in the traditional operations system, a total of 3,764.00 green tons of biomass is required to meet the 4-month demand. The 684.32 green tons of reduction in green biomass delivered to the end user is caused by the drier biomass using the logging residues pile as the storage method suggested by the improved operations system.

Table 6.—The costs of using a traditional operations system to sell biomass feedstock to the end user.[a]

	Storage form		Split cost ($)					
Month	Wood chip pile	Logging residues pile	Chipping	Piling	Machine mobilization	Transportation	Holding cost ($)	Total cost ($)
Aug.	$\sum_{n=0}^{3} WC_n = 3764.00$[b]	$\sum_{n=0}^{3} WR_n = 0.00$[c]	18,820.02	0.00	9,485.29	26,235.08		54,540.36
Sep.	$WC_1 = 906.64$	$WR_1 = 0.00$	0.00	0.00	0.00	0.00	0.00	0.00
Oct.	$WC_2 = 927.32$	$WR_2 = 0.00$	0.00	0.00	0.00	0.00	0.00	0.00
Nov.	$WC_3 = 1{,}008.35$	$WR_3 = 0.00$	0.00	0.00	0.00	0.00	0.00	0.00
Total	3,764.00	0.00	18,820.02	0.00	9,485.29	26,235.08	0.00	54,540.36
Total biomass harvested (green tons)								3,764.00
Additional profit ($)								0.00
Total cost after additional profit ($)								54,540.36
Production cost ($/green ton)								14.49

[a] Definitions of the abbreviations used in the equations are provided in the text.
[b] Total weight of green biomass stored as wood chip pile.
[c] Total weight of green biomass stored as logging residues pile.

Table 7.—The costs of using an improved operations system to sell biomass feedstock to the two end users in improved System B.[a]

Month	End user 1[b]		End user 2[c]		Split cost ($)				Holding cost ($)	Total cost ($)
	Wood chip pile	Logging residues pile	Wood chip pile	Logging residues pile	Chipping	Piling	Machine mobilization	Transportation		
Aug.	$\sum_{n=0}^{3} WC_n = 921.69$[d]	$\sum_{n=0}^{3} WR_n = 2,157.99$[e]	$\sum_{n=0}^{3} WC_n = 1,843.38$[f]	$\sum_{n=0}^{3} WR_n = 4,315.97$[g]	13,825.35	29,715.47	23,282.35	31,802.1	494.89	99,120.16
Sep.	0	671.51	0	1,343.01	10,072.58	0	5,076.58	12,577.3	496.08	28,222.54
Oct.	0	744.49	0	1,488.98	11,167.36	0	5,628.35	13,944.31	497.27	31,237.29
Nov.	0	741.99	0	1,483.98	11,129.85	0	5,609.44	13,897.47	498.46	31,135.23
Total	921.69	2,157.99	1,843.38	4,315.97	46,195.14	29,715.47	39,596.73	72,221.18	1,986.7	189,715.23
Total biomass harvested (green tons)										9,239.03
Additional profit ($)										66,614.65
Total cost after additional profit ($)										123,100.57
Production cost ($/green ton)										13.32

[a] Definitions of the abbreviations used in the equations are provided in the text.
[b] End user 1 refers to Cadillac Renewable Energy.
[c] End user 2 refers to the simulated second feedstock end user, which is added to test the model.
[d] Total weight of green biomass stored as wood chip pile for end user 1.
[e] Total weight of green biomass stored as logging residues pile for end user 1.
[f] Total weight of green biomass stored as wood chip pile for end user 2.
[g] Total weight of green biomass stored as logging residues pile for end user 2.

Improved operations system with two feedstock end users (System B)

To further test the model, a second feedstock end user (end user 2) is introduced to the operations system. End user 2 is assumed to be located 20 miles away from the harvest site, with a monthly demand of 2,000 green tons of woody biomass (1,100 dry tons assuming 45% wet-basis MC). All the parameters remain the same as those in the improved operations System A with one feedstock end user. The corresponding objective function becomes the summed net cost of supplying woody biomass to two end users. The constraints for the improved operations System B are to meet the 1,000 green tons of monthly demand for end user 1 (550 dry tons assuming 45% wet-basis MC) and 2,000 green tons of monthly demand for end user 2 (1,100 dry tons assuming 45% wet-basis MC). The decision variables are the monthly delivered biomass weight in green tons to the two end users.

Table 7 presents the optimized solution with the monthly delivered biomass weight for end user 1 and end user 2. Since the unit cost (dollars per green ton) for chipping, piling, and machine mobilization is the same for the two end users, the total chipping, piling, and machine mobilization costs for end user 2 are doubled compared with end user 1 owing to its doubled biomass monthly demand. For the transportation cost, the unit transportation cost for end user 2 is reduced because of the shorter transportation distance; therefore, the transportation cost will not increase proportionally to the biomass weight increase (Table 2). The simulation showed that the total cost to supply biomass feedstock to the two end users is $123,100.57 with a unit cost of $13.32/green ton.

The results indicate that the logging residue pile is the recommended storage form in operations System B because it can produce drier woody biomass. However, there is a small chance that the biomass from one harvest site can support two feedstock end users at the same time because 1 MW of electrical production requires 3,987 acres of typical pine plantation (National Association of Conservation Districts 2015).

Sensitivity analysis—Effects of transportation distance on the total cost and the improved operations system

In this simulation, the transportation distance from the harvest site to the end user was set at 40 miles. In the sensitivity analysis, the range of the transportation distance considered is from 20 to 60 miles. The transportation distance has no impact on the biomass storage and transportation strategy but affects the total cost through changing the transportation cost. When the distance increases from 20 to 60 miles, the total cost after deducting the additional profit rises linearly from $35,056.08 to $41,806.73 (Fig. 3). The sensitivity analysis indicates that every 1 mile of transportation distance increase will raise the total cost by $168.77. The additional profit earned from selling higher-quality feedstock is $22,204.90. This additional profit can cover the increased transportation cost caused by a one-way distance increase for up of 171 miles. This result suggests that the negative impact of longer transportation distance in the woody biomass supply chain can be mitigated by the higher feedstock quality.

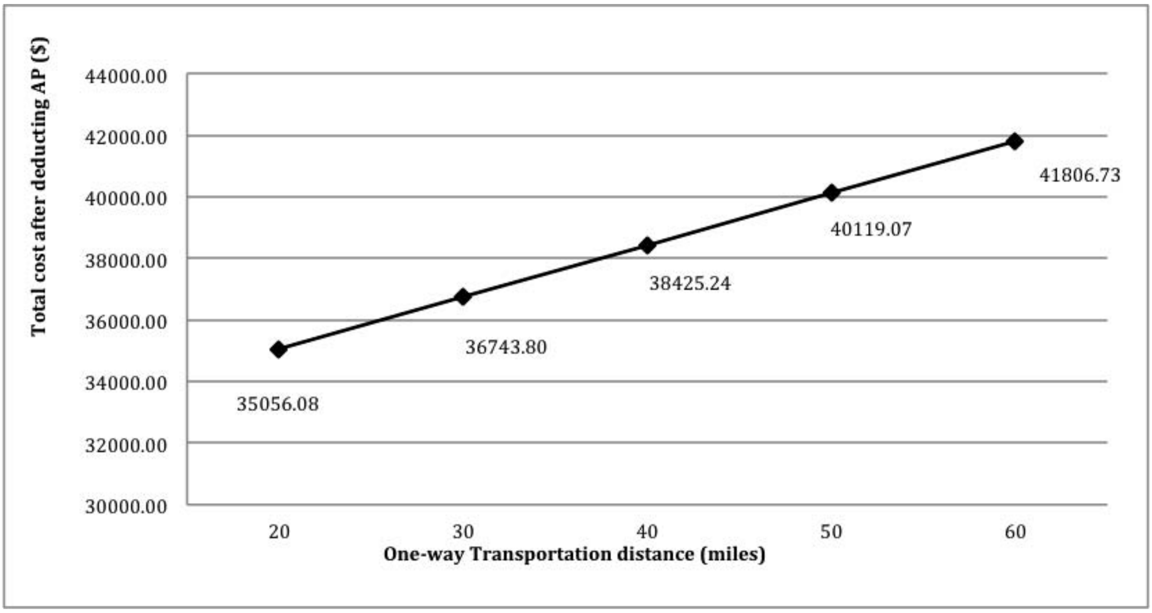

Figure 3.—Total cost after deducting additional profit (AP) associated with different one-way transportation distances.

Sensitivity analysis—Effect of biomass MC on the total cost and the improved operations system

The effect of biomass MC on the total cost was determined by changing the MC at a 5 percent increment (Fig. 4). On average, every 1 percent increase in biomass MC can result in a $760.68 increase in the total cost after deducting additional profit. With every 5 percent decrease in biomass MC, the total cost after deducting additional profit is reduced by $2,976.29. On the other hand, when the biomass MC increases by 5, 10, and 15 percent, respectively, the total cost after deducting additional profit will increase to $3,439.78, $4,023.11, and $4,772.51, respectively. In addition, this cost increase owing to feedstock MC increment presents an ascending curve instead of being linear, indicating that a large increase in MC will have a more significant impact on the total cost. The harvesting operations, therefore, are suggested to take place in the late spring or summer, when initial biomass MC tends to be lower, to reduce the total cost.

Although the effect of biomass MC on the total cost is nonlinear (Fig. 4), the sensitivity analysis indicates that every 1 percent decrease in biomass MC will reduce the total delivered biomass green weight by 52.10 green tons on average. This means that using the improved operations system can prevent 52.10 tons of water from being transported to the end user, thus increasing the transportation efficiency. For different biomass MC, piling unprocessed logging residue is always the preferred way to store biomass mainly because this storage method can produce drier biomass feedstock through air-drying.

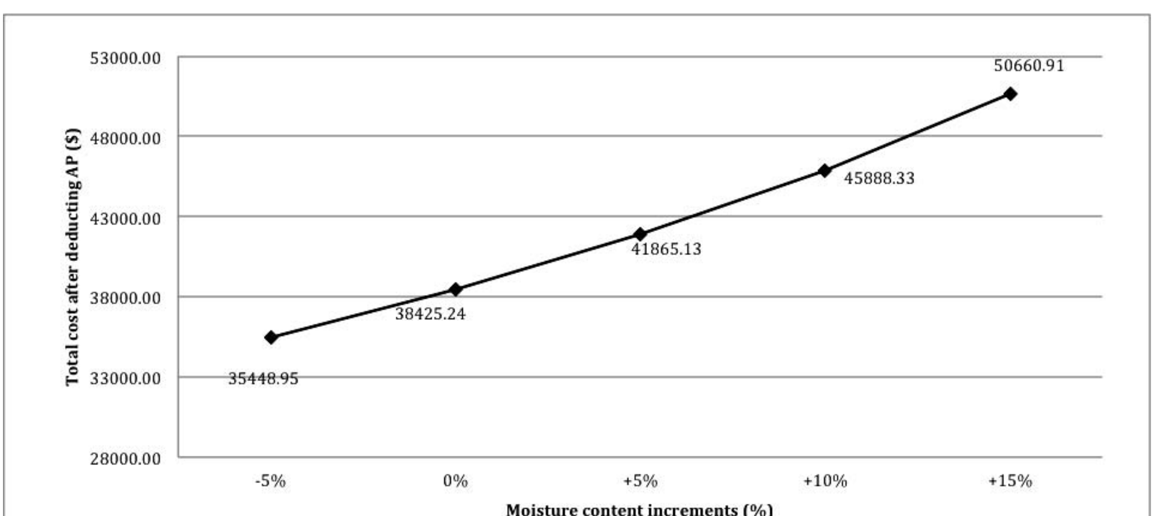

Figure 4.—Total cost after deducting additional profit (AP) it associated with different biomass moisture content.

Model limitations

The improved operations system simulated by the linear programming model has many limitations in real operations. For example, real operations cannot process field-stored biomass at the accurate amount as the computer-aided improved operations system suggests. However, this improved operations system can serve as a guideline for real-world operations. The scheduling of real-world operations can be adjusted toward what the improved operations system indicates; thus, improved feedstock supply chain cost-effectiveness can be realized.

The calculated feedstock purchase price in this simulation is based on a feedstock purchase price provided by a personal research contact (L. Heibel, personal communication, June 11, 2014) because currently the increased economic value of higher-quality feedstock is justifiable only by increased recoverable energy content. In reality, a feedstock conversion and upgrading facility may only partially return its profit from using higher-quality feedstock to the feedstock suppliers. The current US market does not have any mechanism for pricing the higher-quality woody biomass or allocating the increased profit between feedstock suppliers and end users. Using drier biomass is a more profitable way for both feedstock suppliers and end users, as transporting drier biomass (having higher energy content) results in lower energy cost and using drier biomass increases boiler efficiency.

The additional profit from selling higher-quality feedstock discussed in this article is based on using direct combustion as the conversion option. The additional profits from the increased efficiency using different biomass conversion and upgrading options will vary. In addition to direct combustion, other conversion and upgrading options include palletization, fast pyrolysis, torrefaction, and fermentation. In future research, more conversion and upgrading scenarios will be considered.

Conclusions

An improved operations system for biomass storage and transportation is proposed using a computer-based linear programming technique. The case simulation results indicate that when using logging residue pile as the major storage form, the extra cost of $6,089.70 owing to piling operations and machine mobilizations can be offset by the additional profits of $22,204.90 from selling higher-quality feedstock. In addition, because of the drier biomass achieved in the improved operations system, the delivered biomass green weight to satisfy the 4-month energy demand is reduced by 684.32 green tons compared with the traditional operations system. By introducing end user 2 in the additional testing of the operations system, the simulation results confirm that logging residue pile is still the preferred storage method.

Sensitivity analyses were conducted to evaluate the effects of transportation distance and biomass MC on the improved operations system and the total cost. The sensitivity analysis indicates that for every 1-mile increase in transportation distance, the total cost will be raised by $168.77. The additional profit from selling higher-quality feedstock can offset the increased transportation cost for up to 171 miles. The changes in biomass MC affect both the improved operations system and the total cost. It can be concluded that the impact of biomass MC is more significant when it is higher. On average, every 1 percent increase in biomass MC can result in a $760.68 increase in total cost. In addition, a 1 percent decrease in biomass MC will cause a decrease of 52.10 green tons in required total biomass green weight to satisfy the end user's demand.

This computer-aided improved operations system can effectively reduce the total cost, improve the efficiency of the biomass supply chain, and simultaneously provide a reliable supply of higher-quality feedstock. Although the operation details suggested by the improved operations system cannot be exactly applied to real operations, it can be used as a guideline for such operations to achieve the lowest possible operations cost. In the future, the additional profit from selling higher-quality feedstock needs to be quantified for various conversion and upgrading options besides direct combustion.

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